Green hydrogen from RES in Poland

The use of wind and PV power for the production of green hydrogen as an opportunity to implement the assumptions of the EU Climate and Energy Policy in Poland

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Green hydrogen
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The use of wind and PV power for the production of green hydrogen as an opportunity to implement the assumptions of the EU Climate and Energy Policy in Poland

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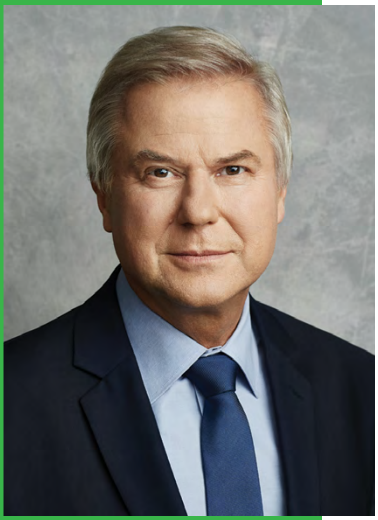


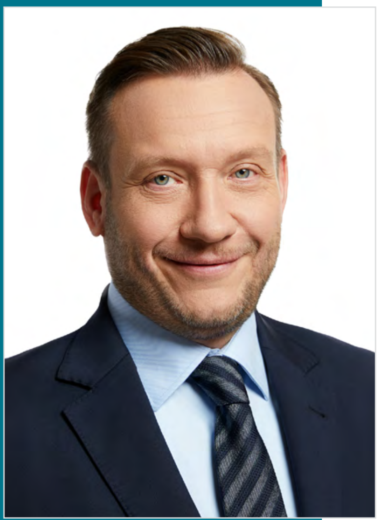
The Polish Hydrogen Strategy specifies 3 key areas, that is industry, power generating sector and transport, 6 specific goals to be achieved and 40 tasks which, when completed, will enable us to become a society that benefits from the hydrogen technologies. In order to get there, we need to ensure implementation of many long-term activities, including but not limited to, achieving a wide agreement for the hydrogen economy with the key role being the cooperation between the government, self-government and business entities; developing positive environment for the so-called hydrogen competency which is a *sine qua non* condition for proper planning of R&D and long-term investment projects.

Facing yet new requirements formulated for example, as part of the European Green Deal policy or of the so-called Fit for 55, from the very beginning, we need to plan how we will base our idea of decarbonization and hydrogen economy on **green hydrogen**. And this requires us to precisely answer to a series of key questions: what are the needs of the Polish and European market in this respect? How can we obtain green hydrogen in large quantities? In what sectors of power generation, gas, industry or transport can we beneficially use it while keeping reasonable technical and financial outlays. What investments are needed for its transfer and storage? And finally, what economic, financial parameters need to be taken into consideration in a long-term funding plan for this kind of strategic investment projects? You will find answers to these questions (and many other important ones) in this report.

I wish to encourage you to read it and widely discuss the recommendations included herein. I believe that both the decision makers and the people of science and industry will be interested in the conclusions. And in the long-term, the conclusions will make it possible to gain competitive advantage on the strategic hydrogen market, yet still open to new solutions.

Maciej Chorowski
President of the Management Board of the National Fund for Environmental Protection and Water Management

FOREWORD by Remigiusz Nowakowski, President of the Management Board of the Lower Silesian Institute for Energy Studies



Green, modern and competitive economy in Poland. Is it possible? I believe so! But there are certain conditions, the most crucial being wide use of "green hydrogen" in power generation, transport and industry. This is also the thesis of this report you're holding now, which was prepared by a multi-discipline team.

When presenting the European Green Deal, the European Commission has outlined a long-term vision of development of the European Union until 2050, which is a challenge for all the member states but also brings a chance for economic development, developing new industries and more importantly, making a green turn by abandoning generation of power from high-emission sources for clean, green and cheap energy from renewable sources.

A key element of energy transformation is sector coupling which will be possible only with the use of zero-emission and preferably renewable, energy sources. Developing the technologies for production and use of hydrogen in the economy will be one of the crucial factors.

It is because hydrogen can be used as raw material, fuel, energy carrier and to store energy. The European Hydrogen Strategy promulgated by the European Commission on 8 July 2020 gives the outline of the necessary actions in order to enable development of the hydrogen technology. Operation of a system for supporting low-emission hydrogen production in the transitional period is one of the key assumptions.

In this report we have attempted to present the necessary conditions to satisfy the postulate of moving Poland towards hydrogen economy. Obviously, using renewable energy sources for hydrogen production is a key factor for the success of this process. In Poland this requires quick development of capacity of onshore wind farms, construction of offshore wind farms and continued expansion of PV installations. This is the only way so that in 10-20 years we would be able to ensure appropriate availability of zero-emission hydrogen that will make it possible to successfully decarbonize Polish economy!

Remigiusz Nowakowski
President of the Management Board of the Lower Silesian Institute for Energy Studies

FOREWORD by Janusz Gajowiecki, President of the Management Board of the Polish Wind Energy Association

The report “Green hydrogen from RES in Poland” confirms that the development of hydrogen economy is inevitable as an important factor in decarbonizing the Polish power generating industry. In order to make the maximum use of the potential of entities operating in this developing sector, we need a well-thought strategy for the hydrogen economy in Poland as well as clear division of roles and responsibilities. Polish Wind Energy Association is one of the signatories of the “Sectoral Agreement for the Development of the Hydrogen Economy in Poland” which constitutes the first important step towards the development of hydrogen economy in our country.

According to the report, maintaining the leading position on this market will not be possible without switching to green hydrogen, the demand for which for the years to come has been created by the European Union with the corresponding incentive mechanisms and legal regulations.

The report emphasizes the fact that the availability of appropriate capacities installed in the RES is the precondition enabling development of economy based on the green hydrogen. In order to make it possible, by 2040 RES generating capacity should have multiplied and the report indicates a specific number. This is important for the government which, when planning the future energy mix, should take into account the growing demand for the green hydrogen from the economy and its key role in the Polish Power System.

Making full use of the benefits from the transition towards the hydrogen economy requires ensuring suitable supply of electricity from such sources. The report clearly indicates that the natural choice for the process of producing green hydrogen is first and foremost electricity generated from wind as the cheapest source, supplemented with PV sources.

The report has also demonstrated that the rate of growth of the hydrogen market depends on adjusting legal regulations and market standards which not only should enable relatively simple scalability of hydrogen technologies, but also contribute to creating the desired incentives to use hydrogen solutions. Such suggestions are also included in the study. I hope you enjoy reading this interesting and extremely substantive document!

Janusz Gajowiecki
President of the Management Board
of the Polish Wind Energy Association

ABOUT OUR PARTNERS

STRATEGIC PARTNERS

Bank Gospodarstwa Krajowego

Bank Gospodarstwa Krajowego is a state-owned development bank – the only institution of this type in Poland, which mission is to support sustainable social and economic growth of Poland. Its activities have an impact on creating workplaces, constructing apartments, developing infrastructure and improving air quality. The Bank cares for the future generations, promotes entrepreneurship and provides responsible funding. It has branches all across Poland and representative offices in Brussels, London, Frankfurt am Main and Amsterdam. BGK supports exports and expansion of Polish companies abroad. Its is the originator, co-funder and main shareholder of the Three Seas Initiative Investment Fund investing in the transport, energy and digital infrastructure in the Three Seas Region. Cooperating with business, public sector and financial institutions, BGK responds to the needs of the economy and undertakes many initiatives promoting sustainable development.

Hynfra

Hynfra operates in the field of development of infrastructure for green hydrogen.
Hynfra's team of experts have skills that are required for development and design of the most efficient and cost-effective systems in the chain of hydrogen technologies applicable in the decarbonized economy.
We deliver general contracting processes by implementing turnkey projects.
We are the best partner for investors in terms of operation and maintenance of technological processes in new plants, as well as in the sale of green hydrogen and medical oxygen.
The company actively develops technologies for the use of green hydrogen in high-efficiency cogeneration. We support market growth by providing our partners with comprehensive hydrogen technologies dedicated to their processes, while cooperating with the best European, Asian and American suppliers.
We also provide consulting services relating to feasibility studies for green hydrogen-based projects.

National Fund for Environmental Protection and Water Management

The National Fund for Environmental Protection and Water Management was established in 1989, during the regime transformation in Poland, as the first public entity of this kind in the world. While preserving its global uniqueness, for over 30 years the National Fund has been playing an important role in implementing the Polish environmental policy.

STRATEGIC PARTNERS

With stable income, competent and experienced personnel and well-developed ways of cooperation with beneficiaries, the NFEPWM is the main link in the Polish system for funding environment protection and water management, having the greatest financial potential in this field.
The National Fund participates in implementation of various projects for the benefit of the environment, in particular the largest ones, the most innovative ones, frequently having strategic importance to the state.
So far, the NFEPWM has spent over PLN 270 billion on environmental protection and water management, of which more than 2/3 were the own funds, and the remaining was the foreign funding, mostly EU. In total, more than 125 thousand agreements have been concluded with the beneficiaries. For the support of environmentally-friendly development of Poland, the National Fund offers loans, grants and other mechanisms for funding projects implemented by, among others, self-government entities, entrepreneurs, public entities, educational and scientific entities as well as social organizations.
The National Fund is the Implementing Institution for the Priority Axes I and II of the EU Operational Programme Infrastructure and Environment 2014-2020, the main goal of which is to support the economy which efficiently and friendly uses the environmental resources. Its budget was EUR 4.8 billion.

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ORLEN Group

According to the CEE TOP 500 report published by Coface, the ORLEN Group is one of the largest corporations in Central and Eastern Europe in terms of revenue.

In line with the new Strategy 2030, the ORLEN Group's ambition is to be a regional leader of energy transition, construct new power generating capacities using renewable energy sources and implement the decarbonizing process while maintaining operational efficiency and financial strength from the traditional business segments.
The ORLEN Group has been consistently diversifying its operations towards becoming a multi-energy corporation. Part of fulfilling this goal were the acquisition of Energa Group in 2020 – one of the largest generators and suppliers of electricity in Poland, as well as continued efforts to pursue other acquisitions (PGNiG, LOTOS Group).
The ORLEN Group's core business consists in the production and distribution of electric energy, crude oil processing, and production of fuels, petrochemical and chemical products, as well as sale of the Group's products on the retail and wholesale markets. The ORLEN Group is also engaged in hydrocarbon exploration, appraisal and production. It is also one of Poland's largest electricity distributors. It manages over 2.8 thousand fuel stations.

STRATEGIC PARTNERS

Ørsted

In 2021, for the third time in a row, Ørsted ranked as the world's most sustainable energy company in Corporate Knights index of the Global 100 corporations. The company is recognised on the CDP Climate Change A List, which confirms their status of a global leader on climate action.

The Ørsted vision is a world that runs entirely on green energy. This Danish corporation operates in several global markets, from Europe, Asia and Pacific to Northern America. Its portfolio includes 12 GW of renewable capacity, of which 7.6 GW in 28 offshore wind farms. The DKK 350 billion in investment projects, of which approximately 80% will be spent on offshore wind farms and green hydrogen, in 2030 will allow Ørsted to hold 50 GW of RES capacity, of which 30 GW from offshore wind farms.

Poland is one of the key markets for Ørsted, where the company has operated for 10 years, employing today approximately 250 people. Ørsted has already made significant investment in offshore electricity generation in the Polish sector of the Baltic Sea, developing jointly with PGE a 2.5-GW Baltica Offshore Wind Farm as phase one of development of the offshore power generation market. In order to provide even greater support for the Poland's transition towards low-emissions, in the second phase of the development of the Polish market of offshore power generation, Ørsted partners with another Polish entity – ZE PAK – which has initiated an ambitious strategy of phasing out coal until 2030 and investing in RES. Read more about Orsted at Orsted.com. Read more about Orsted activities in Poland at orsted.pl

PGNiG

PGNiG SA is a listed company operating in exploration for and production of natural gas and crude oil. Through its key companies, it is also active in the area of storage, sale and distribution of gas and liquid fuels, as well as heat and electricity generation.

The PGNiG Group plays a key role on the Polish gas market and, as its leader, is responsible for preserving Poland's energy security. To this end, it takes measures necessary to satisfy the steadily growing demand for gas fuel. The PGNiG Group ensures supply diversification by developing domestic deposits and sourcing gas from abroad, as the largest importer and supplier of natural gas in Poland. PGNiG has launched research programmes to develop alternative fuels and to ultimately integrate them into its sales offering. The PGNiG Group plans to engage in projects involving the use of biomethane and the storage and distribution of hydrogen, and also to expand its capabilities in electricity generation from renewable sources based e.g. on solar PV farms.

The Company has branches and representative offices in Russia, Belgium, Pakistan, Belarus and Ukraine. It is the sole owner of PGNiG Upstream Norway AS, engaged in deposit exploration and operations on the Norwegian Continental Shelf and in the Norwegian Sea.

TAURON Polska Energia

TAURON Polska Energia is a holding company in the group of companies involved in generation, distribution and sale of energy. The TAURON Group is one of the major business entities and the largest distributor of electricity in Poland. Since 2019 the Group has been implementing the Green Turn Strategy with the aim of increasing the low-emission sources in the power generation mix, investing in the retrofit of distribution grids and developing environmentally-friendly products and services for customers.

Since 2010 TAURON stock has been listed on the Warsaw Stock Exchange, included but not limited to the WIG20 and WIG30 indices. The company is listed in the index of socially responsible companies – RESPECT Index.

MAIN PARTNERS

DZP
więcej niż prawo

Domański Zakrzewski Palinka Law Firm

Domański Zakrzewski Palinka is the largest, independent Polish law firm. It has 180 experts providing advice in 9 practices and 40 specialisations with offices in Warsaw, Poznań and Wrocław. Our clients include both Polish and foreign companies and investors, representing virtually all sectors of the economy. DZP advisers regularly receive awards and recommendations from Polish and international rankings. DZP has an extensive network of relationships with foreign law and advisory firms operating in over 90 countries. The DZP Law Firm has a team providing comprehensive legal services for businesses operating in the renewable, conventional and nuclear energy sectors, those involved in the cogeneration and district heating industry as well as companies active in the gas and liquid fuel field, including the leading Polish and international energy corporations.

edp renewables

EDP Renewables

EDP Renewables (Euronext: EDPR) is a global leader in the renewable energy sector and the world's fourth largest producer of energy from renewable sources. With a sound development pipeline, first class assets, and market-leading operating capacity, EDPR has undergone exceptional development in recent years and is currently present in 17 international markets (Belgium, Brazil, Canada, Chile, Colombia, France, Greece, Hungary, Italy, Mexico, Poland, Portugal, Romania, Spain, United Kingdom, United States and Vietnam).

Eurowind Energy™

Eurowind Energy

Eurowind Energy A/S is headquartered in Hobro, Denmark. It was established in 2006 and started its business with building a wind farm in Denmark and purchasing several projects, ready for construction in Germany. Today, the company is one of the largest developers, owners and operators of wind and PV farms in Denmark and Europe. Its activity spans across Europe, just to mention Poland, Romania, Sweden, France, Portugal, and many more.
Recently, the company's portfolio was extended with large solar parks in the United States with construction to start in the coming year.

As of 2021, Eurowind Energy A/S has a portfolio comprising more than 650 MW of projects under construction (currently, wind turbines are being installed, among others, in Poland, Germany, England, Sweden, Italy and Denmark) and in operation as well as 18 GW in projects being developed. In Poland, the company operates 8 wind parks, 15 projects under construction and 19 under development.

MAIN PARTNERS

LOTOS

LOTOS is a Polish group of companies and its activity has strategic importance for national and European security in the energy sector, and for the Polish economy. LOTOS produces natural gas and crude oil in Poland, Norway and Lithuania. It is the owner of one of the state-of-the-art European refineries in Gdańsk, in which the raw material is processed into high-quality fuels, including LOTOS Dynamic premium-class fuels. There are also more than 510 fuel stations under LOTOS brand, conveniently located along motorways, express routes, in every agglomeration and in many other locations across Poland. As wholesaler and retailer, LOTOS supplies almost 1/3 of the Polish fuel market. It also ranks 2nd in Poland as a railway carrier. Moreover, LOTOS is the leading producer of bitumens for road industry as well as engine oils and lubricants for cars, aircraft, trains, ships, and even military vehicles.

POLENERGIA

Polenergia is the largest Polish, privately-owned energy group. Our mission is to actively support Polish energy market transition by supporting the development of low-emission economy, clean and renewable energy sources as well as to strive to make the European Union climate neutral by 2050.

Our customers include small, medium and large entrepreneurs as well as individual customers that recognize the challenges of the future, including the need for changing the way energy is used. That is why we already provide them with energy of the future, that is an ecosystem of innovative solutions, based completely on clean and green renewable energy. We have been the first company in Poland to introduce Energy 2051 standard which is compliant with the Green Deal guidelines, being 30 years ahead of the market.

We cooperate with RES producers. We support all customers with expertise and provide with comprehensive services they require.

Strategic projects being implemented by the Group include the construction of offshore wind farms in the Baltic Sea with the capacity of 3000 MW as well as development of green hydrogen production plants.

https://polenergia.pl

INDUSTRY PARTNERS

DNV

DNV is an independent expert in assurance and risk management, operating in more than 100 countries. Being a leading global team of independent energy experts and technical advisers, we help the industry and the governments in navigating across many complex and interconnected transformations of the energy industry that are occurring both regionally and globally. We are committed to achieving the goals of the Paris Agreement and we support our customers in quick transition towards a deeply decarbonized energy system. With a wide range of services we offer, we ensure security of the complete energy chain. We help in operating high-risk assets and systems involving wind, photovoltaics, energy storage, hydrogen, fossil and synthetic fuels, gas, power grids as well as "carbon capture". Our state-of-the-art technical solutions and expertise and understanding of the laws and regulations enable us to provide unique assessments, opinions, studies and knowledge that help our customers to deliver/consume energy in a safe and sustainable manner.

Our deep and wide knowledge allows us to pursue our goal which is safeguarding life, assets and environment. We are a trusted partner who can deal with the largest contemporary global transformation – the energy transformation.

QAIR

Qair Polska is an independent producer of energy from renewable sources and part of the international Qair Group that has been operating on the Polish market since 2015. Currently, Qair Polska employs almost 60 experts and has a portfolio of wind and solar assets comprising: 215 MW in fully operational projects, 173 MW under construction and more than 2.5 GW at early development stages. Qair Polska focuses on company-owned projects, cooperation with third-parties as well as purchasing projects at various development stages.

COMMENTS FROM OUR PARTNERS

Bank Gospodarstwa Krajowego

Green hydrogen is the future of the energy industry, and we currently watch its production using RES shifting from trial and pilot stages to the implementation stage. It is one of the least polluting and controversial ways of storing energy, therefore the European Commission's guidelines for the Member States clearly indicate the need for developing technologies that are based on using this element on our route towards zero emissions.

Currently, hydrogen is on everyone's lips as it forms a significant part of a wider phenomenon. The economies in the developed countries face revolutionary changes of the approach to how we should shape our reality. This is a new race for the best possible living conditions for entire populations – but also for a better, sustainable future.

Being an entity advocating for a sustainable development of Poland, we are committed to developing ideas that will include us among the countries which made the most of this opportunity.

Therefore, BGK has established an initiative with the goal of using the unique situation of the Polish economy. This is a concept of sustainable economy based on responsible management of water resources, use of green hydrogen in the power generating industry and use of innovative carbon technologies – such as carbon nanotubes. Hence the Polish name, 3W (Woda-Wodór-Węgiel – Water-Hydrogen-Carbon).

As part of the 3W initiative, we create the best possible environment for sharing knowledge and experience between scientists, businessmen and government. This is our capital that will be used for building modern, innovative and friendly future (both short- and long-term).

Radosław Kwiecień
Member of the Management Board
of Bank Gospodarstwa Krajowego

HYNFRA Green Hydrogen Infarcture

At times of more and more restrictive climate policy of the European Union, green hydrogen becomes the only possibility for decarbonizing all the areas that cannot be electrified.

The combination of the huge value of available funding with the concurrent need for reforming the Polish power system in terms of adapting it to the quickly growing share of RES and the need to replace the generating units (as well as the distribution system) determine the strategic opportunity of green hydrogen.

The direction of changes and reforms is clearly defined by the EU, and the burden of emitting assets for the Polish energy industry is paradoxically a perfect starting point to discount the dividend on the development gap. Learning a lesson from the development of RES in other countries, producing hydrogen using the excess capacity can determine the removal of the barrier for wide-scale development of this branch of the energy industry.

When reviewing the available technologies for hydrogen production, we should take into consideration not the current pricing conditions but the directions indicated by the European New Green Deal as the industrial investments have an assumed service life of several years and, thus they will be subject to new macroeconomic reality announced by the recent increase in price of the European Emission Allowances. Hydrogen requires a wide range of auxiliary solutions such as efficient transport and storage, but according to the available strategic analyses, it is the only option that could enable final, complete decarbonizing.

Tomoho Umeda
President of the Management Board
of Hynfra

National Fund for Environmental Protection and Water Management

National Fund for Environmental Protection and Water Management

Hydrogen is one of the key areas of interest of NFEPWM as we have no doubt that in the coming years the importance of hydrogen produced using energy from RES will gradually increase. The use of wind and solar energy for producing hydrogen brings us an opportunity to implement the goals of the EU climate and energy policy. However, in order to be able to make use of this opportunity, we need to act taking into consideration the system and market conditions, learning from the examples of other countries that decided on a similar step. This will enable us to select the most effective strategy – the one ensuring that production of hydrogen in Poland has both environmental and economic justification. The NFEPWM has the ability and the ambition to play a leading role in implementing the assumptions of the Polish Hydrogen Strategy, among others, by proposing three key programs required for the development of distributed hydrogen projects, already performed on the Polish market. The first component is included in the **New Energy** program. The call for proposals in the area "Production, transport, storage and use of hydrogen" has resulted in selecting 6 promising hydrogen projects for further development. The second component, **Green Public Transportation** provides funding for purchase of, among others, hydrogen-fuelled buses and hydrogen refuelling stations. The third component is a program **"Transition towards hydrogen economy**", currently under development. It was conceived to be a tool supporting the commissioning and implementation of hydrogen technology production in Poland, means for breaking barriers and stabilizing this type of pioneer ventures.

Maciej Chorowski
President of the Management Board of the National Fund for Environmental Protection and Water Management

ORLEN Group

PKN ORLEN becomes a strong multi-energy corporation, ensuring energy security and stability in the Central Europe. In the published strategy, PKN ORLEN has declared to achieve net zero emissions until 2050. On the one hand, this is a huge challenge, but on the other, an opportunity for regional development through investments in new low- and zero-emissions technologies. One of the major directions that could change the economy, industry, transport and how their impact on the climate, is turning towards hydrogen technologies. For years now, hydrogen has been considered fuel of the future. However, it is today that we get a chance to fully use hydrogen to leverage industry decarbonization. PKN ORLEN has been consistently implementing the hydrogen program comprising projects associated with the implementation of hydrogen technologies in transport, such as Clean cities, prototype of hydrogen-fuelled locomotive built in cooperation with PESA or large-scale infrastructure projects, such as the Hydrogen Eagle flagship program.
This report presents a comprehensive spectrum of applications of hydrogen technologies on the way towards neutral emissions and points out the key areas in which Poland has an opportunity to develop competitive advantage. Subjects particularly close to the PKN ORLEN's strategy are the synergies of offshore wind farms with large-scale hydrogen production described in the report as well as the issues connected with development of Polish hydrogen technologies. The document focuses on making more available the comprehensive guidelines for hydrogen economy regulations.
I encourage you to read the report, which constitutes an important step in expanding the knowledge about hydrogen and its role in the energy transition.

Grzegorz Jóźwiak
Director, Alternative Fuels Implementation Office, PKN ORLEN

COMMENTS FROM OUR PARTNERS

Ørsted

Development of commercial technologies for hydrogen production using renewable energy sources is the focal point of international and Polish efforts associated with stopping the global temperature rise below 1.5°C in relation to the pre-industrial era. It is because exceeding this limit would mean starting a domino effect that could cause extreme weather conditions that would force millions to migrate. Today, we are on the verge of climate disaster since we have exceeded the threshold of 1°C with greenhouse gas emissions still rising. That is why we need increased efforts from decision-makers, scientists and companies investing in the fuel of the future, including hydrogen from RES.

At Ørsted we believe that suitable investments and research can make the green hydrogen a cheap and generally available alternative to fossil fuels that will play a key role in the global transformation.

This belief is based on scientific premises. Already in 2008, in response to voices raised by climate experts, we have abandoned fossil fuels and entered the path towards zero emissions. It would not have happened if we hadn't commercialized offshore wind energy generation – a technology that we have been developing since 1991, which is the date of erection of the first offshore wind farm. All activities and entire production of Ørsted will become climate-neutral in 2025, and we expect the same of our business partners until 2040. This is why we support our key suppliers, and sometimes, even competitors, in order to work together on developing green hydrogen and to decarbonize these industries which currently generate a lot of emissions, such as steel production or transport. This is the purpose of our partnerships for development and commercialization of technologies of hydrogen production of RES described herein.

The group of international Ørsted partners has just been expanded with ZE PAK, Polish energy generation company, which creates in Poland an innovative value chain, from hydrogen production from RES to constructing a manufacturing site of hydrogen-fuelled buses, to developing refuelling stations for hydrogen vehicles. We are glad to join our efforts and we plan joint actions through which Ørsted and ZE PAK can support Poland on its path to climate neutrality.

Joanna Wis-Bielewicz
Sustainability and Stakeholders Manager
Ørsted Polska

PGNiG

The EU energy policy provides for a significant increase in Renewable Energy Sources (RES). As a result, hydrogen production using electrolysis will also increase so it can be used a "green" energy carrier. Hydrogen technologies will gradually become less of a curiosity and more of an important part of the European, including Polish, economy. Hydrogen is supposed to be a medium enabling storage of electricity. This will solve the greatest weakness of RES, that is seasonal fluctuations and unstable production in relation to the demand.

Hydrogen-focused technologies have become very interesting for many key players of the electricity and gas market who are getting ready for the transition towards low-emissions economy. Moreover, green hydrogen used in the chemical industry, cogeneration or transport will require appropriate distribution and storage technologies.

Therefore, as the RES share in the energy mix increases, the development of technologies for large-scale storage of energy becomes more and more important in order to enable efficient balancing of the power system.
Providing clear regulations and support mechanisms is particularly important for the new technologies to develop in order to remove the barriers associated with the lack of technological maturity and creating a suitable scale of the market which is currently at its early development stage with low level of both demand and supply. RES and hydrogen technologies could become a pillar for the energy transformation in Poland and increase our safety. That is why it is so vital that many issues requiring actions and innovative approach be properly diagnosed and practically solved.

Arkadiusz Sekściński
Vicepresident of the Management Board
for Development

TAURON Polska Energia

TAURON is working on hydrogen technologies

In 2030, TAURON aims to have 66% of its energy mix made up of low- and zero-emissions assets. This means a huge potential of available green energy that can be used for producing green hydrogen.
For several years now, the Research and Innovations Unit at the TAURON Group has been carrying out pilot projects associated with the production of "green" hydrogen and products based on it. In 2019, we have completed the CO2-SNG project consisting in processing the "green" hydrogen together with CO_2 into synthetic natural gas (SNG). The CO2-SNG project was in turn a foundation for the current TENNESSEE project, in which highly-efficient electrolysis of water vapour and CO_2 capture are supported with fuel cells.
Drawing from the Group's experience from research projects, in March we have submitted the HYDROGEN POLAND project to the Ministry of Development and Technology. The project marks the transition from the pilot stage to the demonstration scale, while encompassing the entire hydrogen technology chain.
TAURON Group's representatives are also involved in the works of the Hydrogen Partnership established by the Ministry of Climate and Environment. TAURON is one of the signatories of the Hydrogen Agreement concluded on 14 October.
TAURON Group recognizes the potential in the development of technologies for obtaining green hydrogen and using products based on it, including for the purposes of hydrogen-fuelled urban transport. In the future, the role of hydrogen as a large-scale means of energy storage can also be important. Moreover, wider use of hydrogen produced from renewable energy sources in the industry and power generation can support phasing out conventional fossil fuels. We expect the support mechanisms outlined in the Polish and European hydrogen strategies to enable business sound investments in this area.

Jerzy Topolski
Vicepresident of the Management Board for Assets
Management, TAURON Polska Energia

List of abbreviations

°C	– degrees Celsius
ALK	– alkaline electrolyser
ARE	– Agencja Rynku Energii S.A. [Energy Market Agency] in Warsaw
AtEx	– Atmosphères Explosibles
ATR	– Autothermal Reforming
CaFCP	– California Fuel Cell Partnership
CAPEX	– capital expenditures for product development
CCS	– Carbon Capture & Storage plant
CCU	– Carbon Capture & Utilization plant
CDGU	– centrally dispatched generation unit
CHP	– cogeneration
CO_2	– carbon dioxide
DRI	– Direct Reduced Iron
DSO	– Distribution System Operator
EC	– European Commission
EHB	– European Hydrogen Backbone
ERO	– Energy Regulatory Office
ETBE	– Tertiary-Butyl-Ethyl Ether
ETS	– Emissions Trading System
EU	– European Union
FCCJ	– Fuel Cell Commercialisation Conference of Japan
FCEV	– Fuel Cell Electric Vehicles
FCH JU	– Fuel Cells and Hydrogen Joint Undertaking
FCR	– Frequency Containment Reserve
FRR	– Frequency Restoring Reserve
GHG	– Greenhouse Gases
GIE	– Gas Infrastructure Europe
GW	– gigawatt
HHV	– Higher Heating Value
HRS	– H_2 Refueling Station
HVAC	– High Voltage Alternating Current transmission line
HVDC	– High Voltage Direct Current transmission line
HySUT	– The Research Association of Hydrogen Supply/Utilization Technology
IBRST	– Iron Bath Reactor Smelting Reduction
IEA	– International Energy Agency
IPCEI	– Important Projects of Common European Interest

IRENA	– International Renewable Energy Agency
JCM	– Joint Credit Mechanism
kWh	– kilowatt hour
LCOE	– Levelised Cost of Electricity
LCOH	– Levelised Cost of Hydrogen
LEW	– onshore wind power
LHV	– Lower Heating Value
LNG	– liquefied natural gas
MMA	– methane methacrylate
Mt	– million tonnes
MTB	– methyl tertiary butyl ether
MW	– megawatt
nCDGU	– non-centrally dispatched generation unit
NEDO	– New Energy and Industrial Technology Development Organization
NFOŚiGW	– National Fund for Environmental Protection and Water Management
NPS	– National Power System
OPEX	– operating expenditures
OWE	– offshore wind power
P2G	– Power to Gas
PEM	– polymer electrolyte membrane electrolyser
PEP2040	– Energy Policy of Poland until 2040
PGNiG	– Polish Oil and Gas Company
PKN Orlen	– Polski Koncern Naftowy Orlen
PSE SA	– Polskie Sieci Elektroenergetyczne S.A. [joint-stock company]
PHS	– Polish Hydrogen Strategy
PV	– photovoltaic
RES	– renewable energy sources
RRF	– Recovery and Resilience Facility
SAF	– Sustainable Aviation Fuel
SOE	– Solid Oxide Electrolyser
SOEC	– Solid Oxide Electrolysis Cell
SPEG	– Solena Plasma Enhanced Gasification
SU	– System services
TSO	– Transmission System Operator
TWh	– terawatt hour

SUMMARY

The *"Green Hydrogen from Renewable Energy Sources in Poland"* report is the first such comprehensive study that takes up the whole subject of green hydrogen. On the one hand, it provides an overview of what is happening in this area in Poland, the EU and the world, and, on the other, it addresses issues of supply and demand for this fuel in the short and long term. The report presents the current condition of the hydrogen market, prospects for its future development and sectors of the economy in which this fuel will be applied. The analysis shows that in the next few decades hydrogen, especially its green variety, may become the basis for the functioning of industry in Poland and the EU. However, for this to happen, it is necessary to remove a number of barriers that have been identified in detail in the report, including above all those currently blocking the development of renewable sources for hydrogen production.
And it is precisely the issues related to the production possibilities of this fuel and the development of demand that constitute the great added value of this report. In the public debate so far, issues related to hydrogen production possibilities have been ignored, taking for granted that in the future there will be enough renewable sources to provide this supply. Meanwhile, the reality is quite different; the report confirms that if we do not quickly eliminate barriers to the development of RES, especially wind power plants, we will have real problems with providing enough hydrogen to meet the growing demand. The dynamics of the hydrogen sector, especially its green variety, is evidenced by the projects described in the report, the completion and implementation of which gives a real chance to boost the development of green hydrogen market in Poland and EU.

Key findings:

- Annual demand for hydrogen in Poland in 2040 will exceed 100 TWh.
- Hydrogen production in Poland should be carried out along three pathways, i.e. use of surplus RES, operation of a dedicated part of RES generation in the off-grid system integrated with dedicated electrolysers and dispersed production for local needs.
- By 2040, there is a realistic chance that electrolysers with a capacity of over 20 GW will be able to meet the demand for hydrogen.
- Rapid action is needed to meet the requirements of the hydrogen economy, in particular, in terms of hydrogen transfer, storage and grid connection capacities.
- A necessary condition for the development of an economy based on green hydrogen is access to adequate RES capacity. To make this possible, in 2040, RES generation should be over 60 GW. Thus, the planned transformation of the Polish energy sector should take into account the growing demand for green hydrogen in the domestic economy and its key role in the NPS.
- Energy transformation requires that conventional coal-fired power plants be retired from the NPS and no new ones be built. In the future, the NPS must operate on the basis of renewable sources (mainly onshore and offshore wind farms and photovoltaics) and energy storage systems.

- At present, the pace and plans for RES development are unlikely to meet future demand for green hydrogen.
- It is necessary to eliminate barriers and to facilitate the construction of renewable energy sources, especially wind energy, which will be the basis for the functioning of the hydrogen economy.
- It is necessary to introduce changes in the licensing of hydrogen production, transmission through the gas network and its storage, as well as to support the development of direct lines connecting RES installations with customers equipped with electrolysers, enabling the storage of surplus electricity produced, regardless of their connection to the power grid.
- It is necessary to allocate a part of RES potential with the highest capacity utilisation rate (offshore wind energy) for direct hydrogen production, without considering the balance needs of the power system and without the need to connect generation sources and electrolysers to the grid (off-grid operation).
- In order to accelerate the development of the hydrogen economy, it is necessary, in the first phase, to provide financial support for this type of investment.
- The challenges of hydrogen market development should be seen from the perspective of the need to reduce the costs associated with hydrogen production, transport, distribution and storage, as well as the costs of hydrogen-using equipment, vehicles and infrastructure.
- The speed of development of the hydrogen market will largely depend on the adaptation of legal regulations and market standards, which should not only enable relatively easy scaling-up of hydrogen technologies, but should also create the expected incentives for the use of hydrogen-based solutions.
- A stable legal framework will be needed to facilitate investment throughout the entire hydrogen supply chain (equipment manufacturers, infrastructure providers, vehicle manufacturers, etc.).

Achieving climate neutrality in Europe, including Poland, will not be possible without the large-scale introduction of hydrogen utilisation technologies in power generation, gas, transport and industry. However, for hydrogen to play its role in the decarbonisation of European economies, it is necessary to ensure access to emission-free production technologies. In Polish conditions, the key role in the production of pure hydrogen should be played primarily by renewable sources, whose operation, thanks to the properties of hydrogen allowing for energy storage, will better stabilize the National Power System.

01

INTRODUCTION

The EU climate policy, with the announcement in 2019 of the *European Green Deal*, has accelerated rapidly, becoming a top priority for the European Commission. Many important decisions and actions have already been taken, including the adoption of the EU Hydrogen Strategy and the European Council's decision to cut carbon emissions by 55% by 2030. And in July 2021, a proposed *Fit for 55* package of legislation was presented to align EU law with ambitious climate protection policies. The EC's clearly uncompromising approach to achieving the climate neutrality by 2050, as announced in the *European Green Deal*, will necessitate deep technological and organisational changes not only in the energy sector, but also in many other economic sectors, such as transport and construction.

Green hydrogen is also the focus of a growing number of economic stakeholders who see significant business potential in this fuel. In July 2020, with the political support of the EC, the European Clean Hydrogen Alliance (ECHA) was established. It brings together industrial entities representing the entire hydrogen value chain, public authorities, research institutions, social organisations. It aims at an ambitious deployment of hydrogen technologies by 2030, bringing together renewable and low carbon hydrogen production, demand from industry, mobility and other sectors, and hydrogen transmission and distribution. With ECHA, the EU wants to build its global leadership in this field to support the EU's commitments to achieve climate neutrality by 2050[1].

The European Union's growing climate ambitions also influence the shape of Poland's energy strategy. The current *Energy Policy of Poland until 2040* declares an increase in the share of RES in gross final energy consumption to at least 23% by 2030 with concurrent reduction of the share of coal down to 56% in the energy sector[2]. In the following decades, the transition away from coal fuel is to be continued until the last mine is phased out by the end of 2049[3]. The final share of green hydrogen in Poland's long-term energy mix is not yet determined. An important impulse for the development of this (hydrogen) sector in Poland is also the initiative led by the Ministry of Climate. Representatives of government administration, the business community, science and business environment units, signed the 'Sectoral Agreement for the Development of the Hydrogen Economy in Poland' on 14 October 2021 in Warsaw. The strategic goal of the Agreement is to maximise the Polish contribution ("local content") in the order processing chain for the needs of building the hydrogen economy. It confirms that green hydrogen as a fuel for decarbonisation is already a permanent element of the public discussion on the course of the transformation of the Polish energy sector and is included in the government's strategic plans.

The report, prepared under the aegis of the Polish Wind Energy Association and DISE Energy, focuses on an analysis of an important issue for the Polish energy sector, namely the possibility of using wind power and photovoltaics (PV) in the process of acquiring green hydrogen. This issue is presented in the context of Poland's implementation of the current EU climate policy. The report includes, therefore, the description of the most important documents of strategic character shaping the development of green hydrogen market in EU and Poland. In view of the above, it is wind power and PV that should be seen as technologies that will make it possible to obtain adequate amounts of green hydrogen for the Polish economy in the future. The political, regulatory, economic and technological aspects of this issue have been taken into account. Clarification of the following issues is considered crucial:

1 European Clean Hydrogen Alliance, https://ec.europa.eu/growth/industry/policy/european-clean-hydrogen-alliance_en

2 B. Sawicki, *Energy Strategy of Poland until 2040 has been officially published*, 10.03.2021, https://biznesalert.pl/strategia-energetyczna-opublikowana-pep-2040-odejscie-od-wegla-oze-atom-gaz-energetyka/

3 https://www.gov.pl/web/aktywa-panstwowe/historyczne-porozumienie-dla-polskiego-gornictwa

- **the problem of how to achieve a sufficiently high share of wind and PV power while at the same time addressing their variable performance in the context of future energy consumption for the production of green hydrogen;**
- **determination of future demand for hydrogen in the national economy, taking into account its role in balancing the NPS and the needs arising from technological transformation of the industry;**
- **comparison of technological and economic conditions of wind and PV power in the context of their ability to produce green hydrogen;**
- **impact of hydrogen production from wind farms and PV on the functioning of the National Power System; the problem is presented mainly in the context of the needs for balancing and regulation of the NPS in the perspective to 2040;**
- **use of green hydrogen as an energy storage cooperating with the power grid in order to stabilize its working conditions.**

The complexity of the issue analyzed in the report required an interdisciplinary and cross-sectional research approach. Therefore, the report was based, inter alia, on a formal analysis including a review of strategic documents of the EU and Poland, a comparative analysis referring to the presentation of strategies and system solutions that support the production of green hydrogen in Germany - a leading country in this field in the EU. Reference was also made to the achievements of economic sciences and knowledge of the functioning of electricity systems.

The analysis is also aimed at a multi-faceted assessment of the possibility of using wind and PV power for the production of green hydrogen, based on a comparison of the strengths and potential limitations of these technologies. The report also focuses on identification of the main barriers blocking the development of green hydrogen production in Poland. This issue was analyzed primarily in the context of current and future production capacity of wind and PV power. Identification of problems that hinder acquisition of adequate volumes of green hydrogen for the national economy was aimed at finding answers to the following questions:

- **What will be the scale and pace of RES development, including in particular wind energy, in Poland?**
- **what is and will be the RES potential for green hydrogen production in Poland in the context of future domestic demand for this raw material?**
- **What infrastructure problems need to be solved for the storage, transport and energy use of green hydrogen?**
- **What is the potential of using green hydrogen for RES energy storage and to what extent can the use of green hydrogen increase the stability of onshore and offshore wind farms?**
- **What should be the scale of investment needed in green hydrogen production?**
- **What financial needs will investments in green hydrogen production generate?**

The list of questions adopted in the publication is obviously not complete, taking into account the complexity of the issue, which is the hydrogen economy. Due to the adopted substantive scope, the consideration of the issue of the future model of the green hydrogen market in Poland and the mechanism of its price formation was omitted. The problem of security of the future green hydrogen market and possible threats were also excluded. In our view, these topics require separate in-depth studies and papers.

An important element of the presented analysis is also the identification and presentation of future benefits for the difficult process of decarbonisation of the Polish economy, obtained after the introduction of green hydrogen into its circulation. The analysis compares, inter alia, different hydrogen production technologies in terms of the emissions associated with their use. It is the reduction of greenhouse gas emissions due to the use of green hydrogen which is to constitute the main justification for incurring significant costs and efforts to overcome technological or organizational barriers in the near future. The scale of this reduction will depend, however, on the extent to which clean hydrogen will be used in the economy, that is, its technological and economic ability to replace the raw materials and fuels currently being emitted. This issue is closely related to the possibility of using the existing transport (gas pipelines), storage (gas warehouses) or industrial (refineries, chemical plants) infrastructure for green hydrogen. Overcoming the technical and logistic barriers will obviously require appropriate financial outlays. Undertaking the investment effort by the Polish economy for the higher goal, which is climate protection, should therefore receive adequate support from the EU and the Polish state. For this reason, the report also includes a description of available and planned measures to support the development of projects dedicated to green hydrogen.

In conclusion, this report points first to wind power and complementary PV sources as the natural choice for green hydrogen production. However, this choice will entail dealing efficiently with the real challenges and constraints in its production, distribution and use.

02

GREEN HYDROGEN – CHARACTERISTICS AND MARKET CONDITIONS

2.1 Characteristics of green hydrogen

Hydrogen is one of the most common elements in the world. It is a component of water and hydrocarbons, and given its beneficial physical and chemical properties, it is a good substitute for fossil fuels in the global energy transition[4]. During the combustion process of hydrogen, water vapor is produced. Hydrogen fuel, compared to conventional fuels, has a relatively high energy value. Hydrogen can be used as a raw material, fuel, energy carrier or also as an energy storage[5].

There are many ways to obtain hydrogen. When making a classification according to the method of receiving, a division into two characteristic groups is introduced:

- Hydrogen produced from fossil fuels (grey, blue, purple) by, inter alia, steam, autothermal or partial oxidation reforming and pyrolysis of hydrocarbons, as well as by waste treatment;
- Hydrogen produced using renewable energy sources (green) through biological processes (e.g. bio-photolysis, dark fermentation, photo-fermentation) and water decomposition (electrolysis, thermolysis, photolysis), as well as steam reforming and pyrolysis of biomethane.

However, taking into account the level of carbon dioxide emissions from the production of hydrogen and classifying it as a final product, the following can be distinguished:

- conventional (high-carbon or grey) hydrogen, commercially produced in large quantities, based on the use of fossil fuels (e.g. steam reforming of natural gas, coal seam gasification or separation from coke oven gas;
- Low-carbon hydrogen (blue), produced using the potential of low-carbon non-renewable sources and the application of technologies for CO_2 capture, storage/use (CCS) or renewable sources with a low carbon footprint (including steam reforming of hydrocarbons with CCS, coal gasification with CCS, electrolysis with electricity from traditional sources with CCS;
- Renewable (green) hydrogen, generated by H_2O electrolysis, powered by electricity produced by renewable energy sources[6].

It is worth stressing that according to the Renewable Energy Directive (Article 2(63)), a distinction is made between renewable fuel of non-biological origin (RFNBO) and this fuel includes: renewable hydrogen and hydrogen based synthetic fuels.

Another nomenclature, which has so far been readily used, was based on defining hydrogen by colour according to the source of its production:

- Brown hydrogen - hydrogen obtained from coal gasification,
- Grey hydrogen - hydrogen obtained from methane reforming,
- Blue hydrogen - hydrogen obtained from methane reforming using CCS or CCU facilities,
- Green hydrogen - hydrogen obtained by electrolysis of water in an electrolyser powered by electricity from RES. Green hydrogen is sometimes subdivided into hydrogen obtained from an electrolyser cooperating with an onshore wind power plant (light green colour) and hydrogen obtained from an electrolyser cooperating with a photovoltaic power plant (yellow colour).

4 *New hydrogen economy - hope or hype?* World Energy Council, 2019, pp. 8-27.

5 *A Hydrogen Strategy for a Climate Neutral Europe*, Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions, Brussels, 8.7.2020. COM(2020)301 final.

6 P. Nikolaids, A. Poullikkas, *A comparative overview of hydrogen production processes*, "Renewable and Sustainable Energy Reviews" 2017, p. 599; I. Dincer, *Green methods for hydrogen production*, "International Journal of Hydrogen Energy" 2012, pp. 1954-1971; M. Newborough, G. Cooley, *Developments in the global hydrogen market: the spectrum of hydrogen colours*, "Fuel Cells Bulletin" 2020, pp. 16-22.

Grey hydrogen, which comes from burning fossil fuels, is said to have the highest carbon footprint. Blue hydrogen also comes from burning natural gas or coal, but using carbon capture technologies (CCS) to keep the carbon dioxide out of the atmosphere. Purple hydrogen, on the other hand, comes from methane pyrolysis obtained by using high temperatures in nuclear reactors. Green hydrogen, on the other hand, is produced by electrolysis from renewable energy sources and is given global priority in the energy transition.

Currently, according to the International Energy Agency (IEA), the dominant role in hydrogen production is played by natural gas, which produces about 76% of the world's production of this fuel[7]. Coal also plays an important role, producing 24% of the world's hydrogen. Electricity is currently used to produce hydrogen only to a marginal extent. Hydrogen obtained in a way which does not generate large CO_2 emissions accounts for only 0.1% of global production[8]. It is estimated that in the EU less than 4% of hydrogen produced comes from electrolysis. The costs of the electrolysis process have been falling steadily over the past decade and have fallen by more than 60%[9] since 2010 to date. This contributes to the growing popularity of renewable hydrogen worldwide[10]. However, most of hydrogen produced today is produced through emission-intensive processes based on the mining of fossil fuels, which affects the generation of its carbon footprint[11]. Spreading of decarbonisation through the use of hydrogen technologies, making hydrogen an environmentally friendly renewable fuel, is predicted within the next few decades[12].

2.2 Review of available and developing hydrogen production technologies with comparative emissions analysis

In 2018, global hydrogen production was around 115 million tonnes and led to emissions of around 830 million tonnes of CO_2. This represents around 2.2% of global emissions from the energy sector and is equivalent to 2.5 times the UK's annual emissions[13]. The vast majority of hydrogen is used in the chemical industry (e.g. for ammonia production), refining and metallurgy, but its importance is also growing in transport and power generation.

The most commonly used method of hydrogen production is Steam Methane Reforming (SMR), although its variants, such as Partial Oxidation (POX) or Autothermal Reforming (ATR)[14] combining both methods, are also commercially used on a smaller scale. SMR technology produces about 48% of the world's hydrogen. It consists in triggering, in devices called reformers, at high temperature (usually above 750°C) and high pressure and in the presence of a catalyst, the reaction of steam and methane (although methanol, propane-butane or natural gas may also be used) whose products are hydrogen and carbon monoxide. A by-product of this process is high CO_2 emissions, due to the need to carry out the process in

7 *The Future of Hydrogen*, Report prepared by the IEA for the G20, Japan Seizing today's opportunities, p. 38.

8 M. Dorociak, M. Tomecki, *Hydrogen. Fuel of the future*, 300 Reserach, Warsaw 2019, p. 14.

9 *Path to hydrogen competitiveness: A cost perspective*, 20 January 2020, p. 23.

10 European Commission, *Hydrogen generation in Europe: Overview of costs and key benefits*, 2020, p. 6; International Energy Agency; *The Future of Hydrogen - seizing today's opportunities*, 2019, pp. 38-42.

11 *Shaping tommorow's global hydrogen market,* Baker McKenzie, 2020, p. 6.

12 *Hydrogen's Decarbonization Impact for Industry Near-term challenges and long-term potential*, Rocky Mountain Institute, 2020, pp. 1-5.

13 International Energy Agency, *The Future of Hydrogen. Japan Seizing today's opportunities*, Paris 2019, p. 38.

14 International Energy Agency, *The Future of Hydrogen...*, p. 28.

the presence of a lot of heat, as well as the characteristics of the gas. This amounts to an average of 9-10 tonnes of CO_2 for each tonne of hydrogen produced (tCO_2/tH_2). Converting this rate to the energy stored in hydrogen results in 0.3 tonnes of CO_2 per MWh. For comparison, the emissivity of electricity production from coal reaches 0.9 t/MWh.

Due to the high economic viability of producing hydrogen from gas, attempts are made to reduce CO_2 emissions by using technologies for its capture, utilisation and storage (CCUS). According to the literature data, at 90% reduction achievable, the amount of emissions in the reforming process is 1 tCO_2/tH_2, and at 56% reduction – about 4 tCO_2/tH_2[15] (0.03 t/MWh and 0.12 t/MWh, respectively).

Reforming is the most thermodynamically and economically efficient way of producing hydrogen - the cost of producing 1 kg of raw material in this technology usually ranges from USD 1 to approx. 2.5[16]. This depends on a number of technological and economic factors, the two most important of which are the price of natural gas itself and capital expenditures. The former, depending on geographical region, accounts for 45-75% of the total cost of steam reforming. This means that the costs are lower in countries with large indigenous gas resources, e.g. Russia, the USA or the Middle East, and much higher in Europe, Japan or China. Investment expenditures, in turn, are influenced e.g. by the availability and possibility of constructing an appropriate infrastructure.

The average cost of producing 1 kg of hydrogen using the steam reforming method is about USD 1 in the USA, Russia and the Middle East, while in the EU it is USD 1.7 and in China USD 1.75. In Poland this cost amounts to ca. PLN 7 for 1 kg of hydrogen (at a gas price of PLN 1200 for 1000 m^3)[17]. These expenses are on average about 50% higher when using CCUS. When converted to energy contained in hydrogen, the cost of obtaining it with the use of steam reforming technology is 210 PLN/MWh (using CCUS: 315 PLN/MWh).

On a global scale, the average CAPEX is in the range of 500-900 USD/kg H_2 for systems without CCUS and USD 900-1 600 for CCUS[18]. However, this largely depends on the price of the CO_2 capture and storage infrastructure, among other factors, so these estimates are only approximate.

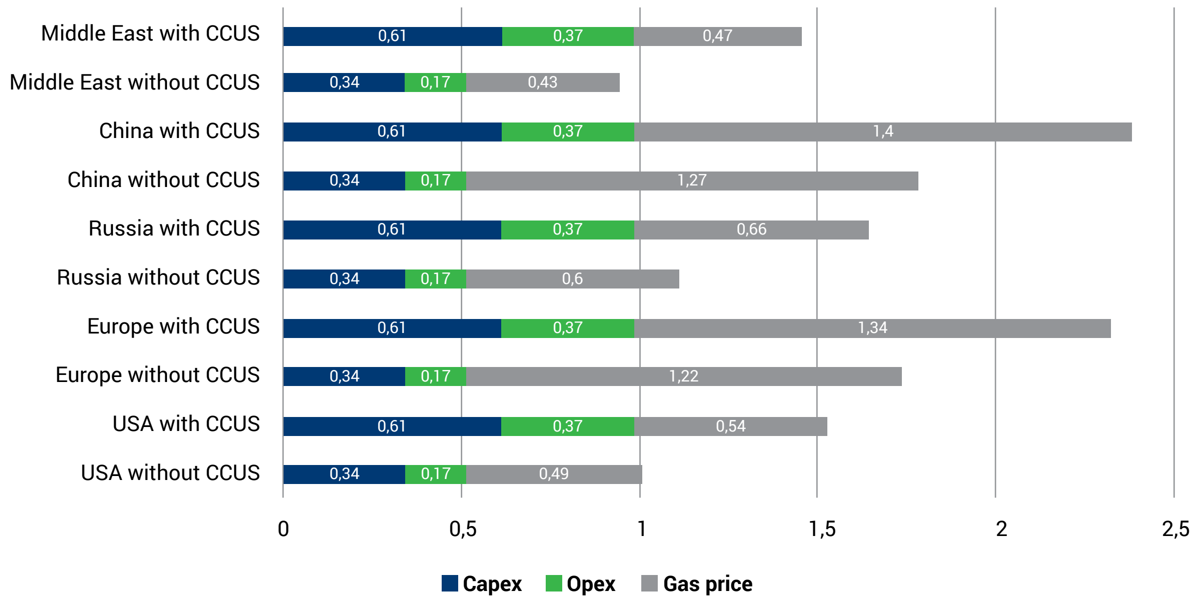
15 T. Chmielniak, *Czy i jakie technologie? Czyli wszystko, co trzeba wiedzieć o nowym globalnym źródle energii, Wodór w Energetyce* 2021, 1/65, Warsaw 2021, p. 77.

16 International Energy Agency, *The Future of Hydrogen...*, p. 42.

17 T. Chmielniak, *Czy i jakie technologie?...*, p. 76.

18 *Ibid.*

Figure 2.1. Averaged costs of producing 1 kg of hydrogen by steam reforming (USD/kg hydrogen; data for 2018)



Source: IEA.

The oldest and one of the most widely used methods of producing hydrogen is coal gasification. It is carried out in high-pressure chemical reactors in which the crushed raw material is heated up to a temperature of about 1000°C and, using a catalyst (e.g. nickel), is exposed to oxygen and usually to steam. The result of this reaction is synthesis gas, from which hydrogen is then extracted. There are over 130 gasification installations in the world, of which over 80% in China, where hydrogen is used primarily in the chemical industry. At the same time, this technology is practically not used in Europe.

The greatest advantage of gasification is large and easy availability of coal, which constitutes more than 50% of the world's fossil fuel reserves. Only raw material with a sufficiently high calorific value (usually not less than 21 MJ/kg) can be gasified. On the other hand, coal waste, e.g. flotation tailings, can be used for this purpose. This makes it possible to produce hydrogen from raw materials whose use in other sectors (e.g. municipal and household) has already been banned in many countries.

Coal gasification emits the most CO_2 of all the methods used to produce hydrogen. It emits as much as 19 tCO_2/tH_2, about twice as much as steam reforming. Thus, the cost of this technology will increase significantly, mainly due to tightening environmental requirements in key economies. This means that in the future, its competitiveness and even acceptability will depend on the simultaneous sequestration of CO_2, which makes it possible to reduce emissions related to gasification to as much as 2 tCO_2/tH_2. The disadvantage of this solution, however, is the high level of hydrogen contamination, including sulphur and ammonia[19].

About 50% of the costs of producing hydrogen from coal are accounted for by CAPEX, and 15-20% by the price of the raw material. They are also affected by the gasification technology used and its possible implementation with the use of CO_2 capture facilities; according to the IEA, the latter raises

19 *Ibid*, p. 50.

the OPEX of this process by as much as 130%, while the CAPEX and fuel costs by 5%[20]. The available data show that, for these reasons, in China and the USA, the cost of gasification is 1.1-1.34 USD/kg H_2 and 1.47-1.63 USD/kg H_2 if sequestration is used. On the other hand, analyses performed in Poland (where gasification is not commercially applied) showed that it is 5.5-6.5 PLN/kg H_2, which is an expense similar to reforming performed at a gas price of 930-1100 PLN/1 000 m^3 [21].

From the point of view of climate policy requirements, the most promising method for producing hydrogen is water electrolysis. It allows the conversion of electrical energy into chemical energy for hydrogen fuel[22]. This process takes place in devices called electrolysers, with a total capacity of around 200 MW worldwide. By 2024 their power in the EU alone is to increase to 6 GW and by 2030 to 40 GW[23]. Poland also has ambitious plans in this respect. The Ministry of Climate and Environment estimates in its draft hydrogen strategy that by the end of this decade the power of domestic electrolysers will reach 2-4 GW. By 2030 the first Polish hydrogen-fuelled combined heat and power plant is to be built.

The biggest advantage of electrolysis is that it can be used with renewable energy sources, such as offshore or onshore wind farms. Owing to this, in contrast to other methods of hydrogen production, it does not generate unwanted by-products, mainly direct CO_2 emissions. The use of electrolysers also gives great opportunities to control the amount of hydrogen production without interrupting the process, depending on current needs and possibilities for raw material storage. In case of reformers, however, this is possible only to a limited extent, due to, among other things, their long start-up time. Moreover, the hydrogen obtained in this way is characterized by a very high "purity" (exceeding 99.9%), which after "purification" allows for its use not only in industrial processes, but also in the propulsion systems of hydrogen vehicles. For this purpose, in various types of electrolysers, special purification systems are used - mainly oxygen removal and drying, but also PSA (Pressure Swing Adsorption) units and membrane systems. Much more difficult and expensive is to inject into fuel cells hydrogen obtained by reforming, whose "purity" is usually 95-99% [24].

Many methods of producing hydrogen by electrolysis are known. The oldest and most common of these is alkaline electrolysis, in which the electrolyte is usually potassium or sodium hydroxide. The plants used for this purpose are characterised by component life of 50-90,000 hours, efficiency of 65-82% and flexibility to ramp up production in about 60 seconds. In this last respect, they are significantly inferior to electrolysers with a polymeric Proton Exchange Membrane (PEM), in which it is possible even within 2 seconds. The latter are characterized by similar efficiency (65-78%), but also shorter lifetime (30-90 thousand hours). The least mature technology and not yet commercially used is Solid Oxide Electrolysis Cell (SOEC). Such installations require a temperature of 800-1000°C (and thus a constant source of large amounts of heat) and are characterized by low efficiency and component life (about 10-30 thousand hours), although, on the other hand, their efficiency is even 85%[25]. In 2019, the total capacity of working alkaline electrolysers was more than 45 MW, PEM electrolysers 38 MW, and SOEC electrolysers less than 1 MW.

20 *Ibid*, p. 51.

21 T. Chmielniak, *Czy i jakie technologie?...*, p. 76.

22 J. Nowicki, *Introduction to hydrogen power*, Networks and Installations, Poznań 2019, p. 1.

23 R. Tomaszewski, *Ciepło do zmiany. How to modernise the district heating sector in Poland*, Polityka Insight, Warsaw 2020, p. 59.

24 Polish Register of Shipping, *Bezpieczne wykorzystanie wodoru jako paliwa w komercyjnych zastosowaniach przemysłowych* [*Safe use of hydrogen as fuel in commercial industrial applications*], Gdansk 2021, p. 14.

25 T. Adamczewski, M. Jędra, *Zielone gazy. Biometan i wodór w Polsce* [*Green Gases. Biomethane and hydrogen in Poland*], *Energy Forum*, Warsaw 2021, p. 13.

A significant drawback of alkaline and PEM type electrolysers is the necessity to use precious and semi-precious metals (e.g. platinum, cobalt or nickel) as catalysts, which significantly increases electrolysis costs. A response to this may be the Anion Exchange Membrane (AEM) electrolysers, currently under development and not yet commercially used, in which hydrogen may also be produced under alkaline electrolysis conditions, but without the use of precious metals.

The scale of the environmental benefits associated with the use of electrolysis is determined by how electrolysers are powered. According to the IEA, converting all of the world's hydrogen production to electrolysis would require the use of 3,600 TWh of electricity per year, which exceeds the annual EU production[26]. For these reasons, depending on local conditions, electrolysers are either directly connected to an RES installation (e.g. a large wind or PV farm), or to an RES installation and the electricity grid (allowing it to be fed from the grid when no green energy is produced), or electrolysers are connected to the electricity grid[27] at other locations than the connection points of the RES installations.

The mere fact of powering the electrolyser from the electricity grid does not determine the elimination of CO_2 emissions from the hydrogen production process. Electricity generation based on fossil fuels transfers the carbon footprint to electrolysis products. Currently (world average) it is estimated even at 0.72 tCO_2/MWh[28] of obtained hydrogen, which is *de facto* twice as much as in case of using the reforming technology. An increase in the installed capacity of RES will cause an energy surplus to appear (above the current demand of consumers), and then the level of emissions of hydrogen coming from electrolysis will significantly decrease,[29] eventually to zero.

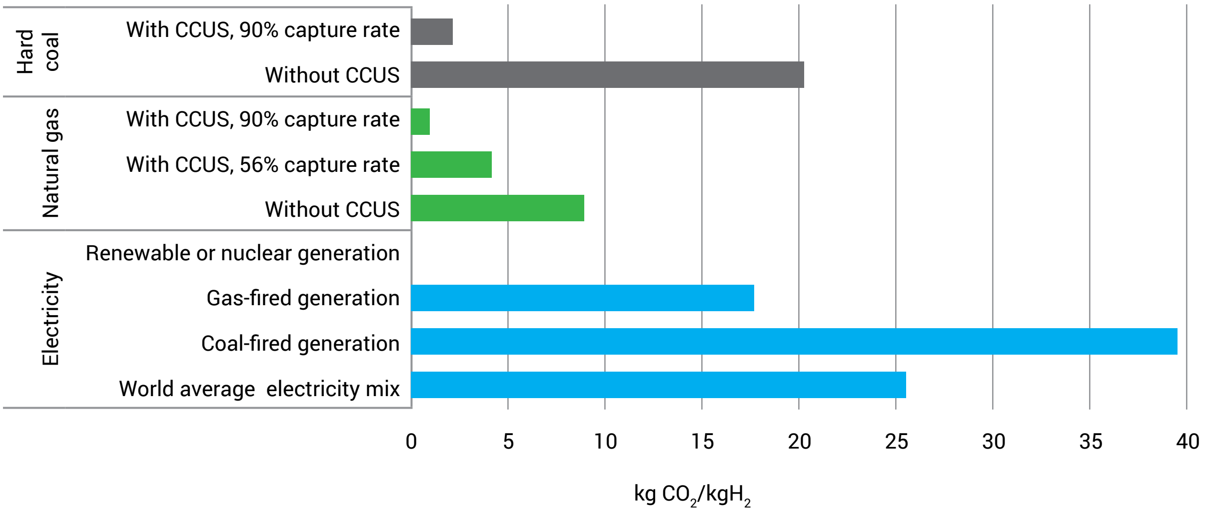
26 *Ibid*, p. 43.

27 *Ibid*, p. 16.

28 *Ibid*, pp. 16-17.

29 A. Chmielewski, J. Kupecki, Ł. Szabłowski, J. Zawieska, K. Fijałkowski, K. Bogdziński, *Dostępne i przyszłe formy magazynowania energii* [*Available and future forms of energy storage*], WWF Poland, Warsaw 2020, p. 83.

Figure 2.2. Emissions of different ways of hydrogen production ($kgCO_2/kgH_2$)



Source: IEA.

2.3 Description of the green hydrogen market in the world, Europe and Poland

As mentioned in previous chapters, the world produces most blue and grey hydrogen. Annual hydrogen production consumes 6% of the world's natural gas consumption, compared with 2% in case of coal. Consequently, global hydrogen production currently accounts for 830 million tonnes of CO_2/year[30]. The main justification for this form of hydrogen production is its price, which, excluding the cost of carbon dioxide emissions, is in this case approximately EUR 1-2/kg,[31] or EUR 30-60/MWh. For the time being, the production of green hydrogen, i.e. using RES, is still a much more expensive solution (see Chapter 4.1). However, as a long-term solution, green hydrogen is a better option due to environmental factors. The most attractive production markets for green hydrogen are those where there is also a high supply of RES, namely some regions in the Middle East, China, the USA and Australia. In these areas, green hydrogen can already be produced today at a price of 3-5 EUR/kg[32].

Wind power generates about 5% of the world's electricity, with most installations on land. Compared to onshore wind, offshore wind reaches higher speeds and is more stable, making it much more attractive for electricity generation. However, the main disadvantages of this solution are the higher cost and greater technical challenges of transmitting electricity onshore, due to the harsh marine conditions to which the equipment is exposed. Traditional AC cables have high capacitance causing significant reactive power flow and therefore exhibit higher losses than overhead lines. In contrast, direct current (HVDC) systems are expensive. However, in this case, an alternative solution could be to produce hydrogen at sea and transport it to land through pipelines, which have much lower losses (<0.1%) than electricity flow-

30 *The Future of Hydrogen. Seizing today's opportunities*, Report prepared by the IEA for the G20, Japan, p. 37, https://iea.blob.core.windows.net/assets/9e3a3493-b9a6-4b7d-b499-7ca48e357561/The_Future_of_Hydrogen.pdf

31 *The green hydrogen economy. Predicting the decarbonisation agenda of tomorrow*, PwC, https://www.pwc.com/gx/en/industries/energy-utilities-resources/future-energy/green-hydrogen-cost.html

32 *Ibid.*

ing through marine cables[33]. Transporting hydrogen by special tankers is also an option. Offshore wind farms have increasing generating capacity and are being built farther and farther from shore, and have seen a significant decrease in the Levelized Cost of Energy. In addition, with the development of floating platforms, wind turbines can be placed in deeper waters, making more sites available for electricity generation[34].

Taking into account high dependence of green hydrogen on the development of RES, a decrease in its price can be expected along with a decrease in the costs of renewable energy production owing to numerous support projects and technological progress. It is undoubtedly a challenge to predict future trends, particularly over decades, so it should be remembered that forecasts of hydrogen market development are currently subject to a large margin of error. In the case of hydrogen, the rate of development of the hydrogen economy will depend on the prices of, *inter alia*, hydrogen technology, electricity from RES and hydrogen itself. This means that, depending on these costs, the hydrogen market, which is currently *in statu nascendi*, can either develop rapidly over the next decade or grow only slightly and not revolutionise energy and industry at all.

In recent years, there has been a great dynamic of interest in hydrogen on a global scale, which is reflected in the number of strategies adopted as well as investment plans. The analysis of available forecasts indicates that in the perspective to 2050 the trend of increasing its importance on a global scale will continue. According to the PwC analysis, the demand for green hydrogen will grow at a moderate but constant rate until 2030. During this period, production costs are expected to fall by around 50% and hydrogen will dominate primarily through applications in niche areas of sectors such as industry, transport, energy and construction. Over the longer term, demand growth is projected to accelerate, especially from the mid 2030s onwards. It is estimated that hydrogen demand could range from 150 to 500 million tonnes per year by 2050 (currently 70 million tonnes), depending on global climate ambitions and sectoral developments[35]. According to the BP report, in the 2050 horizon, green and blue hydrogen as an energy carrier will provide close to 15% of total final energy consumption[36]. The analyses referred to in the *Hydrogen Strategy for a Climate Neutral Europe* indicate that pure hydrogen could meet up to 24% of the world's energy needs by 2050[37]. At the same time, hydrogen production prices are not expected to fall dramatically after 2030, which, according to PwC estimates, should be in the range of EUR 1-1.5/kg by 2050 for countries with the most developed RES sector, and EUR 2/kg for others[38]. This means that in the coming years significant investments in electrolysers should be expected on a global scale, the scale of which will be co-responsible for the rate of penetration of this energy carrier.

At the same time, the development of green hydrogen will require, in particular, the expansion of renewable energy infrastructure, including new wind power capacity and photovoltaics. Taking into account that the production of green hydrogen by electrolysis is an energy-intensive process, in the 2050

33 G. Calado, R. Castro, *Hydrogen Production from Offshore Wind Parks: Current Situation and Future Perspectives*, "Applied Sciences" 2021, 11, 5561, p. 2, https://doi.org/10.3390/ app11125561.

34 *Ibid.*

35 *The green hydrogen economy. Predicting the decarbonisation agenda of tomorrow*, PwC, https://www.pwc.com/gx/en/industries/energy-utilities-resources/future-energy/green-hydrogen-cost.html

36 *BP Energy Outlook 2020 edition*, p. 129.

37 *Hydrogen Strategy for a Climate Neutral Europe*, Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions, Brussels, 8.07.2020. COM(2020)301 final, p. 2.

38 *The green hydrogen economy. Predicting the decarbonisation agenda of tomorrow*, PwC, https://www.pwc.com/gx/en/industries/energy-utilities-resources/future-energy/green-hydrogen-cost.html

perspective, a significant part of the electricity produced would have to be dedicated to hydrogen production. Taking into account the growing importance of hydrogen in the economy, it is concluded that the amount of energy produced would have to double[39]. In addition to the need to implement investments in new distribution infrastructure and to provide sufficient electricity, the main barriers to the development of the hydrogen economy include issues such as:

- hydrogen storage and long-distance transmission,
- the high cost of producing hydrogen,
- high cost of fuel cells[40].

Currently, the cost of producing hydrogen is 3-4 times what is ultimately expected, and with PEM electrolysers the difference is as much as 7 times.[41] The institutional and administrative area could also become a barrier to the hydrogen economy depending on how safety regulations, codes and standards evolve.

An analysis of trends in the most important countries developing hydrogen economies reveals indications of a significant increase in hydrogen use in the future. In the United States, production of green hydrogen from electrolysis currently amounts to 1%, while over 95% is the result of methane reforming with steam[42]. In the perspective of 2030, the U.S. strategy is to increase the scale of hydrogen production, expand the transport infrastructure to enable the transport and distribution of hydrogen in gaseous and liquefied form; develop domestic production capacity in the field of fuel cells, turbines and other components; invest in research and education of future hydrogen energy experts. Commercialization of turbines capable of burning hydrogen and natural gas is already being seen today. In the longer term beyond 2030, it is estimated that the use of hydrogen in the U.S. will be deployed on a large scale because of the cross-sector benefits of its use.

It is widely pointed out that the leaders in hydrogen technology are the Japanese, who published their hydrogen strategy back in 2017. An important element of the Japanese strategy is the expansion of the national infrastructure for refuelling hydrogen and popularizing it as a fuel for transport. In the perspective to 2030, they plan to build nearly 900 stations, as well as develop the fleet of FCEVs to 800 thousand[43]. The Japanese promote the use of hydrogen due to the fact that it ensures the security of energy supply, and at the same time is a clean and flexible energy carrier. Japan is supporting projects to build supply chains from abroad to produce hydrogen from renewable sources or fossil fuels with CO_2 capture and storage[44]. In addition, Japan's strategy highlights the drive to develop the commercialization of the liquefied hydrogen supply chain[45].

From the perspective of the European Union, hydrogen production fits in with the strategic goals of the climate and energy policy. At present, annual production of hydrogen in the EU is approximately 10 million tonnes, using high-emission methods. If this method of producing hydrogen were to be replaced

39 *BP Energy Outlook 2020 edition, p. 105; Green Hydrogen, The next transformational driver of the Utilities industry*, The Goldman Sachs Group, 2020, p. 4.

40 More on barriers in chapter 4.2.

41 R.K. Dixon, *Global Status & Trends of The Hydrogen Economy*, https://www.un.org/esa/sustdev/sdissues/energy/op/hydrogen_seminar/presentations/05_dixon_iea.pdf

42 *Fuel Cell & Hydrogen Energy Association, US Hydrogen Industry Roadmap, 2020*, p. 7. U.S. Department of Energy, Hydrogen Strategy - Enablin a Low-Carbon Economy 2020, p. 5.

43 *Clean hydrogen Monitor 2020, Hydrogen Europe*, p. 81.

44 *Hydrogen and fuel cells in Japan, EU-Japan Centre for Industrial Cooperation*, 2019, p. 122.

45 *Japan. The H2 Handbook*, K&L 2020, p. 5.

by electrolysis in its entirety, as much as 450 TWh of electricity would be needed, which today is about 10% of current production in the EU[46]. The EU hydrogen strategy therefore calls for a significant increase in electrolysis capacity by 2030. In the long-term perspective, until 2050, hydrogen is to achieve the level of 13-14% share in the EU energy mix, which is to contribute to the creation of nearly 1 million new jobs in the economy. The majority of EU countries see the use of hydrogen mainly in transport. The most ambitious assumptions regarding the expansion of electrolyser capacity by 2030 are made by France (6.5 GW), Germany and Italy (5 GW).

In line with the Hydrogen Strategy for a climate-neutral Europe,[47] the EU plans to develop a hydrogen economy based on a complete value chain. It is therefore not only about developing the area of hydrogen production and transmission infrastructure, but also about creating market demand, which is the driving force for increasing supply. This entails lowering the costs of production and distribution technologies. Taking into account that the EU is committed to hydrogen produced from clean and emission-free sources, the market competitiveness of RES against fossil fuels is also expected to further increase[48]. At the same time, it is equally important to secure the raw materials which are indispensable for RES, especially those on the EU list of critical raw materials[49].

In line with the above plans and assumptions, countries such as the USA, Japan and the EU area are coming up with initiatives to support hydrogen. The USA plans to allocate about USD 1.7 billion over 5 years, Japan about USD 300 million per year, and the EU about EUR 200-300 million per year for hydrogen technologies[50].

In case of Poland, there is scientific and research potential in the field of hydrogen technologies. Annual production of hydrogen in Poland is about 1 million tonnes, all of which is based on fossil fuels[51]. However, work on building a complete value chain, including production, storage and conversion, distribution and applications of hydrogen (i.e. demand stimulation) is just beginning. As emphasized in the draft of the *Polish Hydrogen Strategy until 2030 with an Outlook until 2040*, which is currently being prepared, Poland faces the need to prepare a comprehensive research programme, to support research groups which are active in the hydrogen field and to stimulate interest of the best research and production centres in the field of hydrogen[52]. In relation to these objectives, the draft *Polish Hydrogen Strategy* assumes that by 2025 investments will consume about PLN 2 billion (about EUR 440 million). Expenditures foreseen in this period will include hydrogen technologies in the energy, transport, and production sectors. In turn, by 2030, investments related to electrolysers alone are expected to reach about PLN 9 billion (ca. EUR 2 billion), depending on the technology chosen: alkaline/PEM/SOE. However, in the case of hydrogen transport, the costs in this period are estimated at approx. PLN 5.6 billion (approx. EUR

46 G. Calado, R. Castro, *Hydrogen Production from Offshore Wind Parks: Current Situation and Future Perspectives*, "Applied Sciences," 2021, 11, 5561, p. 11, https://doi.org/10.3390/ app11125561

47 Communication From The Commission To The European Parliament, The Council, The European Economic And Social Committee And The Committee Of The Regions. A hydrogen strategy for a climate-neutral Europe, Brussels, 8.7.2020 COM(2020) 301 final, https://ec.europa.eu/energy/sites/ener/files/hydrogen_strategy.pdf

48 *Ibid*, pp. 9-10.

49 *Critical Raw Materials for Strategic Technologies and Sectors in the EU A Foresight Study*, Luxembourg 2020, pp. 25-26, https://rmis.jrc.ec.europa.eu/uploads/CRMs_for_Strategic_Technologies_and_Sectors_in_the_EU_2020.pdf

50 R.K. Dixon, *Global Status & Trends of The Hydrogen Economy*, https://www.un.org/esa/sustdev/sdissues/energy/op/hydrogen_seminar/presentations/05_dixon_iea.pdf

51 *Polish Hydrogen Strategy until 2030 with an Outlook until 2040. - Draft*, pp. 18-21, https://bip.mos.gov.pl/strategie-plany-programy/polska-strategia-wodorowa-do-roku-2030-z-perspektywa-do-2040-r/

52 *Ibid*.

1.2 billion)[53]. Preparation of a multi-institutional and business agreement (on the initiative of the Ministry of Climate and Environment) to be signed in October 2021 shows the great determination of the authorities to include Poland in the global trend of development of the hydrogen economy.

2.4 Power to Gas Technology - basic concepts and relationships

The Power-to-Gas (P2G) technology can be most simply characterised as the conversion of electricity into gas, which in subsequent stages can be subjected to[54]:

- storage for later use,
- further distribution,
- end use through further processing or consumption.

Direct use of the produced hydrogen without further conversion is known as a single-stage system. When hydrogen is converted in successive stages, the P2G technology is known as a two-stage system. In addition, there are also single-stage P2G systems for direct methane production[55]. In the case of wind turbine electricity used for gas production, the term windgas is also encountered[56].

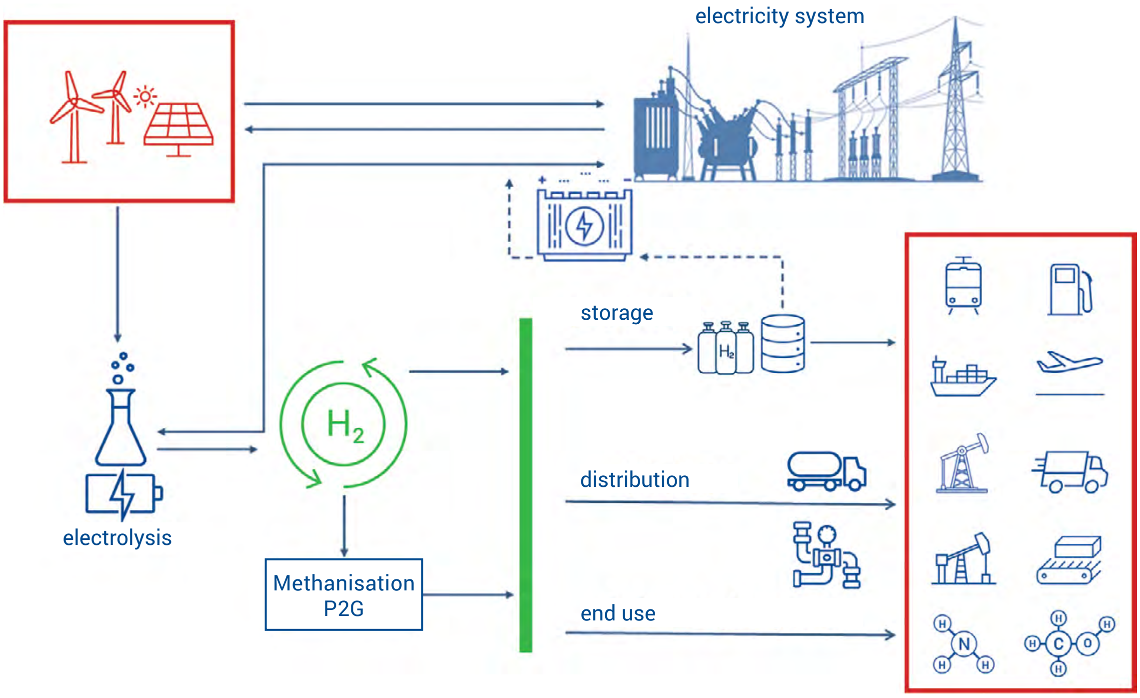
53 *Ibid*, pp. 42-43.

54 W. Liu, F. Wen, Y. Xue, *Power-to-gas technology in energy systems: current status and prospects of potential operation strategies*, "J. Mod. Power Syst. Clean Energy," April 2017, p. 27. DOI: 10.1007/s40565-017-0285-0; https://www.researchgate.net/publication/316439688_Power-to-gas_technology_in_energy_systems_current_status_and_prospects_of_potential_operation_strategies/fulltext/58fe3ac0aca2725bd71d1a42/Power-to-gas-technology-in-energy-systems-current-status-and-prospects-of-potential-operation-strategies.pdf

55 Reversible solid oxide cell (ReSOC) technology.

56 J. Popczyk, P. Kucharczyk, *Zintegrowane wiatrowo-gazowe technologie energetyczne [Integrated wind-gas energy technologies]*, Scientific Papers of the Silesian University of Technology "Electrics", z. 1, 2007, pp. 27-38.

Figure 2.3. Simplified scheme of a hydrogen economy with Power-to-Gas (P2G) technology, assuming the production of hydrogen from RES sources



Source: own study based on: A. Maroufmashat, M. Fowler, *Transition of Future Energy System Infrastructure; through Power-to-Gas Pathways*, Energies, 26 July 2017, pp. 3-8.

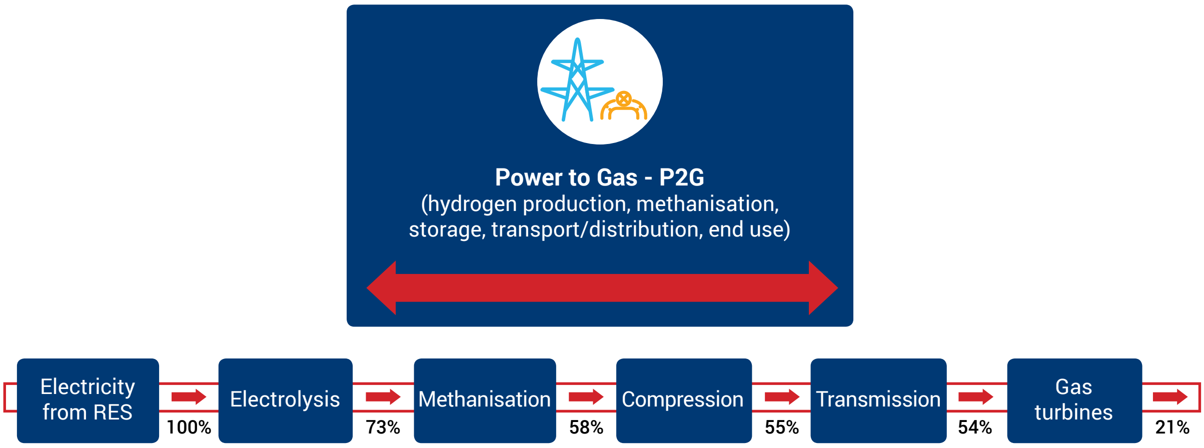
The first stage of the process is to produce renewable hydrogen by electrolysis from water and renewable energy sources. This hydrogen can be used directly, doped into other gases or subjected to a second step, such as reacting with carbon dioxide to produce methane. Methane is a key component of natural gas and can be used directly in all of today's standard gas applications. The CO_2 used in the methanisation process is captured from air, biomass or biogas to provide a closed carbon cycle.

Large amounts of energy are required for electrolysis, methanisation and storage. The efficiency of electrolysis depending on the temperature level (low/high) is estimated at 67-81% and 80-90% by 2050[57]. In addition, the methanisation process gives efficiency of about 58%[58].

57 *The Future Cost of Electricity-Based Synthetic Fuels*, AGORA Energiewende, Berlin, 19 September 2018, pp. 61-64, https://www.agora-energiewende.de/fileadmin/Projekte/2017/SynKost_2050/Agora_SynKost_Study_EN_WEB.pdf

58 T. Chmielniak, S. Lepszy, P. Mońka, *Energetyka wodorowa – podstawowe problemy [Hydrogen energy - basic issues], Polityka energetyczna* 2017, vol. 20, z. 3, pp. 55-56.

Figure 2.4. Effectiveness levels in the transformation chain for P2G technology



Source: own study based on T. Chmielniak, S. Lepszy, P. Mońka, *Energetyka wodorowa – podstawowe problemy [Hydrogen energy - basic issues]*, "Polityka Energetyczna" 2017, vol. 20, z. 3, pp. 55-56.

The choice of the way and form of hydrogen storage for subsequent use depends on the purpose of its future use, i.e. whether it will be transported and over what distances and in what quantities, or whether it will be used on-site, e.g. in providing system services to an electricity operator, or in industrial processes.

2.5 Description of selected industrial applications of hydrogen

Key industrial technologies where hydrogen is used today and those where green hydrogen will be viable in the future are discussed below.

As already stated, in 2019 Poland ranked third in Europe in terms of hydrogen production, i.e. about 1 million tonnes per year[59] (34 TWh). This production was entirely allocated to cover domestic needs, among which industrial needs dominate. This is a volume that could potentially be replaced by renewable hydrogen. Apart from the existence of sufficient RES energy potential, the possibilities of this substitution are determined primarily by the possibilities and flexibility of adjusting production processes in individual industries, as well as the related costs. Furthermore, equally important are the strategies adopted by the major stakeholders in the hydrogen production market. In view of the above, it can be assumed that the need to move to a zero-carbon economy in 2050 will, for industries using hydrogen in their technology, require changes in their operating models:

- conversion of used hydrogen of a different colour to green hydrogen - great potential for hydrogen production from wind turbines and PV. In this case, the industry can make additional investments to develop hydrogen production facilities or go to the market with a purchase offer. A market offer to purchase will be an opportunity for hydrogen producers to increase their share in an unbundled part of the market;

59 *Polish Hydrogen Strategy to 2030, with an Outlook to 2040* - draft, p. 20; During water electrolysis the chemical bond between hydrogen and oxygen is broken in solution, creating hydrogen and oxygen gas. Assuming that 50 kWh of electricity is needed to produce 1kg of hydrogen, 50TWh of electricity will be needed to produce 1 million tonnes of hydrogen. For comparison, according to data presented by PSE S.A., the annual production of electricity in Poland in 2020 was 152 TWh, including production from RES of about 16.4 TWh (10.75%). More on this subject in the chapter: WIND ENERGY - GREEN HYDROGEN PRODUCTION AND ITS IMPACT ON THE NATIONAL POWER SYSTEM .

- changing non-hydrogen industrial processes to hydrogen-based processes - adapting processes and installations to produce green hydrogen, or organisational changes to purchase green hydrogen from the market. Organizational changes will mean increased demand for hydrogen from the market.

Current and projected uses of hydrogen in selected industries are briefly discussed below.

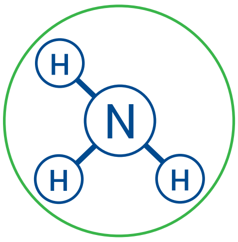
Current and projected demand for hydrogen in selected industries

The **refining industry** is one of the leading industries using hydrogen in the production process. The use of hydrogen in the EU in 2019 was at the level of 3.7 million tonnes/year, which covers 45% of the total demand for hydrogen[60]. The projected demand for hydrogen in Poland in this area is estimated at 2.2 TWh (about 65.5 thousand tonnes). Nevertheless, due to forecasts of progressive electrification of transport, it is difficult to predict the importance of the refining industry in 2050[61].

The largest producers of hydrogen for the purposes related to the refining industry are Grupa Lotos and Orlen.

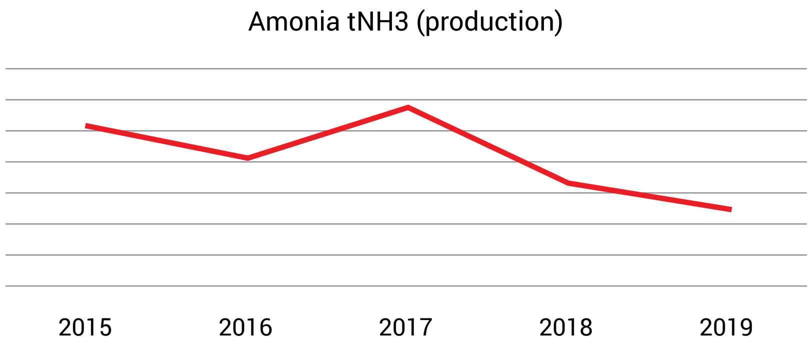
60 *Clean Hydrogen Monitor 2020*, Hydrogen Europe, p. 14, https://www.hydrogeneurope.eu/wp-content/uploads/2021/04/Clean-Hydrogen-Monitor-2020.pdf

61 T. Adamczewski, M. Jędra, *Zielone gazy [Green Gases...]*, p. 18

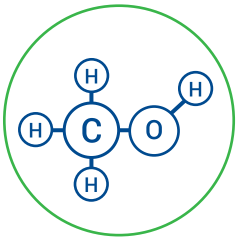


Ammonia production in EU countries in 2018 accounted for 34% of the total hydrogen demand i.e. 2.8 million tonnes[62].

Grupa Azoty is Poland's largest and a significant producer of ammonia in Central and Eastern Europe. The procurement strategy in this area is based mainly on optimising supplies within the Group, hence without a change in strategy or appropriate regulatory incentives, this part of the hydrogen application market will not be released soon. Nevertheless, due to the fact, and according to 2018 data, 2.5 million tonnes of ammonia were produced in Poland[63] by converting 22.5 TWh of natural gas into 15.2 TWh (about 452 thousand tonnes) of hydrogen, which means that in the future this amount of hydrogen will be produced from electricity derived from RES. Nevertheless, according to the statistical data, ammonia production maintains a downward direction. Below is a graph of ammonia production (in tonnes) in Poland in 2015-2019, based on CSO data.



Source: own work based on CSO data.



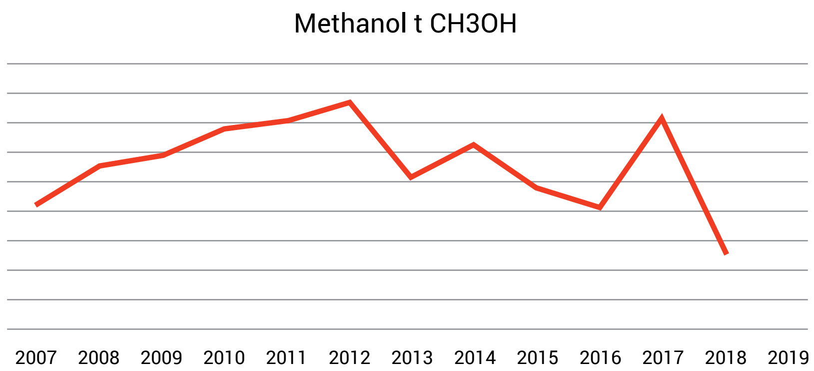
Methanol is used to produce biofuels and other chemical raw materials. Methanol is one of the most important chemical raw materials. It is used to produce formaldehyde (30% of global methanol consumption), acetic acid (10%), chloromethane (3-4%), methyl methacrylate (MMA) (2.5%) and methylamines (2%). The demand for formaldehyde is mainly driven by the construction industry, where the compound is used to manufacture the adhesive used in building panels. In addition to purely chemical applications, the role of methanol as an additive or raw material in the manufacture of fuel components is becoming increasingly important[64]. Methanol as a gasoline additive can be used in its pure form (12% of its world production) or in the form of methyl tert-butyl ether (MTBE; 12% of methanol production), currently replaced by ethyl tert-butyl ether (ETBE). Methanol can be used in various proportions, along with conventional petroleum products. Increasing the percentage of methanol in gasoline, however, necessitates modification of motor

62 Hydrogen Europe...

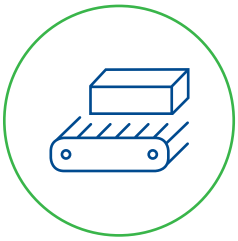
63 *Production of industrial goods in 2015-2019*, CSO 2020.

64 M. Krupa, M. Moskalewicz, A.P. Sikora, A. Szurlej, *Perspektywiczne zapotrzebowanie na metanol jako paliwo okrętowe [Prospective demand for methanol as marine fuel], Przemysł Chemiczny* 2015, vol. 94, no. 12, pp. 2059-2066.

vehicles as well as fuel distribution methods. In diesel engines it is not possible to use methanol directly, because the cetane number of methanol is too low and methanol is not ignitable[65]. Nevertheless, this area of methanol application due to electrification of transport should not be considered in growth categories. In addition, methanol production in Poland in 2018 was at the lowest level in the period 2007-2018. Unfortunately, there is no data for 2019. Below is a graph of methanol production (in tonnes) in Poland in 2007-2019 based on CSO data.



Source: own work based on CSO data.

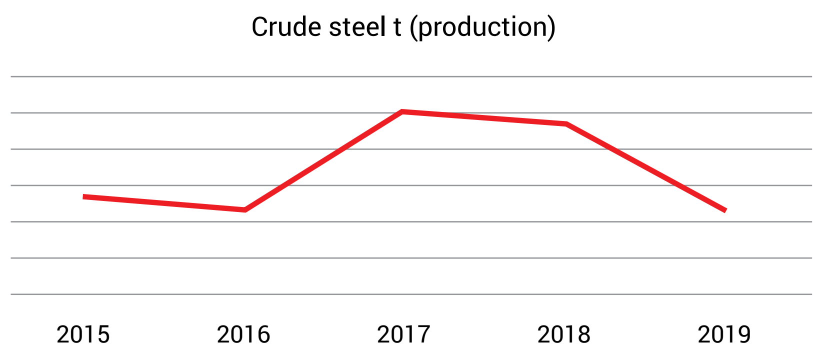


Steel production in Poland in 2019 was 9.1 million tonnes. It was based on "blast furnace" technology (4.8 million tonnes) and production using electric furnaces (4.3 million tonnes)[66]. Assuming a constant level of production (although there is a decrease compared to 2017 and 2018), in order to decarbonise this part of the industry, "blast furnace" technology will be replaced by solutions such as DRI (Direct Reduced Iron) and IBRSR (Iron Bath Reactor Smelting Reduction). This means that for 4.8 million tonnes of production, a process change will be required through the use of low carbon gaseous fuel technologies (hydrogen and biomethane). It is difficult to assess what proportion of hydrogen and what proportion of biomethane will be used in the production process, hence it is difficult to assess the future demand for hydrogen in this sector. According to the analysis based on 2018 data, the demand for hydrogen in steel production in 2050 will be 3 TWh[67]. Below is a graph of crude steel production (in tonnes) in Poland in 2015-2019 based on CSO data.

65 S. Dobras, L. Więcław-Solny, T. Chwoła, A. Krótki, A. Wilk, A. Tatarczuk, *Odnawialny metanol jako paliwo oraz substrat w przemyśle chemicznym [Renewable methanol as fuel and substrate in chemical industry]*, Zeszyty Naukowe Instytutu Gospodarki Surowcami Mineralnymi i Energią Polskiej Akademii Nauk, 2017, no. 98, pp. 27-38.

66 National Center for Balancing and Emission Management, *National Inventory Report 2021*, 2021.

67 T. Adamowicz, M. Jętka, *Zielone gazy. Biometan i wodór w Polsce [Green Gases. Biomethane and hydrogen in Poland]*, p. 11.



Source: own work based on CSO data.

Depending on the adopted future strategy for the production of hydrogen for selected purposes (regardless of the type and power of electrolysers), a decision should be made on the scheme of operation of the electrolyser in combination with an electricity generation unit. The hydrogen obtained, depending on the needs, will be able to be transformed into other chemical forms. At the same time, each additional conversion will relate to further losses, which in consequence may turn out to be economically unprofitable, and certainly not effective. Hence, in areas of the economy where electricity from RES can be used directly, it will be more economically efficient than adapting existing electrical equipment to use hydrogen. Nevertheless, hydrogen will be important in areas of the economy where electrification cannot take place.

03

DESCRIPTION OF DOCUMENTS SHAPING THE DEVELOPMENT OF THE HYDROGEN MARKET IN THE EUROPEAN UNION AND POLAND

At the time of writing this report, Poland's hydrogen strategy has not yet been adopted in an official government document. The following analyses were carried out on the basis of currently binding EU strategic documents and key EU legal acts, Poland's current energy policy and the draft *Polish Hydrogen Strategy until 2030 with an Outlook until 2040* put out for public consultation.

3.1 The European Green Deal

Development of the hydrogen market in the coming years will take place mainly as a consequence of implementation of the current EU climate policy. It was expressed in the European Commission's document titled *European Green Deal*. It is a fundamental document of strategic importance, which sets out the directions of changes in regulatory and sectoral policies of the EU, and consequently of individual member states. The already widely known goal of the EU expressed in the *European Green Deal* is to achieve climate neutrality by 2050. In other words, the goal is to eliminate greenhouse gas emissions generated by EU economies and societies within the next 30 years. In the case of the energy sector in its broadest sense, this goal is to be achieved through a "transition to clean energy", which in practice means the dominance of renewable energy sources (RES). It is this segment of the energy economy that, as part of the energy transition, is to be continuously developed to become the main producer of electricity in all the EU member states. Of course, technological changes leading to the reduction of greenhouse gas emissions are also to concern other economic sectors. In this far-reaching and ambitious vision of a qualitative change in the economic model on an EU scale, there is no extensive section dedicated to the hydrogen economy. However, the indicated directions of change for individual economic sectors and the general paradigm on which they are to be based define a convenient strategic framework for economic development. These include, in particular:

- decarbonisation of the gas sector, through the introduction of low-carbon gases,
- reducing raw material consumption in industry (as part of a closed loop economy),
- support for clean technologies for industry, including clean hydrogen and energy storage technologies,
- decarbonisation of transport (air, road, rail and waterborne), inter alia through the introduction of 'alternative sustainable transport fuels'.

It can also be assumed that the dissemination of green hydrogen will be facilitated by the policy announced in the *European Green Deal* to initiate reforms of taxes on fossil fuels. On the other hand, the beneficiaries of the EU climate strategy will be research centres working on new breakthrough technologies which will make it possible to achieve the strategic goal of climate neutrality.

3.2 A hydrogen strategy for a climate-neutral Europe

The Hydrogen Strategy for a Climate-Neutral Europe (hereafter referred to as the Strategy), announced by the European Commission in its Communication of 2020, is based on the general assumption that hydrogen has "many potential applications in the industrial, transport, energy and building sectors". In the case of energy, green hydrogen, referred to as 'renewable' in the Strategy, can be used as a fuel, an energy carrier, as well as an energy storage facility[68]. At the same time, the Strategy indicates a close relationship that will occur between the development of RES increasing the share of clean electricity and the dissemination of clean hydrogen in the economy. The EC clearly states in the discussed document that "the large-scale and fast deployment of clean hydrogen is crucial to achieve the EU's more ambitious climate target of a cost-effective reduction of greenhouse gas emissions by at least 50-55% by 2030"[69].

The Strategy indicates very concrete objectives for the development of the hydrogen economy, to be achieved within a specific time horizon:

- installation of electrolysers powered by renewable energy sources with a capacity of at least 6 GW by 2024,
- next installation of electrolysers powered by renewable energy with a capacity of at least 40 GW by 2030,
- renewable hydrogen technologies to mature and be widely deployed in carbon-intensive sectors between 2030 and 2050.

The EU Strategy therefore assumes a phased approach to the full development of production and dissemination of green hydrogen. In the transition period, the EC allows the use of hydrogen produced with the use of, among others, fossil fuels in combination with the carbon capture and storage technology (CCS). Gradually, by increasing the scale of production, renewable hydrogen will become cost-competitive with other types of hydrogen currently produced using emission technologies. After 2050, only green - zero-emission hydrogen should be used in the EU economy. Obviously, in order to achieve the goals set out in the EU Hydrogen Strategy, it will be necessary to incur appropriate investment outlays. Costs related to the comprehensive development of green hydrogen have been estimated at between EUR 180 and 470 billion by 2050.

At the time of writing this report, Poland's hydrogen strategy has not yet been adopted in an official government document. The basic framework for such a strategy and general directional guidelines are already set out in the above-mentioned EU documents. The basis can also be found in the existing strategies and policies relating to socio-economic development and energy. Such direct references can be found in the draft *Polish Hydrogen Strategy until 2030 with an Outlook until 2040,* which was put up for public consultation.

3.3 Directive on the promotion of the use of energy from renewable sources (RED II)

Supporting the development of renewable energy sources is a priority for the EU energy policy, being at the same time a means to achieve climate policy objectives. The entry into force of Directive of the European Parliament and of the Council (EU) of 11 December 2018 on the promotion of the use of energy from renewable sources (RED II Directive), primarily set a new higher target for the share of RES in total energy production in 2030, which was set at a minimum of 32% share of renewable energy in gross final energy consumption in the EU (Article 3). The Directive imposed an obligation on the member states to determine their projected contributions to achieving the new EU energy targets. The regulations included in the RED II Directive introduce, first of all, support systems for RES (Article 4) as well as many facilities for clean energy producers, especially prosumers (Article 21). It also opens other sectors such

68 Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions: *A hydrogen strategy for a climate-neutral Europe*, Brussels, 8.7.2020, p. 1.

69 *Ibid*, p. 3.

as transport and heating (air conditioning) to clean fuels[70].

3.4 Taxonomy of the European Union

A unified classification of sustainable development actions, the so-called taxonomy, was introduced by Regulation (EU) 2020/852 of the European Parliament and of the Council of 18 June 2020 establishing a framework to facilitate sustainable investment and amending Regulation (EU) 2019/2088. This regulation serves to establish clear eligibility criteria and is intended to create a mechanism to guide the flow of public and private capital towards sustainable investments that aim to achieve EU climate neutrality by 2050. It is aimed at economic operators willing to make sustainable investments and at financial institutions, which will be able to offer dedicated products based on clear criteria. Investments classified as sustainable will have to meet the following requirements:

- provide a significant contribution to at least one of the six environmental objectives: climate change mitigation and adaptation, sustainable use and protection of water and marine resources, the transition to a closed cycle economy, pollution prevention and control, protection and restoration of biodiversity and ecosystems;
- not cause significant harm to any of the above environmental objectives;
- respect the technical evaluation criteria;
- provide minimum guarantees regarding social security and governance.

The Regulation contains, *inter alia*, a qualification of economic activities that contribute to climate change mitigation by "stabilizing greenhouse gas concentrations in the atmosphere". (Article 10). One of these is: "establishing the energy infrastructure necessary to enable the decarbonisation of energy systems"[71]. The directive under review thus creates favourable regulatory conditions for the launch of new investments in RES and clean hydrogen technologies.

3.5 Fit for 55 package

Fit for 55 is a legislative package published by the European Commission on 14 July 2021, containing 13 legislative proposals introducing changes in, among others:

- emissions trading (EU ETS),
- Land Use, Land Use Change and Forestry Regulation (LULUCF),
- the Effort Sharing Regulation (ESR),
- Directive on renewable energy (RED II is to be replaced by RED III),
- the Energy Efficiency Directive (EED),
- the Alternative Fuels Infrastructure Directive (AFID),
- Regulation setting CO_2 emission standards for cars and vans,
- Energy Taxation Directive.

70 Directive of the European Parliament and of the Council (EU) of 11 December 2018 on the promotion of the use of energy from renewable sources, https://eur-lex.europa.eu/legal-content/PL/TXT/PDF/?uri=CELEX:32018L2001&from=PL

71 Regulation (EU) 2020/852 of the European Parliament and of the Council of 18 June 2020 establishing a framework to facilitate sustainable investment and amending Regulation (EU) 2019/2088, Article 10, p. (g), https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:32020R0852&from=EN

The amendments are to be very profound and concern all sectors of the economy. In the area of energy, the European Commission's legislative proposal is to accelerate technological progress, reduce dependence on imports of fossil fuels and increase final energy savings.

At the same time, new regulations are proposed aimed at greening of fuels used in air, road and maritime transport carried out in the European maritime space. Objectives in this respect are to be achieved, *inter alia*, by including sea transport in the ETS system, additional taxation of "dirty" fuel for sea-going vessels, raising requirements concerning reduction of emission of fuels used in sea and air transport. New limits of carbon dioxide emissions are also envisaged for new cars entering the market - according to the EC, their emission capacity is to be reduced by 55% until 2030 and by 100% until 2050. There are also plans to reduce the supply of emission allowances and to introduce a carbon tax at the EU's external borders.

To sum up, the legislative proposals presented by the EC in the *Fit for 55* package will still be subject to the process of negotiation and finalisation. Ultimately, they aim to eliminate fossil fuels from member states' economies. At the same time, the proposed regulations are to create wide opportunities for the development of RES as well as production and widespread use of green hydrogen in European economies.

3.6 National Energy and Climate Plan 2021-2030

The National Energy and Climate Plan 2021-2030 (hereinafter: NECP) adopted in 2019 identifies hydrogen as one of the alternative fuels to enable energy-efficient and low-carbon transport. This is to be achieved by supporting innovative solutions for the entire infrastructure chain for the widespread use of hydrogen in the economy (including in the energy sector). The document also announces the launch of a project called *Hydrogen Technology Development Programme* which is to determine the potential for future production, application and development of hydrogen technologies in Poland[72]. The NECP assumes that due to its properties hydrogen may become a new dynamically developing segment of the national economy. This is because there are "new potential opportunities to use hydrogen in: energy, transport, natural gas transmission network. The use of hydrogen is becoming an important direction of research and development, therefore actions are planned to support the areas of hydrogen economy and research and development activities"[73].

3.7 Energy Policy of Poland until 2040

The directions of changes and strategic objectives for the broadly understood energy sector outlined in the SRG[74] were developed in the *Energy Policy of Poland until 2040* adopted on 2 February 2021 by way of a resolution of the Council of Ministers (hereinafter referred to as PEP2040). This document also takes into account the objectives of the European Green Deal announced by the European Commission in 2019. Achieving Poland's goal of climate neutrality by 2050 will require an energy transition that is expected to lead to a zero-emission energy system through, among other things, the development of wind

72 *National Energy and Climate Plan 2021-2030*, p. 64.

73 *Ibid*, p. 65.

74 *Strategy for Responsible Growth to 2020 (with an Outlook to 2030)*, 2017, p. 322.

power as the leading green technology. Assuming future development of green hydrogen production, information on the planned scale to be achieved by the RES sector in Poland becomes important: The general goal set in PEP2040 for RES is as follows:

> **Increase the share of RES** in all sectors and technologies.
> In 2030 the share of RES in gross final energy consumption will be **at least 23%**.
> - not less than 32% in the electricity sector (mainly wind and PV)
> - 28% in the heating sector (up by 1.1pp y/y)
> - 14% in transport (with a large contribution from electromobility).

Within the framework of RES development, offshore wind energy is expected to reach an installed capacity of approximately 5.9 GW in 2030 and this figure is to increase to approximately 11 GW in 2040. In the case of photovoltaics, the increase in installed capacity is expected to reach about 5-7 GW in 2030 and about 10-16 GW in 2040[75]. For the future of green hydrogen, it is also important to assume that the energy transformation process will involve the creation of "new industries participating in the transformation of the energy sector" and the "development of low-emission transport, in particular aiming at zero-emission public transport in cities with population over 100,000 by 2030"[76].

The Polish version of energy transition described in PEP2040 also defines the future role of hydrogen. In the future it is to constitute:

- an alternative fuel to oil for transport,
- a tool to decarbonize industry,
- support for increasing the share of renewable energy sources (Power-to-X energy storage technology),
- support for decarbonisation of the gas sector (use of a mixture of natural gas and hydrogen)[77].

Therefore, the development of hydrogen technologies and the whole hydrogen market is expected. This process is to be supported by "successive regulatory work and adjustment of support systems for investment, research and development activities and the construction of a national technological base. It is therefore necessary to take advantage of favourable conditions for the development and financing of hydrogen technologies created within the framework of the EU policy (European Green Deal, reform of the European gas market)[78]. The transport and distribution of produced hydrogen volumes will use, among other things, the existing gas infrastructure. It is assumed that by 2030 the Polish gas network will achieve the capacity to transport a mixture containing about 10% of gases other than mine gas (biomethane, green hydrogen)[79].

3.8 Draft Polish Hydrogen Strategy

The material under analysis was an updated version of the draft *Polish Hydrogen Strategy until 2030 with an Outlook until 2040* (hereinafter referred to as the draft PHS) published and submitted for public

75 *Energy Policy of Poland until 2040*, p. 7.
76 *Ibid*, p. 6.
77 *Ibid*, p. 7.
78 *Ibid*, pp. 9-10.
79 *Ibid*, p. 38.

consultation by the Ministry of Climate and Environment (hereinafter referred to as the MoCE) on 21 June 2021[80]. At the outset, it is pointed out that the domestic production of hydrogen at the level of more than 1 million tonnes ranks Poland third in Europe. However, as already stated in the first part of this report, this is not hydrogen produced using renewable energy sources and therefore cannot be included in the energy transition leading to climate neutrality. The general objective included in the draft PHS is therefore "to create a Polish hydrogen industry and its development to achieve climate neutrality and maintain the competitiveness of the Polish economy"[81]. This is a strategic challenge for the authorities and the national economy that requires a comprehensive approach considering the whole value chain and solving the whole spectrum of problems. Three priority areas for future use of green hydrogen in Poland have been identified:

- power industry;
- transport;
- industry.

In all cases, green hydrogen is expected to minimise the use of fossil fuels and thus reduce the emission of greenhouse gases into the atmosphere. The implementation of green hydrogen is to be based on the concept of combining sectors[82].

The draft PHS defines six necessary objectives to be achieved:

Objective 1 - Implementation of hydrogen technologies in the power sector

Achievement of this goal is closely related to the development of RES and increasing their share in the Polish energy mix. Dependence of these sources on weather conditions requires effective solutions for their balancing. It was estimated that in Polish natural and geographical conditions, the most economically beneficial variant of green hydrogen production will be based on electricity obtained from offshore wind farms.

Objective 2 - Use of hydrogen as an alternative fuel for transport

In the light of the PHS assumptions, green hydrogen is also to become a commonly used fuel in transport, which will reduce its emissions. This objective is to be achieved primarily in urban transport, heavy long-distance road transport, rail and waterborne transport.

The anticipated use of hydrogen in transport will require the construction of appropriate infrastructure to enable storage and refuelling of e.g. sea-going vessels, aircraft and buses. The draft PHS predicts, among other things, that in a perspective of 5 years the demand for hydrogen generated by buses will be over 1700 tonnes per year and will require servicing by more than 30 refuelling stations[83].

80 https://www.gov.pl/web/klimat/rozpoczely-sie-konsultacje-publiczne-projektu-polskiej-strategii-wodorowej

81 Updated version of the draft *Polish Hydropower Strategy until 2030 with an Outlook until 2040*, Warsaw, 21.06.2021, p. 3.

82 *Ibid*, p. 10.

83 *Ibid*, p. 14.

Objective 3 - Support the decarbonisation of industry

Heavy industry, which includes the production of fuels, non-metallic minerals, steel and chemicals, requires decarbonization. According to the PHS, the industry "has a high chance of being the largest consumer of low-carbon hydrogen due to the lack of alternative decarbonisation options"[84]. The way to provide adequate quantities of green hydrogen to industry is to be through hydrogen valleys, i.e. locations close to industrial customers where there will be a concentration of hydrogen management activities. The production of clean energy to power electrolysers, which will transfer the produced green hydrogen to nearby industrial consumers, is to be concentrated in hydrogen valleys. Application of such a model of organization of the hydrogen economy is to enable integration of industrial sectors, gaining business partners as well as to optimise processes and costs.

Objective 4 - Production of hydrogen in new installations

The draft PHS provides for the creation of appropriate conditions for the development of infrastructure producing hydrogen from low- and zero-emission sources. It is explicitly declared that only hydrogen investments based on renewable sources and using zero-emission technologies will receive government support. The draft PHS recognizes that the most beneficial forms of hydrogen production are projects implemented within energy clusters and in locations as close as possible to the places reporting demand for hydrogen (local markets).

Objective 5 - Efficient and safe distribution of hydrogen

The construction of an infrastructure system for hydrogen transport is a basic condition for the emergence of a hydrogen economy. It is envisaged that in the first period of its functioning, road and rail transport (tankers) will be used. It is also assumed that the existing infrastructure (transmission and distribution) for natural gas will be used for large-scale hydrogen transport in the future, provided that it is properly prepared. The construction of pipelines dedicated only to hydrogen is not excluded either. However, this infrastructure will be developed on the basis of a "cluster model" in which production and demand centres will be connected[85].

The implementation of the hydrogen distribution objective also includes the issue of hydrogen storage. The use of the whole range of technical options for hydrogen storage is foreseen, from above-ground storage facilities to underground storage in the form of depleted oil and gas fields, aquifers, rock caverns or abandoned mines[86].

Objective 6 - Creation of a stable regulatory environment

The future hydrogen economy should operate within the framework of appropriate legal norms and standardization regulations providing a formal basis for the functioning of the future market. The

84 *Ibid*, p. 15.
85 *Ibid*, p. 19.
86 *Ibid*.

draft PHS assumes that in the period between Q3 2021 and the end of 2023 legislative actions will be taken on:

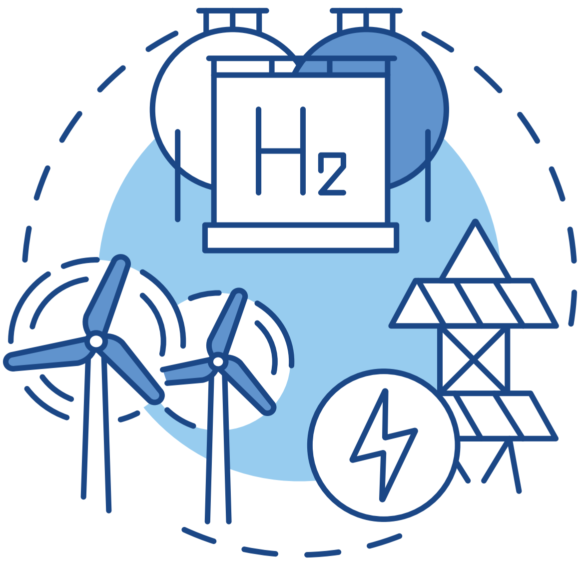
- to provide a regulatory framework for the operation of hydrogen as an alternative fuel for transport,
- to develop a hydrogen legislative package that lays the foundations for a functioning market,
- to develop legislation setting out the details of how the market will operate (another package), implementing EU law in this area and implementing a system of incentives for the production of low-emission hydrogen.

The draft PHS, however, does not address the issue of the future model of the green hydrogen market and its exact structure. Thus, the draft does not contain, for example, an explicit declaration that the future green hydrogen market will be based on a liberalised gas market model. Thus, the issue of the price formation mechanism for green hydrogen remains to be resolved, including whether it will be based on a market mechanism, e.g. on an exchange, or whether the price will be formed within a strict regulatory framework supervised by a market regulator.

The draft PHS foresees a total of 40 activities for the implementation of the set objectives, which are to take advantage of Polish technological, scientific and research resources and potential in the field of modern hydrogen technologies and the creation of a Polish hydrogen industry. The draft outlines the directions in which a hydrogen economy should develop and, at the same time, presents the main technological and business obstacles that could hinder this development.

The draft PHS assumes that, *inter alia*, due to the application of support mechanisms, the demand for green hydrogen will grow. It is also expected that the growing popularity of hydrogen, also on a global scale, will result in a decrease in its price and an increase in its market attractiveness. As a consequence, this may lead to further increase in demand and create needs to expand production capacity. In such a scenario of the hydrogen economy development, extending to 2040, the draft PHS envisages relying production on nuclear power plants and electrolysers connected to them[87].

87 *Ibid*, p. 21.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04

GREEN HYDROGEN – ECONOMIC CONDITIONS AND DEVELOPMENT BARRIERS

4.1 Costs of producing hydrogen

The cost of producing hydrogen depends on many factors, including primarily the generation method and the fuel/energy carrier used, as described in Chapter 2.2.

Currently, the cost of producing green hydrogen is at least twice as high as the cost of producing hydrogen through steam reforming of hydrocarbons. However, this is expected to change in the future due to falling costs of electrolysers and unit costs of electricity generation from RES. The following figures present the costs of hydrogen production for different technological options, based on the latest data presented by recognised research centres[88].

To compare the costs of hydrogen production, the Levelised Cost of Hydrogen (LCOH) was used, which is an indicator analogous to the one used to compare the costs of electricity production from different sources, i.e. the Levelised Cost of Energy (LCOE).

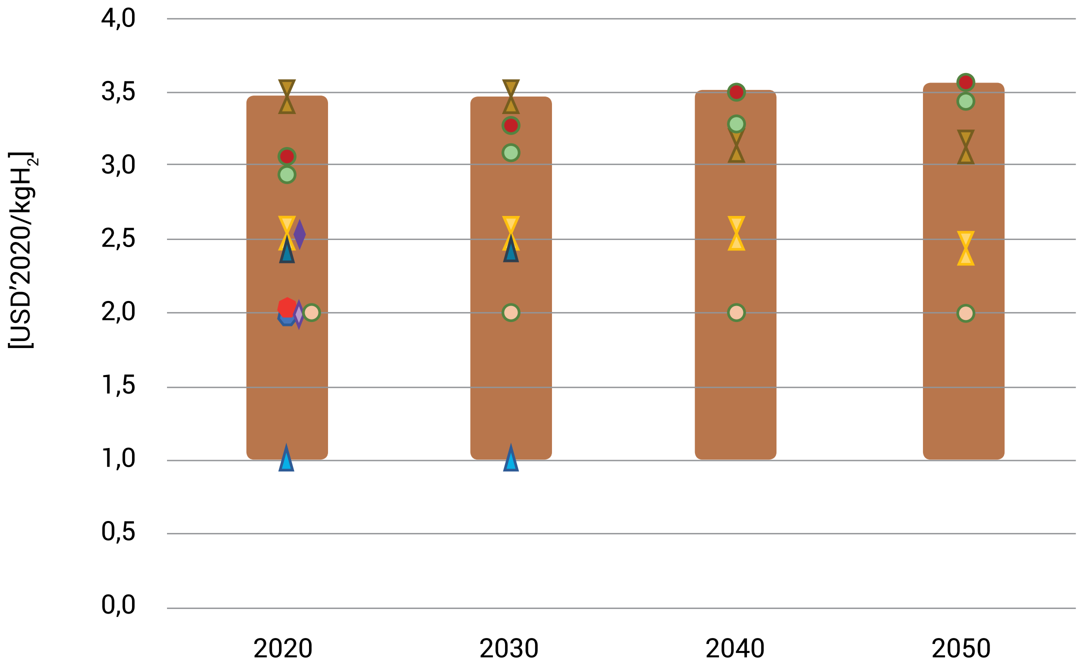
The cost of producing hydrogen, as with the cost of producing electricity, depends on a number of factors such as:

- investment costs (CAPEX),
- operating costs (OPEX),
- installation type and efficiency,
- installation lifetime,
- capacity factor (CF),
- electricity costs and, in the case of the steam reforming process, the raw material costs and the costs of purchasing CO_2 emission allowances.

The results of the analysis show that the cost of hydrogen production using conventional methods is currently about 1.0 to 3.5 USD'2020/kgH_2 (in Polish conditions from 1.8 to 3.1 USD'2020/kgH_2, depending on the raw material used) and it is expected that this cost will not change significantly in the future. Rising costs of purchasing CO_2 emission allowances may even cause their increase. Conversely, the cost of producing green hydrogen will come down significantly over the next decade, making it competitive with hydrogen from reforming. Currently, green hydrogen costs are in the range of 2.0-7.5 USD'2020/kgH_2 (median at 4.1 USD'2020/kgH_2) and by 2030 will fall to 0.8-4.2 USD'2020/kgH_2 (median at 2.2 USD'2020/kgH_2). In subsequent periods, they are expected to fall further. In 2050, the cost of green hydrogen is expected to be 0.8-3.5 USD'2020/kgH_2 (median at 1.7 USD'2020/kgH_2), with electrolysers integrated with PV power plants assumed to be a slightly cheaper option.

88 Listed under each of the graphs showing the cost of obtaining hydrogen of a particular type.

Figure 4.1. Production costs of brown hydrogen

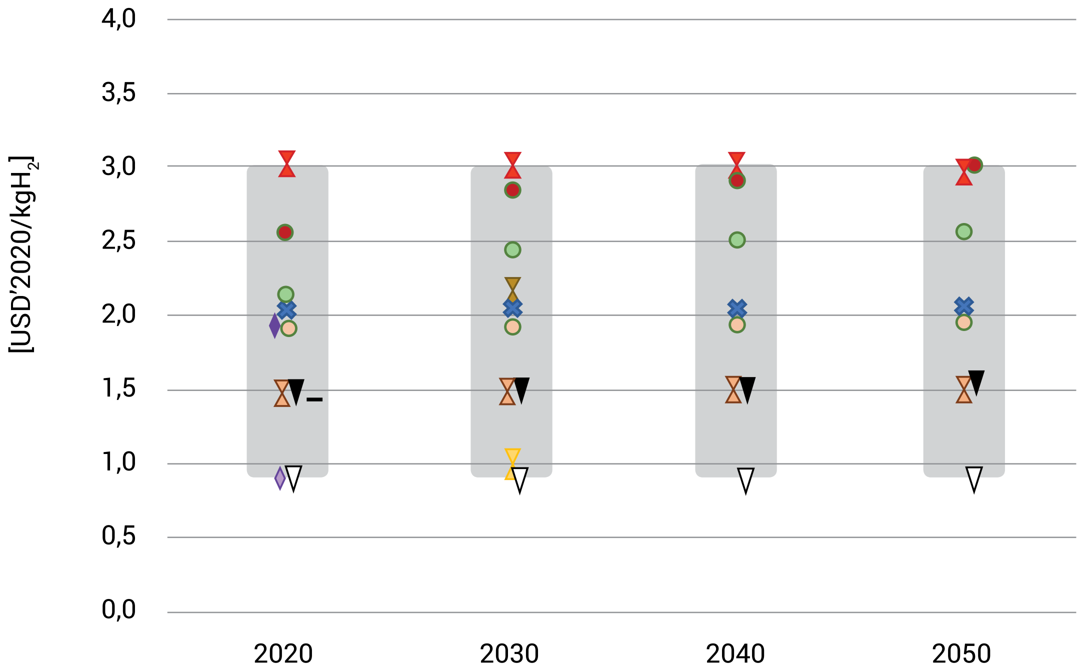


USD'2020/kgH$_2$

Source:	2020	2030	2040	2050
IRENA_1_low	1,9	n.a.	n.a.	n.a.
IRENA_1_avg	2,1	n.a.	n.a.	n.a.
IEA_min	2,0	n.a.	n.a.	n.a.
IEA_max	2,6	n.a.	n.a.	n.a.
BNEF_1_min	2,6	2,6	2,5	2,3
BNEF_1_max	3,4	3,4	3,2	3,1
Kearney_min	1,0	1,0	n.a.	n.a.
Kearney_max	2,3	2,3	n.a.	n.a.
ARE_base	2,9	3,1	3,3	3,4
ARE_min	2,0	2,0	2,0	2,0
ARE_max	3,1	3,3	3,5	3,6

Source:
IRENA_1 - *"Hydrogen: A Renewable Energy Perspective"*. International Renewable Energy Agency. Abu Dhabi, 2019.
IRENA_2 - *"Green Hydrogen Cost Reduction"*. International Renewable Energy Agency. Abu Dhabi, 2020.
IEA - *"Energy Technology Perspectives 2020"*. International Energy Agency, Paris, 2020.
BNEF_1 - *"Green Hydrogen to Outcompete Blue Everywhere by 2030."* BloombergNEF, 2021.
Kearney - *"Hydrogen applications and business models. Going blue and green?"* Energy transition Institute, 2020.
ARE - Agencja Rynku Energii SA in Warsaw, own study. Warsaw, 2021.

Figure 4.2. Production costs of grey hydrogen

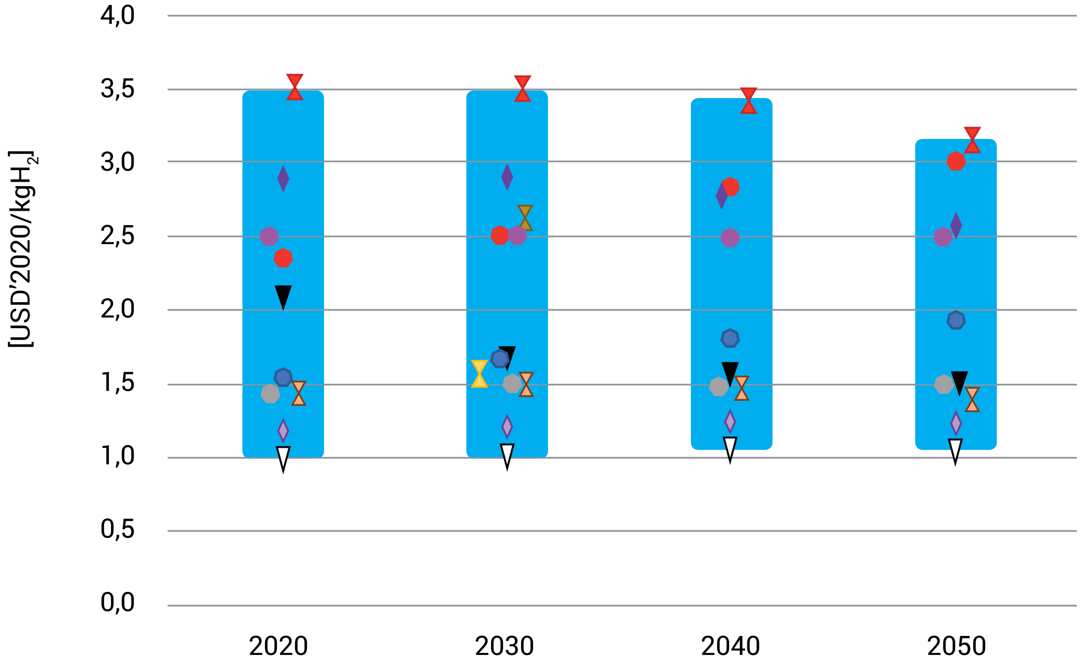


USD'2020/kgH$_2$

Source:	2020	2030	2040	2050
Platts EU	1,4	n.a.	n.a.	n.a.
BNEF_1_min	n.a.	1,0	n.a.	n.a.
BNEF_1_max	n.a.	2,2	n.a.	n.a.
IEA_min	0,9	n.a.	n.a.	n.a.
IEA_max	1,8	n.a.	n.a.	n.a.
BNEF_2_min	1,5	1,5	1,5	1,5
BNEF_2_max	3,0	3,0	3,0	2,9
Hydrogen Council_min	0,9	0,9	0,9	0,9
Hydrogen Council_max	1,5	1,5	1,5	1,6
Fraunhofer	2,1	2,1	2,1	2,1
ARE_base	2,2	2,4	2,5	2,6
ARE_min	1,8	1,8	1,8	1,8
ARE_max	2,6	2,8	2,9	3,0

Source:
Platts EU - *"Platts Hydrogen Assessments"*. S&P Global Platts, 2021.
BNEF_1 - *"Green Hydrogen to Outcompete Blue Everywhere by 2030."* BloombergNEF, 2021.
IEA - *"Energy Technology Perspectives 2020"*. International Energy Agency, Paris 2020.
BNEF_2 - *"Hydrogen Economy Outlook, Key messages"*. BloombergNEF, 2020.
Hydrogen Council - *"Hydrogen Insights. A perspective on hydrogen investment, market development and cost competitiveness"*. Hydrogen Council, McKinsey & Company, 2021.
Fraunhofer - *"Hydrogen technologies for a CO_2 neutral chemical industry - a plant-specific bottom-up assessment of pathways to decarbonize the German chemical industry"*. Fraunhofer Institute for Systems and Innovation Research ISI. Germany, 2020.
ARE - Agencja Rynku Energii SA in Warsaw, own study. Warsaw, 2021.

Figure 4.3. Production costs of blue hydrogen



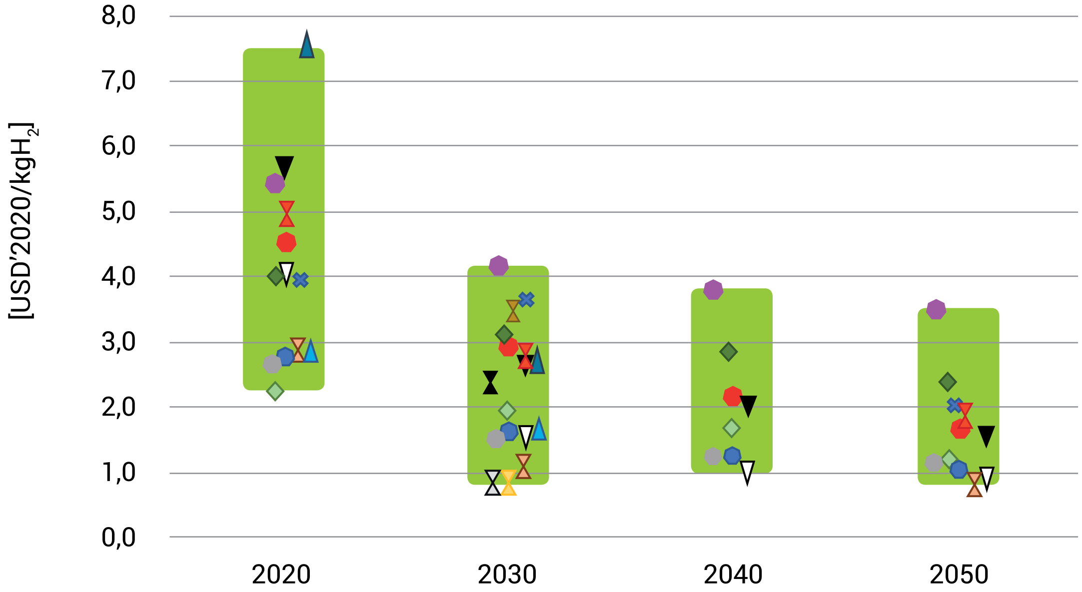
USD'2020/kgH_2

Source:	2020	2030	2040	2050
BNEF_1_min	n.a.	1,6	n.a.	n.a.
BNEF_1_max	n.a.	2,7	n.a.	n.a.
IRENA_1_low	1,6	1,7	1,8	1,9
IRENA_1_avg	2,3	2,5	2,8	3,0
IEA_min	1,2	1,2	1,2	1,2
IEA_max	2,8	2,8	2,7	2,6
Hydrogen Council_min	1,0	1,0	1,1	1,1
Hydrogen Council_max	2,2	1,7	1,6	1,5
IRENA_2_min	1,3	1,4	1,4	1,5
IRENA_2_max	2,5	2,5	2,5	2,6
BNEF_2_min	1,3	1,5	1,4	1,3
BNEF_2_max	3,5	3,5	3,4	3,2

Source:

BNEF_1 - *"Green Hydrogen to Outcompete Blue Everywhere by 2030."* BloombergNEF, May 2021.
IRENA_1 - *"Hydrogen: A Renewable Energy Perspective"*. International Renewable Energy Agency. Abu Dhabi, 2019.
IEA - *"Energy Technology Perspectives 2020"*. International Energy Agency, Paris 2020.
Hydrogen Council - *"Hydrogen Insights. A perspective on hydrogen investment, market development and cost competitiveness"*. Hydrogen Council, McKinsey & Company, 2021.
IRENA_2 - *"Green Hydrogen Cost Reduction"*. International Renewable Energy Agency. Abu Dhabi, 2020.
BNEF_2 - *"Hydrogen Economy Outlook, Key messages"*. BloombergNEF, 2020.

Figure 4.4. Production costs of green hydrogen (electrolyser + wind turbine)

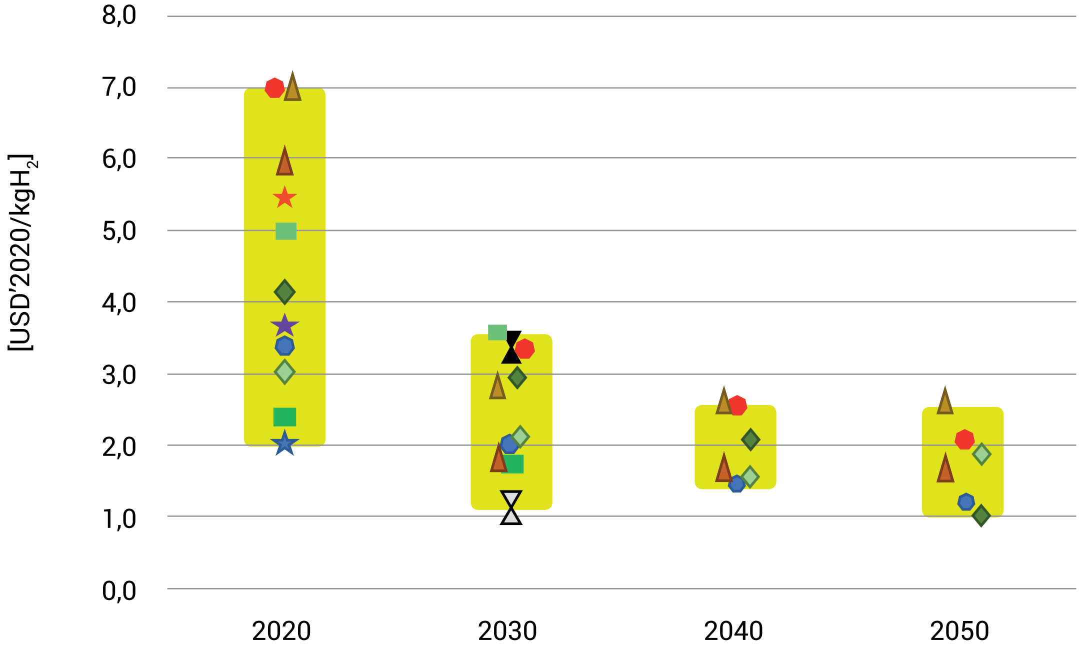


USD'2020/kgH_2

Source:	2020	2030	2040	2050
BNEF_1_min	n.a.	0,8	n.a.	n.a.
BNEF_1_max	n.a.	3,4	n.a.	n.a.
IRENA_1_low	2,7	1,6	1,2	1,0
IRENA_1_avg	4,5	2,9	2,2	1,6
BNEF_2_min	2,6	1,2	n.a.	0,8
BNEF_2_max	4,9	2,7	n.a.	1,8
BNEF_3_min	n.a.	0,8	n.a.	n.a.
BNEF_3_max	n.a.	2,3	n.a.	n.a.
Hydrogen Council_min	4,1	1,5	1,0	0,9
Hydrogen Council_max	5,7	2,6	2,1	1,5
EWI_min	2,3	1,9	1,6	1,2
EWI_max	4,1	3,2	2,8	2,4
IRENA_2_min	2,4	1,5	1,2	1,1
IRENA_2_max	5,4	4,2	3,8	3,5
Fraunhofer	3,9	3,7	n.a.	2,0
Kearney_min	2,6	1,6	n.a.	n.a.
Kearney_max	7,5	2,6	n.a.	n.a.

Source:
BNEF_1 - *"Green Hydrogen to Outcompete Blue Everywhere by 2030"*. BloombergNEF, May 2021.
IRENA_1 - *"Hydrogen: A Renewable Energy Perspective"*. International Renewable Energy Agency. Abu Dhabi, 2019.
BNEF_2 - *"Hydrogen Economy Outlook, Key messages"*. BloombergNEF, 2020.
BNEF_3 - *"1H 2021 Hydrogen Levelized Cost Update"*. BloombergNEF.
Hydrogen Council - *"Hydrogen Insights. A perspective on hydrogen investment, market development and cost competitiveness"*. Hydrogen Council, McKinsey & Company, 2021.
EWI - *"Estimating Long-Term Global Supply Costs for Low-Carbon"*. Institute of Energy Economics at the University of Cologne (EWI), 2020.
IRENA_2 - *"Green Hydrogen Cost Reduction"*. International Renewable Energy Agency. Abu Dhabi, 2020.
Fraunhofer - *"Hydrogen technologies for a CO_2 - neutral chemical industry – a plant-specific bottom-up assessment of pathways to decarbonize the German chemical industry"*. Fraunhofer, Germany 2020.
Kearney - *"Hydrogen applications and business models. Going blue and green?"* Energy transition Institute, 2020.

Figure 4.5. Production costs of green hydrogen (electrolyser + PV system)



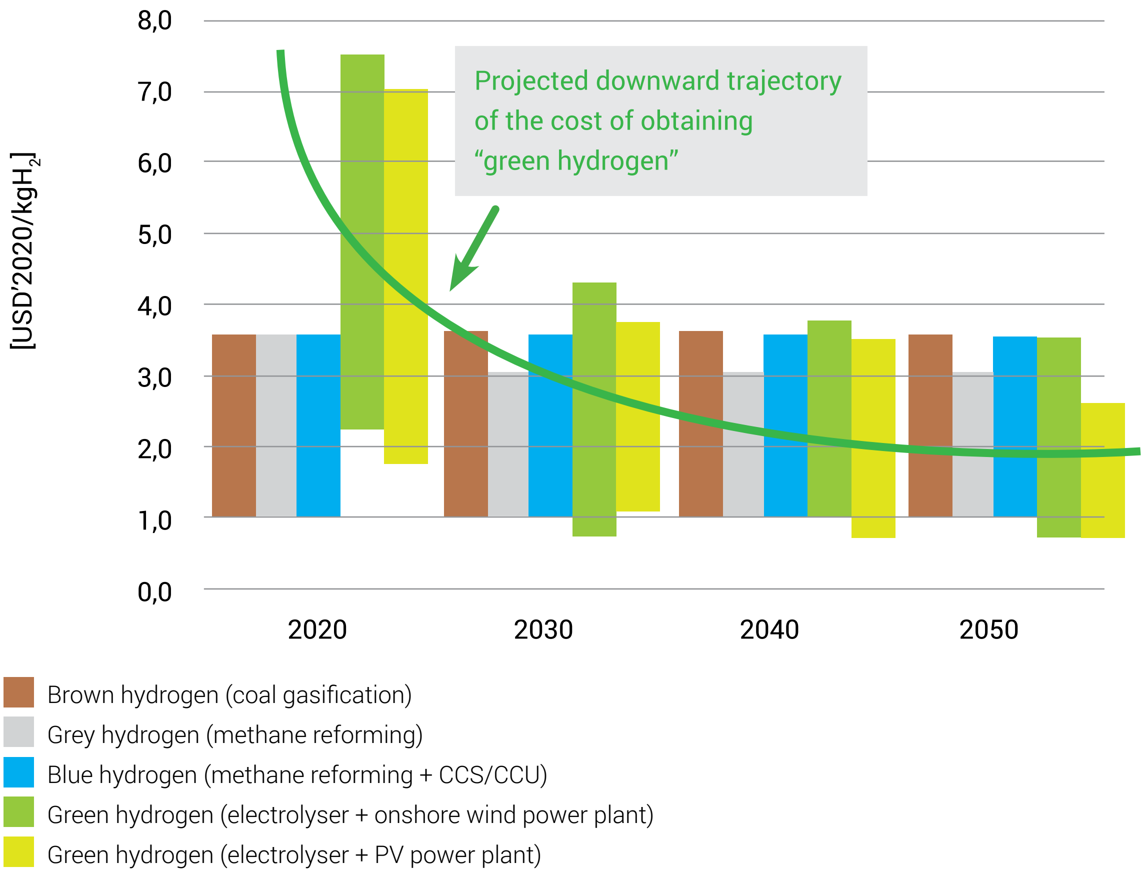
USD'2020/kgH_2

Source:	2020	2030	2040	2050
BNEF_3_min	n.a.	1,1	n.a.	n.a.
BNEF_3_max	n.a.	3,3	n.a.	n.a.
IRENA_1_low	3,3	2,0	1,5	1,2
IRENA_1_avg	7,0	3,3	2,7	2,1
EWI_min	3,0	2,1	1,6	1,0
EWI_max	4,1	2,9	2,2	1,9
Gallardo_min	2,3	1,7	n.a.	n.a.
Gallardo_max	5,0	3,5	n.a.	n.a.
Yates_min	2,0	n.a.	n.a.	n.a.
Yates_avg	3,6	n.a.	n.a.	n.a.
Yates_avg	5,5	n.a.	n.a.	n.a.
Wildfire_min	5,8	1,7	1,7	1,7
Wildfire_max	7,0	2,6	2,6	2,6

Source:
BNEF3 - "*1H 2021 Hydrogen Levelized Cost Update*". BloombergNEF.
IRENA_1 - "*Hydrogen: A Renewable Energy Perspective*". International Renewable Energy Agency. Abu Dhabi, 2019.
EWI - "*Estimating Long-Term Global Supply Costs for Low-Carbon*". Institute of Energy Economics at the University of Cologne (EWI), 2020.
Gallardo - Felipe Ignacio Gallardo, Andrea Monforti Ferrario, Mario Lamagna, Enrico Bocci, Davide Astiaso Garcia, Tomas E. Baeza-Jeria. *"Techno-Economic Analysis of solar hydrogen production by electrolysis in the north of Chile and the case of exportation from Atacama Desert to Japan"*. International Journal of Hydrogen Energy, 2020.
Yates - Jonathon Yates, Rahman Daiyan, Robert Patterson, Renate Egan, Rose Amal, Anita Ho-Baille and Nathan L. Chang. "*Techno-economic Analysis of Hydrogen Electrolysis from Off-Grid Stand-Alone Photovoltaics Incorporating Uncertainty Analysis*". Cell Reports Physical Science, Volume 1, Issue 10, 21 October 2020
Wildfire - Perkins Greg. "*What is the Levelized Cost of Clean Hydrogen Production?*" Wildfire Energy, Austria 2019.

Figure 4.6. presents a comparison of the costs of producing hydrogen using different technologies. It shows that already around 2030, production of green hydrogen will become competitive in relation to the conventional methods of hydrogen production based on fossil fuels.

Figure 4.6. Comparison of hydrogen production costs



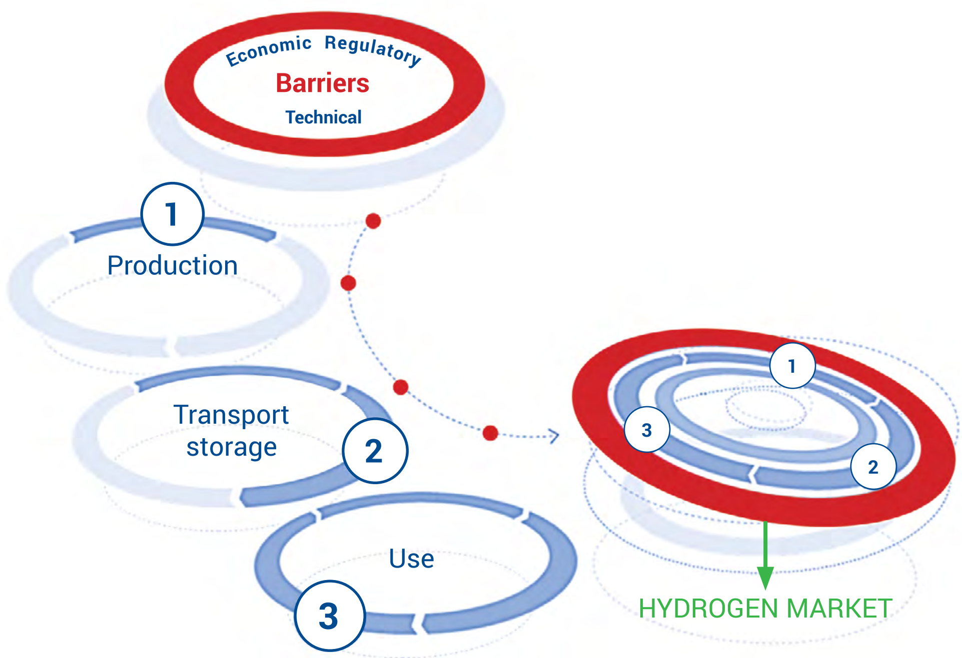
Source: own study.

Achievement of such a significant decline in the production costs of green hydrogen is possible due to the expected reduction of electrolyser costs (technology development and increase in the scale of production of these devices) and further decline in the costs of electricity generation from RES. Determinants of achieving this goal are described in detail later in this report. The next ten years will be crucial for this technology, as huge funds are expected to be allocated to research and development. At least a few years ago major energy companies started to work on improving the technology and the race to fully commercialize the hydrogen economy.

4.2 Barriers to green hydrogen development

When talking about barriers to the production of green hydrogen, one should look at the problem in a broader context than just its production. Each of the elements in the hydrogen economy chain is important. The possibility of effective production of hydrogen can only be discussed in the context of the existence of a market for this product. Therefore, regardless of whether production is expensive or not, if there is no demand for the product produced, then production will not make sense. In addition, if there is no market for the product being produced, and therefore no competition, then the rate of development of technology both for hydrogen production, storage, transport and end use will be too slow to achieve the assumed maturity by 2030.

Figure 4.7. Arrangement of elements influencing the development of the hydrogen market



Source: own study.

The main challenges for the development of a renewable hydrogen market should be approached from the perspective of the need to reduce the costs associated with production, transport (including transmission and distribution) and storage, as well as the costs of hydrogen-using equipment, vehicles and infrastructure. The speed of hydrogen market development will largely depend on the adaptation of market regulations and standards, which should not only enable the relatively easy scaling up of hydrogen technologies, but also create the expected incentives to use hydrogen-based solutions. Each of the issues associated with the development of hydrogen technologies is also an opportunity for stakeholders in this market. Solving key technological and non-technological problems may prove to be an important axis of building competitive advantages[89]. The barriers for individual elements of the hydrogen chain, understood as production, transport and storage, and the target application (E-economic, T-technical, R-regulatory) are identified below:

89 *The global supply chain and value of the hydrogen economy*, Report prepared for the Office of the Marshal of Wielkopolska Region as part of funding from the European Regional Fund, p. 61 (accessed 30.07.2021).

Renewable hydrogen production:

- high installation and technology costs for the production of hydrogen (E),
- high energy losses in the process of hydrogen production, the need to seek technological solutions to reduce losses, more efficient energy management[90] (T/E),
- immature solutions using high-capacity electrolysers, which, in the case of hydrogen production from wind power and, in particular, offshore farms, could be a barrier to the development of the hydrogen market (T),
- no rules and conditions for connection and cooperation of the electrolyser with the power grid, especially in the case of high power electrolysers[91] (R),
- no regulations dedicated to the concept of Power to Gas technology[92] with its individual components (R),
- limited/underdeveloped market for the hydrogen produced (R/T),
- limited ability to define business models designed to create value by seizing business opportunities that provide returns (R/E),
- the lack of an established vision of the future hydrogen market and of its function and place in the whole national economy, enabling the creation of stable regulations for its production and guaranteeing its future sale (R),
- the existence of unpredictable regulations making it difficult to correctly forecast changes in electricity prices and the speed and scale of development of individual RES sources (R)[93],
- no regulation on certification to prove green hydrogen production (R)[94],
- The lack of a comprehensive hydrogen law[95] governing the production of renewable hydrogen (R),
- uneconomic use of sea water for hydrogen production from farms located at sea or in direct access to it (T).

90 T. Chmielniak, S. Lepszy, P. Mońka, *Energetyka wodorowa – podstawowe problemy [Hydrogen energy - basic problems], Polityka Energetyczna* 2017, vol. 20, z. 3, pp. 55-66.

91 At this point, it is also worth pointing out numerous problems with the connection of wind farms to the power grid, resulting from the lack of capacity (in selected locations of the grid) to accept additional power injected into the system without expenditures on the development of the power infrastructure. There are also cases of connection refusals due to the lack of appropriate power infrastructure.

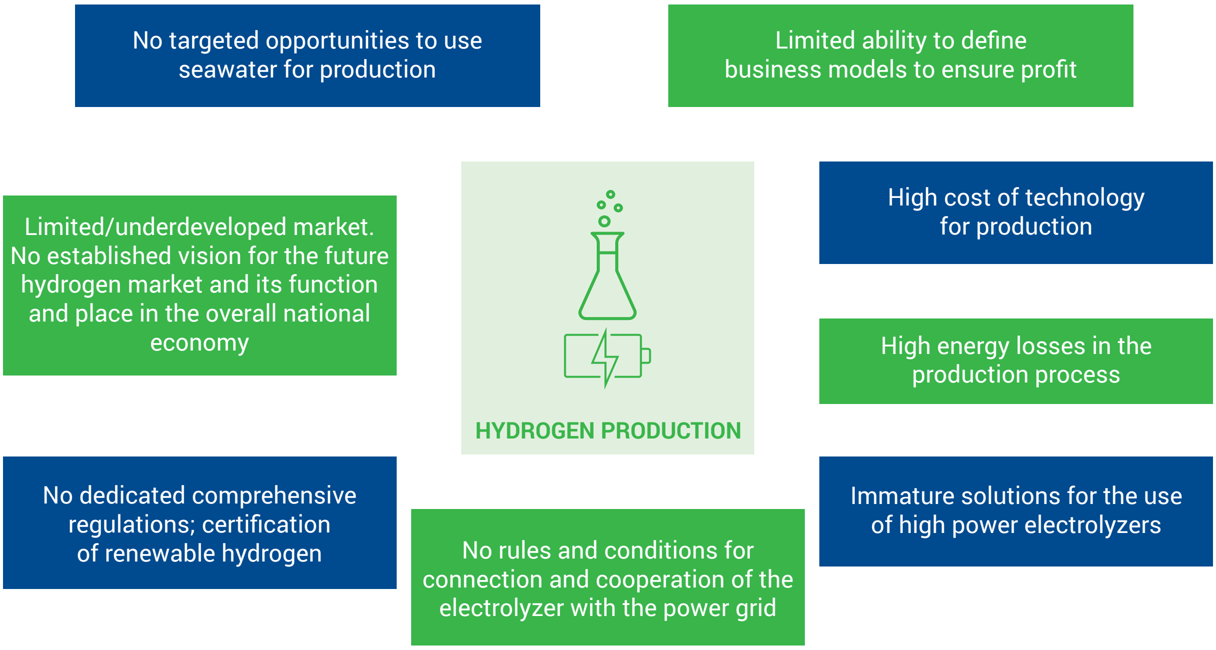
92 Production of hydrogen from electricity.

93 The example of the distance law, freezing energy prices, changes to prosumer billing, extending coal use.

94 The Australian Government launched a consultation on the Hydrogen Certification of Origin document in June 2021. Based on this document, regulations will be created in this area to enable the promotion of green hydrogen, https://consult.industry.gov.au/climate-change/hydrogen-guarantee-of-origin-scheme-discussion/

95 Along the lines of the Renewable Electricity Sources Act or the Power Market Act.

Figure 4.8. Barriers to renewable hydrogen production



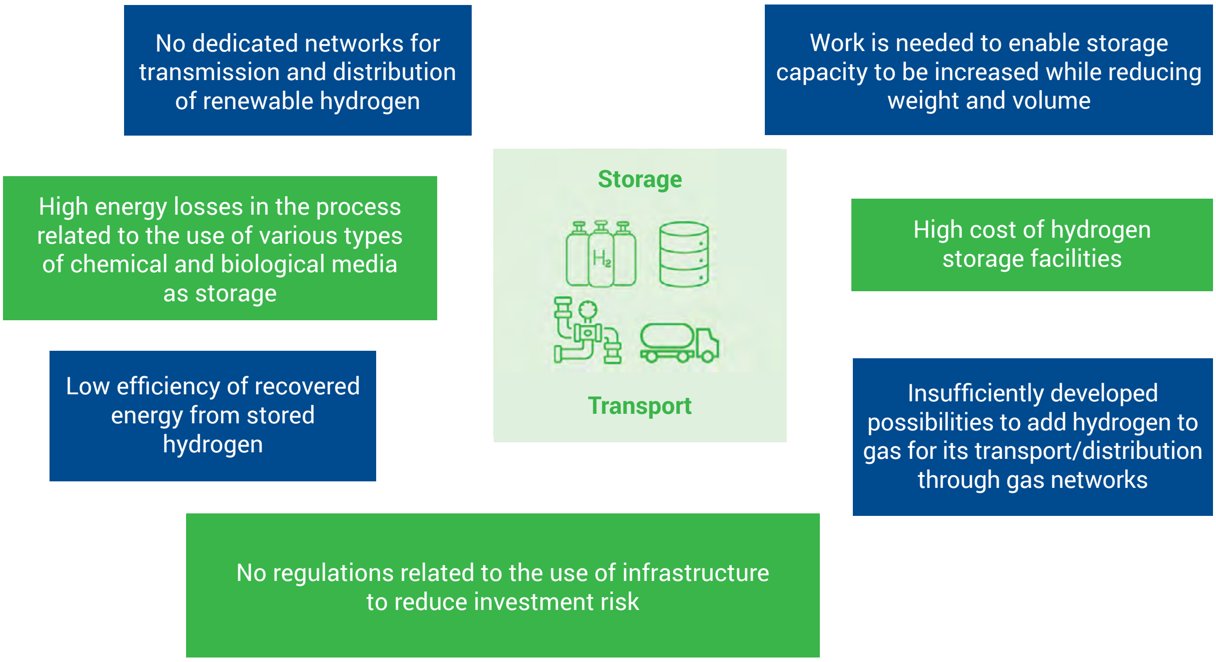
Source: own study.

Hydrogen transport/storage:

- lack of dedicated networks for hydrogen transmission and distribution. Development of such networks will be associated with high costs of their construction and maintenance (T, E),
- underdeveloped technology related to the possibilities of adding hydrogen to gas for transmission/distribution through gas transmission/distribution networks (T),
- insufficient number of analyses of the long-term impact of hydrogen on the network infrastructure components of the existing gas networks in Poland for the transport of doped gas (T),
- The need to optimize hydrogen transport technology using different types of chemical and biological carriers to reduce losses from adaptation to transport and storage (T, E),
- lack of road regulations and regulations related to the location of hydrogen distribution infrastructure enabling to reduce investment risk (R),
- high cost of hydrogen storage facilities (E),
- all hydrogen storage technologies require special, specified conditions for processing (depending on the form adopted), which can cause problems with large-scale storage[96] (T),
- it is necessary to work on enabling the storage capacity to be increased while at the same time reducing storage weight and volume, especially for transport (T),
- high losses in the conversion of hydrogen into storable energy (T),
- low efficiency of recovered energy from stored hydrogen (T).

96 T. Chmielniak, S. Lepszy, P. Mońka, *Energetyka wodorowa – podstawowe problemy...*, pp. 55-66.

Figure 4.9. Barriers to hydrogen transport and storage



Source: own study.

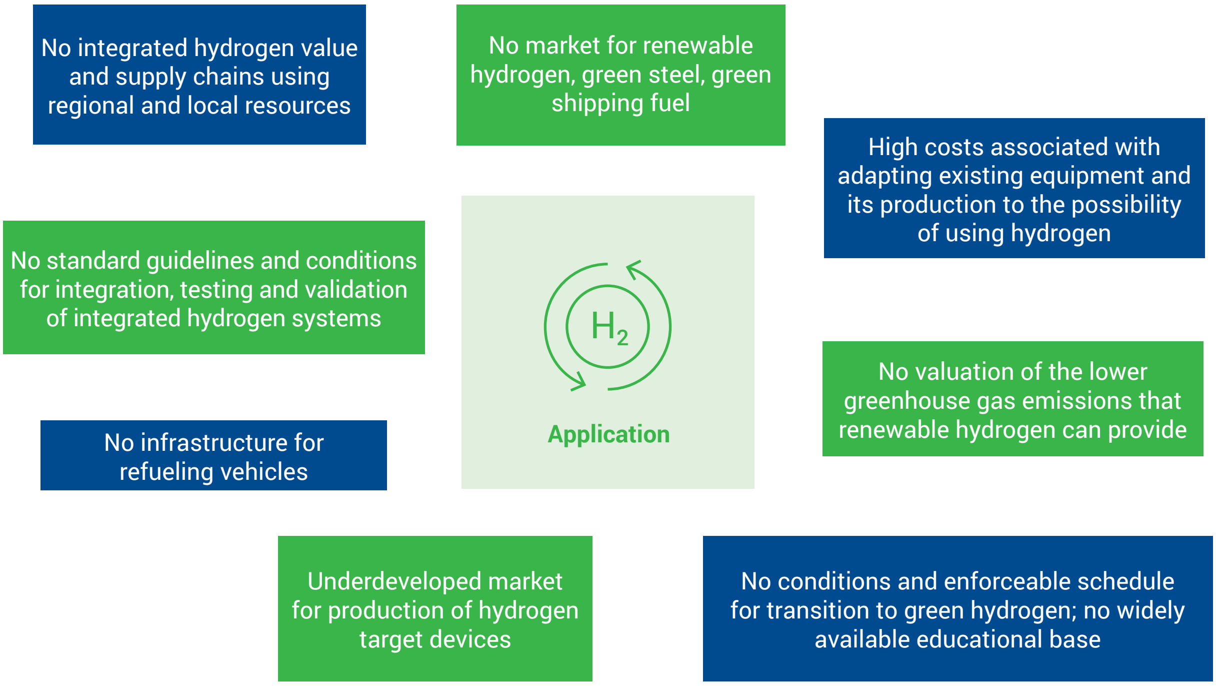
Target application areas:

- no market for green hydrogen, green steel, green marine fuel, and essentially no valuation of the lower GHG emissions that renewable hydrogen can provide. State support is needed to initiate market development for renewable hydrogen (R),
- high costs associated with adapting existing equipment and its production to the possibility of using hydrogen. Financial support needed in the first phase of market development[97] (E),
- lack of integrated hydrogen value and supply chains using regional and local resources. Necessary incentives to develop local initiatives (R/E),
- lack of standardised guidelines and conditions for the integration, testing and validation of integrated hydrogen systems tailored to the specificities of each of the key application areas (R),
- lack of refuelling infrastructure for hydrogen vehicles and the assumptions and directions of its development, also in connection with existing conditions for vehicles powered by other fuels (T, R),
- high costs associated with the production of hydrogen vehicles (E),
- lack of standards and norms for household devices that could use hydrogen as an energy source (R),
- underdeveloped market for the production of hydrogen target devices (R),
- lack of direction and an enforceable timetable for transitioning to green hydrogen in those indus-

97 For example, replacing existing coal-fired boilers in district heating with ‘hydrogen-ready’ boilers, i.e. condensing gas-fired boilers which are designed to burn a mixture of methane + hydrogen or pure hydrogen. Hydrogen and natural gas have different combustion properties. Hydrogen has a higher combustion velocity and combustion temperature. So compared to a coal gas boiler, a hydrogen boiler has different components. The control system and burner control is also completely different. Heating companies are working on such a solution, which today can be a natural gas boiler or a natural gas boiler with a mixture of hydrogen, and in the future it will be easy to changeover to a fully hydrogen boiler.

tries where hydrogen is already used in production processes today (R),
- lack of a widely available educational base specialising in the production, transport and application of green hydrogen (R).

Figure 4.10. Barriers in the area of targeted applications



Source: own study.

It is also worth pointing out that with respect to many of the barriers identified above and related to the implementation of hydrogen technologies in the economy, it is necessary to involve the state more closely in financing R&D projects. Such involvement would allow for quicker identification of solutions to eliminate the barriers that exist today or at least to reduce their impact to accelerate the development of the hydrogen economy.

4.2.1 Brief analysis of barriers along the value chain

In the case of green hydrogen production from RES-based electricity, **the first level of barriers should be approached from the perspective of the costs necessary to start producing electricity**. However, when considering a business model whose main premise is the production of hydrogen from RES, the cost of installing, commissioning and operating an electrolyser must also be added to the cost of the RES installation. While it can be assumed that there will be a sufficient surplus of electricity from RES to produce green hydrogen, without an adequate market for the produced hydrogen, there is no business case for such a model. Moreover, assuming that the produced hydrogen can be stored for later sale/use (in various forms), another cost of the whole undertaking will be to set up a hydrogen storage facility or to establish cooperation with entities providing such services.

Renewable electricity generation technologies are often confronted with the above-mentioned barriers in the early stages of their development. These barriers can be largely addressed by pursuing the right policies, creating an enabling environment for renewable hydrogen production, transport and trade.

Current government incentives and policies for electrolysers and the infrastructure needed to use them are limited, if any. However, expert knowledge promoting renewable energy in the power and heating industry, as well as regulation in the industrial sector, may provide answers on how to construct a hydrogen strategy and policy that will enable electrolyser cost reduction. This could be achieved by emphasising and supporting innovative projects to improve the performance of electrolysers, increasing their capacity from today's megawatt level to multi-gigawatt (GW). Mass production of electrolysers with their standardisation and increased efficiency levels will also contribute to reducing costs along the supply chain. While producing electricity at the lowest possible cost is a prerequisite for competitive green hydrogen production, the costs not only of installing green hydrogen production facilities, but also of storing[98] and transporting green hydrogen need to be significantly reduced.

If a market for the stored hydrogen is found, the next step will be the need to ensure that the hydrogen is transported to its final destination.

One option for bringing hydrogen to its final destination could be to mix it with natural gas and transport it through existing gas pipelines. Here, however, while the economic conditions themselves have less influence, technology begins to play a significant role, namely the possible level of hydrogen doping, which in Europe varies between 0.2% and 10%, and in the perspective of the next 10 years will reach 20%[99]. The question arises of the need to modernise existing gas pipelines to enable the transport of gas with doped hydrogen, or to build new installations intended for the transport of pure hydrogen. Further investment in infrastructure is therefore necessary, irrespective of the form of transport chosen. However, when talking about infrastructure, we should not only consider the gas pipelines themselves, but also the equipment and systems for monitoring the safety of the entire infrastructure[100].

According to the Draft Polish Hydrogen Strategy until 2025, the existing gas infrastructure should be examined from the point of view of hydrogen injection and transmission of hydrogen/gas mixtures. Whereas, in the perspective of 2030, it is envisaged that selected sections of the gas network will be adapted to the transmission/distribution of hydrogen doped into gas[101]. In this context, it will be important to regulate the technical conditions that should be met by the existing pipelines (including specialized tests) to confirm their readiness for transporting hydrogen doped into gas. The physico-chemical properties of hydrogen make[102] it more difficult to transport it through gas networks, especially in the

98 Directive (EU) 2019/944 of the European Parliament and of the Council of 5 June 2019 on common rules for the internal market in electricity and amending Directive 2012/27/EU (Official Journal of the EU L 158/125, 14.6.2019, Article 2, 59) *'energy storage' means the deferral, in the electricity system, of the final consumption of electricity from the moment of its production or its conversion into another form of energy, enabling it to be stored, to store such energy and then to convert such energy back into electricity or to use it in the form of another energy carrier*. This definition expressly covers hydrogen produced by electrolysis, its storage and its reconversion into electricity, but is also intended to cover sector coupling and to allow for other end uses of hydrogen produced by electrolysis

99 The Netherlands' hydrogen strategy,

100 a) A hydrogen content of up to 36% in a natural gas mixture does not change the quality of its energy parameters. b) The maximum amount of hydrogen that can be injected into high-methane natural gas so that the resulting mixture can be safely combusted in household and commercial gas appliances without the need to make any changes to their design is 23%. However, in order for the resulting mixture to be safely and efficiently combusted, the addition of hydrogen should not exceed 15%. c) The mixture of natural gas with 15% addition of hydrogen has no negative effect on medium pressure regulators. J. Jaworski, E. Kukulska-Zając, P. Kulaga, *Wybrane zagadnienia dotyczące wpływu dodatku wodoru do gazu ziemnego na elementy systemu gazowniczego [Selected issues concerning the influence of hydrogen addition to natural gas on gas system components], Nafta-Gaz* 2019, no. 10, pp. 625-632. DOI: 10.18668/NG.2019.10.04.

101 *Draft Polish Hydrogen Strategy until 2030 with an Outlook until 2040*, p. 35, https://bip.mos.gov.pl/strategie-plany-programy/polska-strategia-wodorowa-do-roku-2030-z-perspektywa-do-2040-r/

102 M. Maj, A. Szpor, *Kierunki rozwoju gospodarki wodorowej w Polsce [Directions of Hydrogen Economy Development in Poland]*, Polish Economic Institute, Working Paper" 2019, no. 7, ISBN 978-83-66306-61-5, Warsaw, December 2019, p. 10.

absence of detailed analyses of the long-term impact of hydrogen on network infrastructure components (this also applies to doped gas), so it seems extremely important to place great emphasis on carrying out research in this area[103].

Of course, the scope, type and capabilities of the terminal equipment that would operate on the doped gas are not without significance (it all depends on the specification of the equipment). Some devices will not require replacement or adaptive changes, others, unfortunately, will have to be replaced with new ones. This once again leads to costs, this time on the part of the end users.

It is also reasonable to consider the construction of dedicated gas pipelines for hydrogen transport. In this case, high costs of such investments must be taken into account, connected, above all, with the need to use appropriate materials which will make it possible to transport pure hydrogen, but also important here will be the whole security infrastructure which will monitor the condition of such a pipeline to ensure its safety. Moreover, as it has already been emphasized, research is necessary, the final effect of which will be the creation of such conditions for the new infrastructure which will allow its long-term and safe use.

Meeting a number of safety standards also seems critical, as Australia has pointed out. In July 2020, the Australian Federal Government, through the Hydrogen Technology Committee, adopted eight international standards for hydrogen to facilitate its safe use, transport and trade. The standards include, but are not limited to[104]:

- safety and efficiency of hydrogen generators, including systems for producing hydrogen via water electrolysis,
- design and safety features of hydrogen purification systems to meet quality standards,
- design, construction and testing of portable hydrogen storage tanks,
- design, manufacture and testing of tanks for hydrogen powered vehicles,
- safety and testing of high-pressure valves used at filling stations for hydrogen-powered vehicles.

The above standards can also be seen from the perspective of seeking to overcome technical barriers to hydrogen development.

Another important element classified as a barrier to the development of hydrogen is efficiency, that is, effectiveness along the entire hydrogen chain from production to use. From the point of view of the assumptions for the promotion of energy efficiency (one of the four pillars of the concept of the energy sector integration presented by the European Union[105]) and the promotion of solutions that serve this purpose, the losses of electricity produced from RES for hydrogen applications will be so high along the whole hydrogen chain that, depending on the selected way of calculating the level of energy efficiency, they may not bring the expected results of its improvement. The efficiency of the systems is therefore one of the main technological barriers in each part of the hydrogen value chain[106].

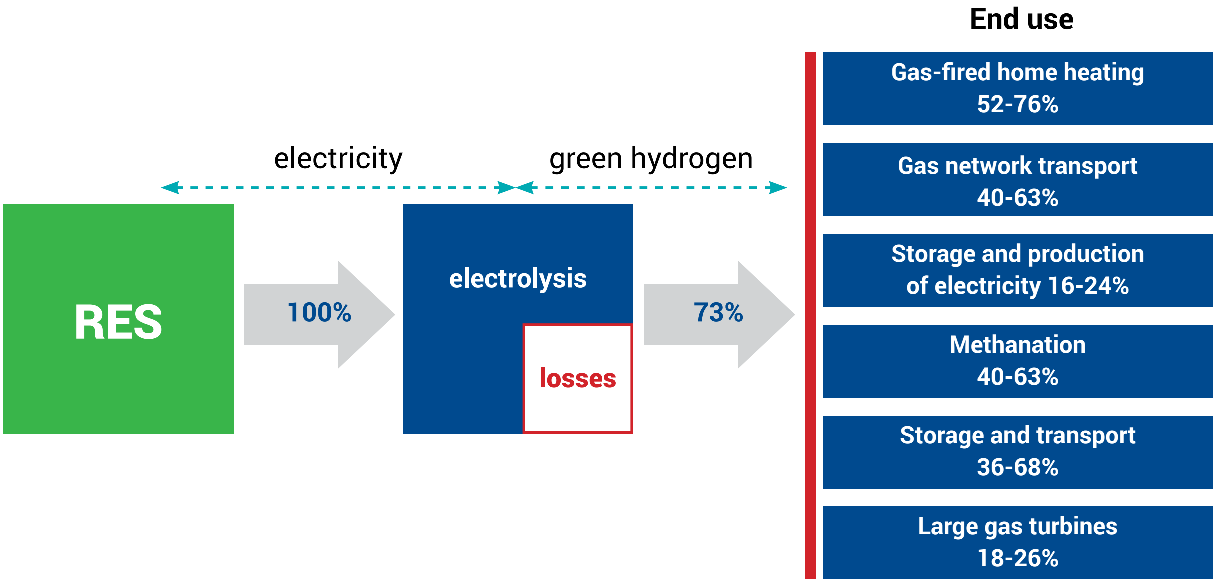
103 These issues are highlighted by ACER *(the European Union Agency for the Cooperation of Energy Regulators)*, setting out guidelines that should be taken into account when designing regulations for hydrogen networks. ACER, *When and How to Regulate Hydrogen Networks?* "European Green Deal" Regulatory White Paper series (paper #1) relevant to the European Commission's Hydrogen and Energy System Integration Strategies 9 February 2021, https://extranet.acer.europa.eu/Official_documents/Position_Papers/Position%20papers/ACER_CEER_WhitePaper_on_the_regulation_of_hydrogen_networks_2020-02-09_FINAL.pdf

104 *Hydrogen standards release summary*. Standards Australia, July 2020.

105 European Commission, *Impetus for a climate neutral economy: an EU strategy for energy system integration*, Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions, Brussels, 8.07.2020. COM(2020) 299 final.

106 A scheme is considered here in which having electricity to produce hydrogen is considered as an initial step. It does not consider losses in the process of electricity production, which in the case of production from wind are at zero level (for comparison, the efficiency of electricity production in coal power plants is at the level of 33-46%). It is also worth mentioning that losses in the transmission and distribution of electricity through power grids amount to 6.54% in 2020, according to PTPiREE's Report for 2020, http://raport.ptpiree.pl/raporty/2021/raport_ptpiree_2021.pdf

Figure 4.11. Selected efficiency levels in the hydrogen value chain



Source: own study based on: A. Maroufmashat, M. Fowler, *Transition of Future Energy System Infrastructure; through Power-to-Gas Pathways*, Energies, 26 July 2017.

Depending on the processing chain adopted, about 73% of the efficiency of the produced hydrogen can be obtained from electrical energy during the electrolysis process. If we allocate the hydrogen obtained to the methane production process, we obtain an efficiency of about 63%. At this stage of the process, heat is produced as a by-product, which unfortunately is not used in other processes. In the final stage, the re-generation of electricity is approximately 16-24% efficient in relation to the energy used at the input of the chain. Depending on the needs and the variety of subsequent processing steps of the produced hydrogen, the final efficiency levels vary from 16% to 83%. The more elements there are in the chain on the way to end use, the lower the efficiency is, as each successive conversion process generates additional process-specific losses[107].

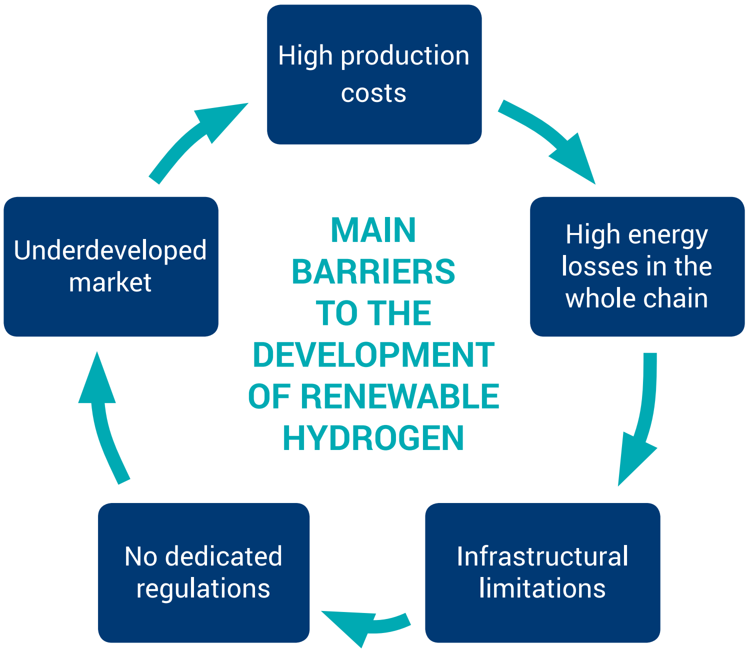
It is clear from the above that where there is a possibility to use electricity from RES directly for its final consumption, this will be the most effective and economically optimal. Hence the common belief that electricity whose supply exceeds current demand should be used to produce hydrogen (hence the term: surplus energy). However, as shown later in this report, this will not be sufficient if the expected development of the hydrogen economy takes place.

4.2.2 Possible ways to overcome barriers

The biggest impetus for green hydrogen market development is the existence of profitable business opportunities. Hence, high cost in every link of the hydrogen economy chain should be considered as the primary barrier to the development of renewable hydrogen.

107 The Oxford Institute for Energy Studies, *Power-to-Gas: Linking Electricity and Gas in a Decarbonising World?*, October 2018, https://www.oxfordenergy.org/wpcms/wp-content/uploads/2018/10/Power-to-Gas-Linking-Electricity-and-Gas-in-a-Decarbonising-World-Insight-39.pdf

Figure 4.12. Main barriers to renewable hydrogen development



Source: own study.

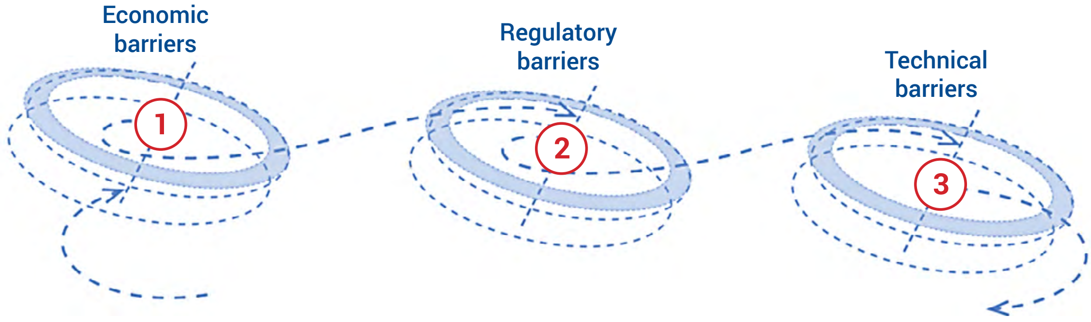
The cost issues that green hydrogen faces at the electrolysis-based production stage should be perceived as the most significant. Without stabilisation of these costs at a level that allows hydrogen technologies to compete with other technologies, the hydrogen economy will not be able to develop quickly and efficiently. To this end, to facilitate and accelerate the emergence of a competitive and efficient hydrogen market in Poland, it is necessary, first, to provide financial support to enable its development and, second, to create regulations that will contribute to the removal of the remaining barriers and encourage a gradual increase in the use of RES for electrolysis, making it possible to use hydrogen more widely as an energy source or as an alternative form of fuel. A secure and supportive legal (policy) framework will be needed to facilitate largely private investment along the hydrogen supply chain (equipment manufacturers, infrastructure providers, vehicle manufacturers, etc.).

However, for these investments to make sense, there must be targets and incentives to promote the use of green products, as their absence inhibits many possible further applications of green hydrogen. This in turn reduces the demand for green hydrogen. In the short term, additional measures will also be required to cover the initial cost gap for incumbent technologies to be replaced by new hydrogen-based technologies. Such incentives (e.g. tax credits for new technologies, subsidies to reduce CAPEX costs), with a defined phase-out schedule, combined with the identification of priority technologies will be an important element in driving the hydrogen market forward[108]. Another way to encourage the maximum use of renewable hydrogen production capacity could be to promote renewable hydrogen certification. Certification through the provision of traceability of energy consumption to support decarbonisation will emphasise the systemic added value of electrolysers.

108 T. Burandt, B. Xiong, K. Löffler and P.-Y. Oei, *Decarbonizing China's energy system - modeling the transformation of the electricity, transportation, heat, and industrial sectors*. Appl. Energy 255:113820, 2019.

Figure 4.13. Selected ways to reduce barriers to renewable hydrogen

SELECTED WAYS TO REDUCE BARRIERS TO RENEWABLE HYDROGEN



1 Economic

- a secure and supportive regulatory framework to facilitate investment
- additional funding to cover the initial cost gap for incumbent technologies
- incentives (e.g. tax credits for new technologies, grants, financial schemes),

2 Regulatory

- certification of hydrogen from renewable sources
- phase-out schedule for emitting sources
- prioritization of technologies
- clear targets and incentives to promote the use of green products
- promotion of low emission regions
- carbon price caps,

3 Technical

- state support for R&D programs
- regulatory sandboxes to allow effective testing of new technologies
- involvement in pilot and demonstration projects,

Source: own study.

Another significant barrier is the lack of a dedicated hydrogen infrastructure (e.g. for transport, storage and refuelling), the development of which should be supported at the same time as support for hydrogen production. Transporting hydrogen requires a change in its physical state: liquefaction, which is energy-intensive, while the alternative of converting hydrogen to other carriers, such as ammonia or methanol, is limited due to significant efficiency losses. Unlike renewable energy production, hydrogen has no existing distribution infrastructure or basic market that effectively links supply and demand to establish a competitive market price. Furthermore, the supply chain (including production) is also at an early stage of development compared to, for example, electric vehicles, which are already gaining popularity and market relevance[109]. Although the possibility of using hydrogen in the economy represents a great opportunity for deep decarbonisation, the above factors make its implementation very difficult.

Hydrogen demand and infrastructure spending in many sectors can be stimulated through technology-neutral end-user tools. These could be incentives including carbon price caps, pollution regulation (low emission regions, emission standards or targets), renewable energy content regulation or sector-specific carbon prices[110]. It seems that, following the example of the Electromobility Act, clear assumptions should be made regarding the number of hydrogen vehicle charging stations and the number of hydrogen vehicles per municipality/city/institution.

Nevertheless, an important element in overcoming the barriers is the need for support and ongoing investment in research, development and deployment of new solutions to further reduce the costs and increase the overall efficiency of production, transport and storage systems, which in turn will help

109 Although without support in the form of subsidies or relief, the process is also prone to slow development.

110 B. Nastasi *Hydrogen policy, market, and R&D projects*, Solar Hydrogen Production, Chapter 2, Cambridge, Academic Press, pp. 31-44.

to reduce the end-use costs of hydrogen, giving it a competitive edge in the market. Hence, pilot and demonstration projects are needed for full deployment, also using regulatory sandboxes, to best match future regulations with actual market conditions and needs.

05

WIND ENERGY – PRODUCTION OF GREEN HYDROGEN AND ITS IMPACT ON THE NATIONAL POWER SYSTEM

5.1 The role of wind energy in the Polish energy mix - a 2030-2040 perspective

With cautious optimism we may presume that the times of absolute rejection of the possibility and need for onshore wind energy development in Poland are gone. On the other hand, energy transformation and meeting the requirements of the decarbonisation process not only require the acceptance of wind energy development trends, but also the stimulation of its growth. The purpose of this paper is to analytically demonstrate the validity of such a position and to support forecasts formulated by[111], according to which the target capacity of onshore wind energy should be several times higher than the 9.5 GW indicated in PEP 2040 and should constitute the third pillar of RES power generation, together with offshore wind and photovoltaics.

For several years now, both in Europe and in Poland, the interest in offshore wind energy has been particularly strong. It is justified by much better wind conditions at sea than on land and gradually decreasing investment costs of offshore farms[112]. Looking at the perspectives of wind power generation development in Poland, one may certainly notice the media-publicized high interest of investors in the offshore segment, officially supported by various government institutions. Offshore wind energy, together with photovoltaic and nuclear energy, is perceived as a potential field of economic activity of the Polish industry and a flywheel for its development.

Figure 5.1a presents the annual variability of onshore wind power scaled down to 9 GW installed capacity, based on information from wind generation in[113] Poland for 2019. Figure 5.1b shows the annual variability of wind farm capacity at sea scaled up to 9 GW installed capacity, based on information on wind generation at ten points in the Polish economic zone in the Baltic Sea (own study), using 8-12 MW turbines.

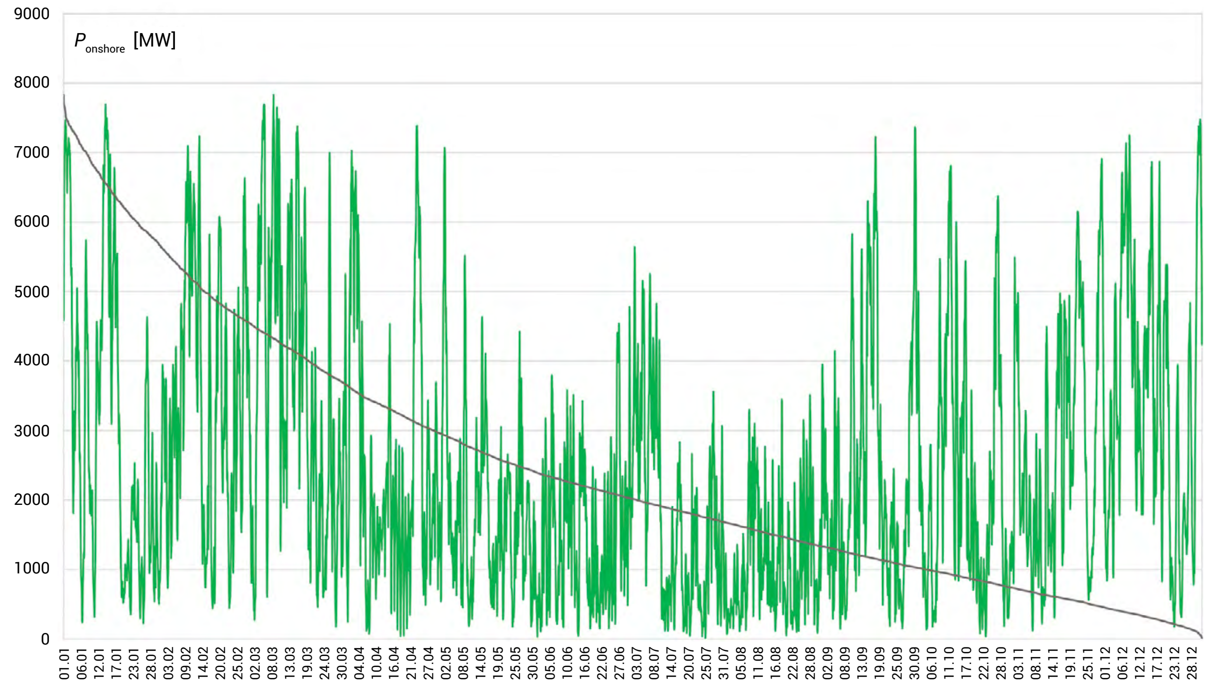
111 *How to close the carbon gap, 43% RES in 2030*, 2020 Report, Energy Forum (in cooperation with the Energy Institute), https://www.forum-energii.eu/pl/analizy/jak-wypelnic-luke-weglowa; T. Adamczewski, M. Jędra, *Zielone gazy...*; H. Engel, M. Purta, E. Speelman, G. Szarek, P. van der Pluijm, *Neutralna emisyjnie Polska 2050. Jak wyzwanie zmienić w szansę [Emission-neutral Poland 2050. How to turn a challenge into an opportunity]*. McKinsey & Company 2020, https://www.mckinsey.com/pl/our-insights/carbon-neutral-poland-2050#; Energy Data Platform in Poland, http://energy.instrat.pl/

112 J. Rączka, *Energetyka morska. Z wiatrem czy pod wiatr [Offshore power generation. With the wind or against the wind]*. Energy Forum, Warsaw 2018, https://www.forum-energii.eu/pl/analizy/offshore

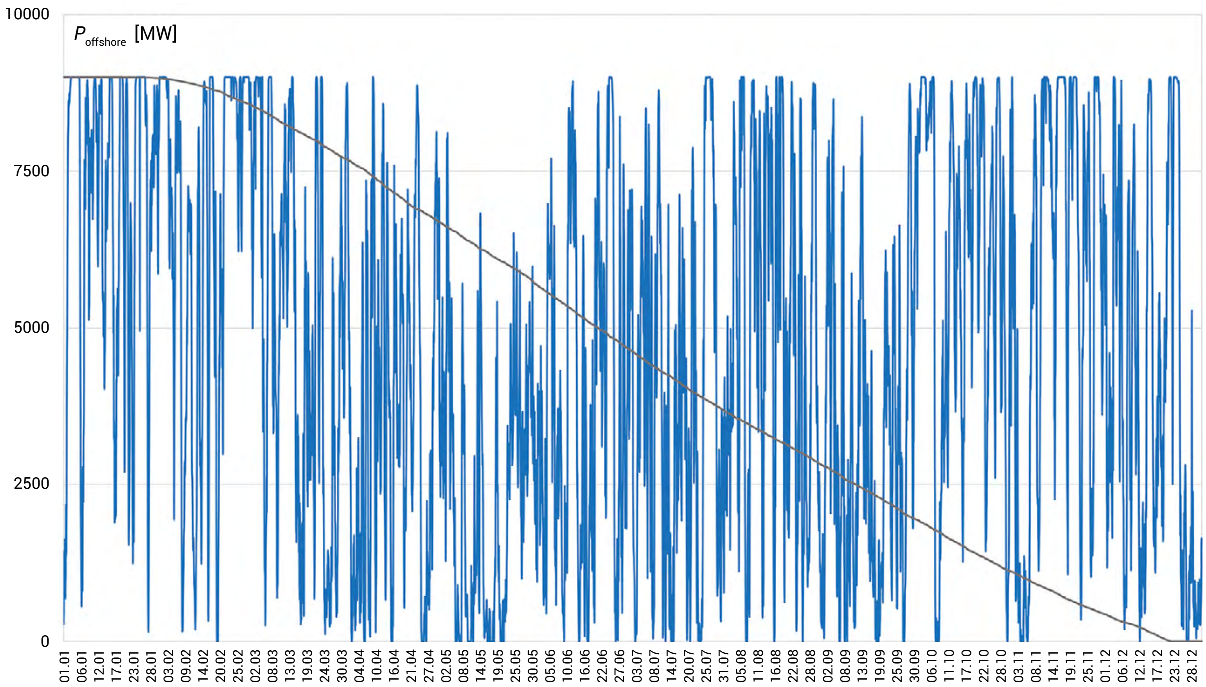
113 Polskie Sieci Elektroenergetyczne S.A. , “System Data” tab, https://www.pse.pl/dane-systemowe

Figure 5.1. Annual power output of wind farms: a) onshore, P_{nFW}=9 GW; b) offshore P_{nMFW}=9 GW; c) PV P_{nPV}=12 GW

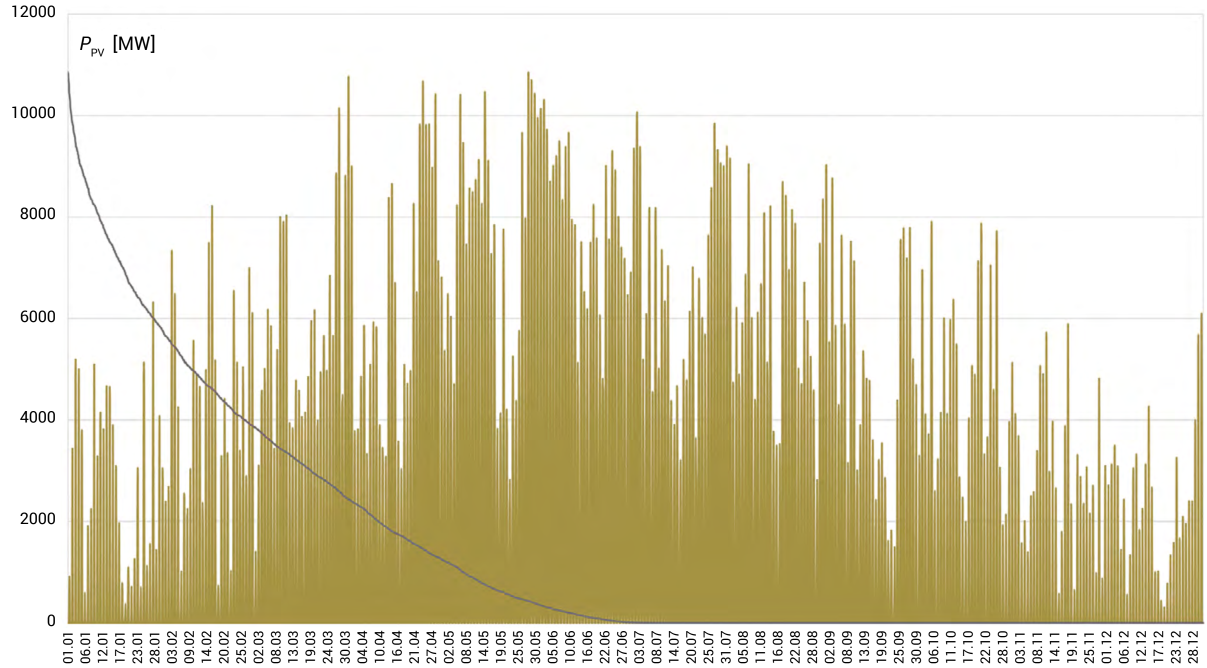
a)



b)



c)



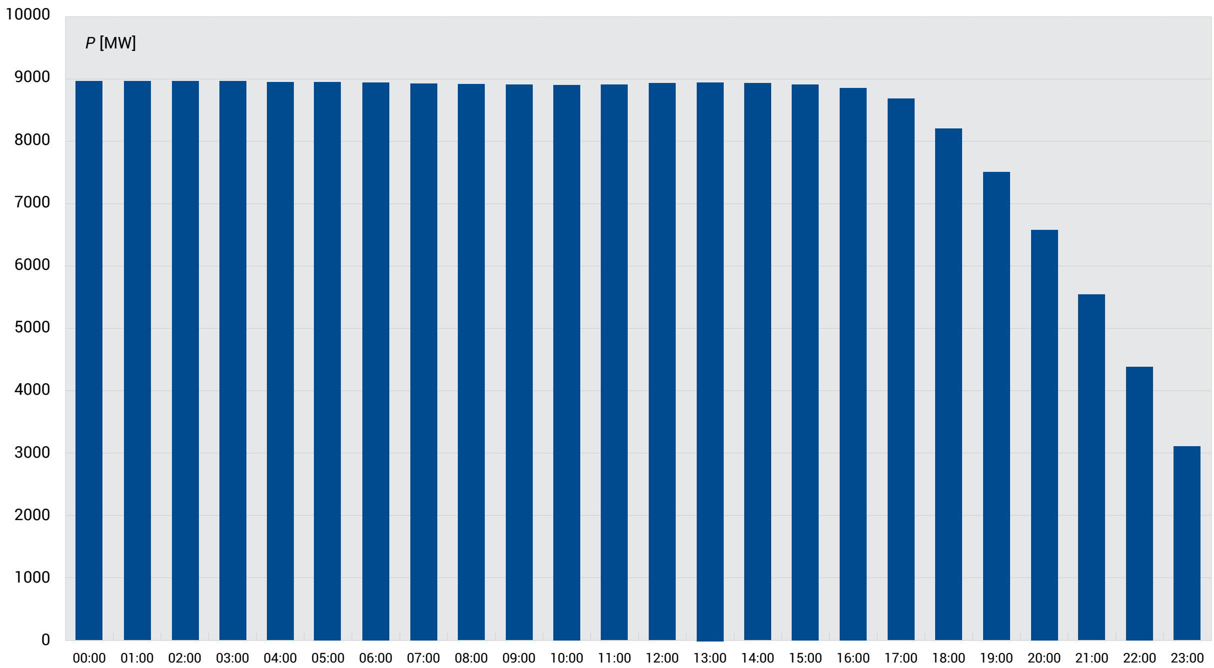
Source: own study.

Fig. 5.1b shows a more regular pattern and a much longer period for maximum output, which in the analyses is 2800 hours onshore and 4600 hours offshore (compared to less than 1100 hours per year for PV in Fig. 5.1c). The term ‘intermittent generation’ is often used for wind-based power. This is partly incorrect. In fact, in the Polish language “intermittent” of a time-distributed process means the invariability of its parameters (in this case the capacity to generate power). The process of electricity generation in wind turbine generators understood in this way is indeed not stable, as the generated power is subject to changes resulting from changes in wind speed, or more precisely, the properties of the air stream washing over the blades of the wind wheel. However, in scientific sense,[114] the term “intermittency’ denotes the ability to maintain a state of equilibrium after a momentary disturbance. Wind power sources have such an ability, hence a much more correct term for the generation associated with them is variable generation (VG). It should also be emphasized that the variability of wind generation resulting from the impact of the air stream on the turbine blades (gusts, turbulence, blasts) is intensively limited by the turbine control system, whose structure in the case of high power units is very complex and technologically advanced. As a result, the output of a wind farm consisting of multiple turbines is not subject to as much variability as might appear from subjective experience with locally varying wind conditions. Fig. 5.2 shows the generation of a hypothetical offshore wind farm for a winter day; Fig. 5.2a (extremely even course, maximum generation level) and a following day with variable but predictable generation based on meteorological data: Fig 5.2b.

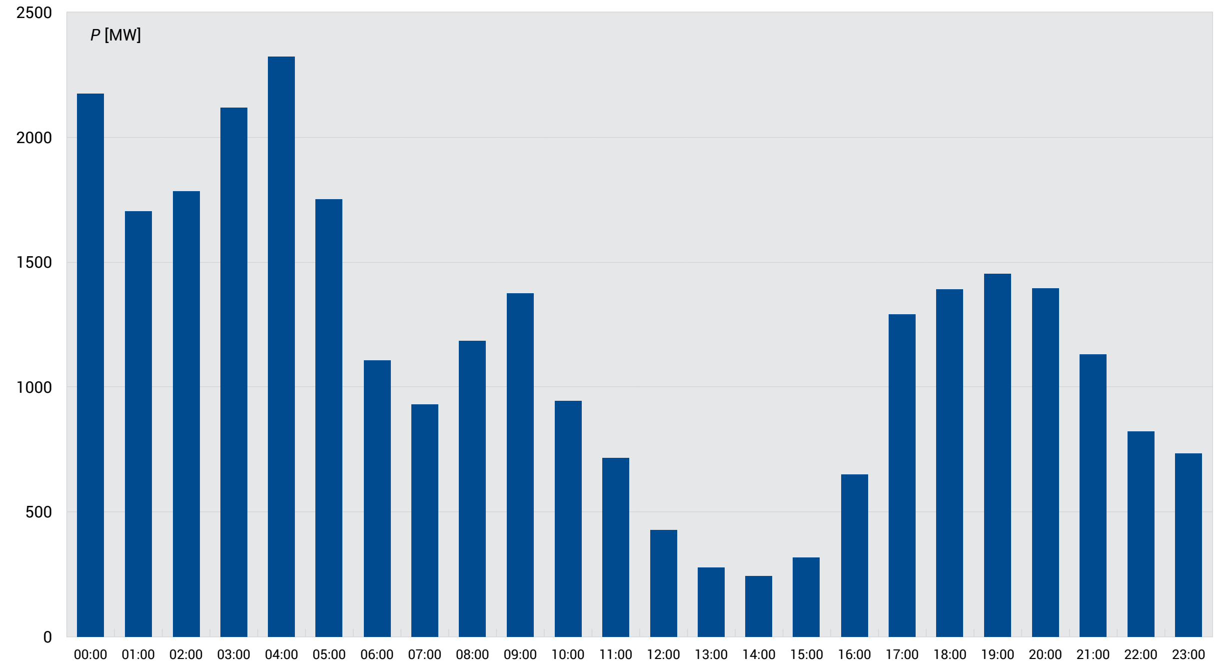
114 J. Machowski, Z. Lubośny, *Stabilność systemu elektroenergetycznego [Stability of the power system]*, WNT, Warsaw 2018.

Figure 5.2. Average hourly power generated in hypothetical offshore wind farms in Polish economic zone (OWF - 9000 MW) for two subsequent days in the winter period a) first day; b) next day

a)



b)



Source: own study.

There are many common opinions about wind energy; some of them are correct and some are not confirmed by research. One of these opinions is that there are distinct cycles in wind speed changes (during the day the wind weakens and at night it intensifies). This is indeed the case in Poland, but average daily power generation in wind turbines shows differences between daytime and night time at a level of no more than about 30-40%. One should also keep in mind that changes in wind power generation are even over long periods of time predictable owing to more and more perfect forecasting systems[115].

When considering the future of wind energy in Poland, one must realize that it will become a fundamental element of the mix of decarbonized energy and hydrogen-oriented green economy. This is due to the fact that there is no alternative to wind sources, which despite their variable generation guarantee high energy production (e.g. in comparison to photovoltaics), especially when considering the offshore segment. When looking for opportunities to balance Poland's energy needs in 2030-2040, RES sources supported by nuclear energy and energy storage capacities should be considered. Other solutions will inevitably lead to an inability to ensure continuity of power supply in the national power system. Being aware of the large discrepancy in forecasts concerning wind power in Poland, it should be remembered that apart from the barriers to its development known for years (balancing in the system and connection possibilities or, more broadly, infrastructural barriers), there is inevitably a third issue related to the sufficiency of such generation for the needs of the hydrogen economy. Production of green hydrogen will not find other sources of energy without disturbing the balancing possibilities of the power system, which may turn out to be fragile anyway[116]. That is, on the one hand, the volatility of wind energy and, in a perspective, also the scale of its development, means problems for the power system, but, on the other hand, without it no significant amounts of energy can be obtained for the development of the hydrogen economy.

Table 5.1 and Table 5.2 summarise the forecast wind and PV capacity in 2030 and 2040, together with the expected electricity demand.

115 *Renewable Energy Weather Data*, https://insights.spire.com/offshore-renewables

116 *Development Plan for Meeting Current and Future Electricity Demand in the Years 2021-2030*, Polskie Sieci Elektroenergetyczne, Konstancin-Jeziorna 2020, https://www.pse.pl/documents/20182/21595261/Dokument_glowny_PRSP_2021-2030_20200528.pdf.

Table 5.1. Forecasts of installed RES capacity in the NPS and expected demand for electricity in 2030, data according to various sources[117, 118, 119, 120, 121]

2030	Onshore windmills [GW]	Offshore windmills [GW]	Photovoltaics [GW]	Demand [GWh]
PEP 2040	9,5	6	7	201
McKinsey	18	8	no data (12)	280
Instart	18	6	no data (12)	220
Energy Forum	18	8	17	no data (220)
PSE S.A.	6,5	11	2,9	185
PK analyses (*)	12	8	12	190

(*) Author's own analyses.
( ) Author's estimates.

Table 5.2. Forecasts of installed RES capacity in the NPS and expected demand for electricity in 2040, data according to various sources[122, 123, 124, 125, 126]

2040	Onshore windmills [GW]	Offshore windmills [GW]	Photovoltaics [GW]	Demand [GWh]
PEP 2040	9,5	11	16	225
McKinsey	28	29	no data (25)	340
Instart	36	18	no data (25)	320
Energy Forum	no data	no data	no data	no data
PSE S.A.	no data	no data	no data	205
PK analyses (*)	16	12	25	207

(*) Author's own analyses.
( ) Author's estimates.

117 Announcement of the Minister of Climate and Environment on the national energy policy until 2040. (M.P. 10.03.2021, item 264); T. Adamczewski, M. Jędra, *Zielone gazy...*; H. Engel, M. Purta, E. Speelman, G. Szarek, P. van der Pluijm, *Emission-neutral Poland 2050...; Energy Data Platform in Poland*, http://energy.instrat.pl/; *Development Plan for Meeting Current and Future Electricity Demand for 2021-2030*. Polskie Sieci Elektroenergetyczne, Konstancin-Jeziorna 2020, https://www.pse.pl/documents/20182/21595261/Dokument_glowny_PRSP_2021-2030_20200528.pdf.

118 Adamczewski T., Jędra M., *Zielone gazy. Biometan i wodór w Polsce [Green Gases. Biomethane and hydrogen in Poland]*, Energy Forum. *Analizy i dialog*, https://www.forum-energii.eu/pl/analizy/zielone-gazy.

119 Engel H., Purta M., Speelman E., Szarek G., van der Pluijm P., *Emission neutral Poland 2050. How to turn a challenge into an opportunity*, McKinsey & Company 2020, https://www.mckinsey.com/pl/our-insights/carbon-neutral-poland-2050#.

120 *Energy Data Platform in Poland*, http://energy.instrat.pl/

121 *Development Plan for Meeting Current and Future Electricity Demand in the Years 2021-2030*. Polskie Sieci Elektroenergetyczne, Konstancin - Jeziorna 2020, https://www.pse.pl/documents/20182/21595261/Dokument_glowny_PRSP_2021-2030_20200528.pdf.

122 Announcement of the Minister of Climate and Environment on the national energy policy until 2040. (M.P. 10.03.2021, item 264); T. Adamczewski, M. Jędra, *Green Gases...*; H. Engel, M. Purta, E. Speelman, G. Szarek, P. van der Pluijm, *Emission-neutral Poland 2050...; Energy Data Platform in Poland*, http://energy.instrat.pl/; *Development Plan for Meeting Current and Future Electricity Demand for 2021-2030*. Polskie Sieci Elektroenergetyczne, Konstancin-Jeziorna 2020, https://www.pse.pl/documents/20182/21595261/Dokument_glowny_PRSP_2021-2030_20200528.pdf.

123 Adamczewski T., Jędra M., *Green Gases. Biomethane and hydrogen in Poland*, Energy Forum. Analizy i dialog, https://www.forum-energii.eu/pl/analizy/zielone-gazy.

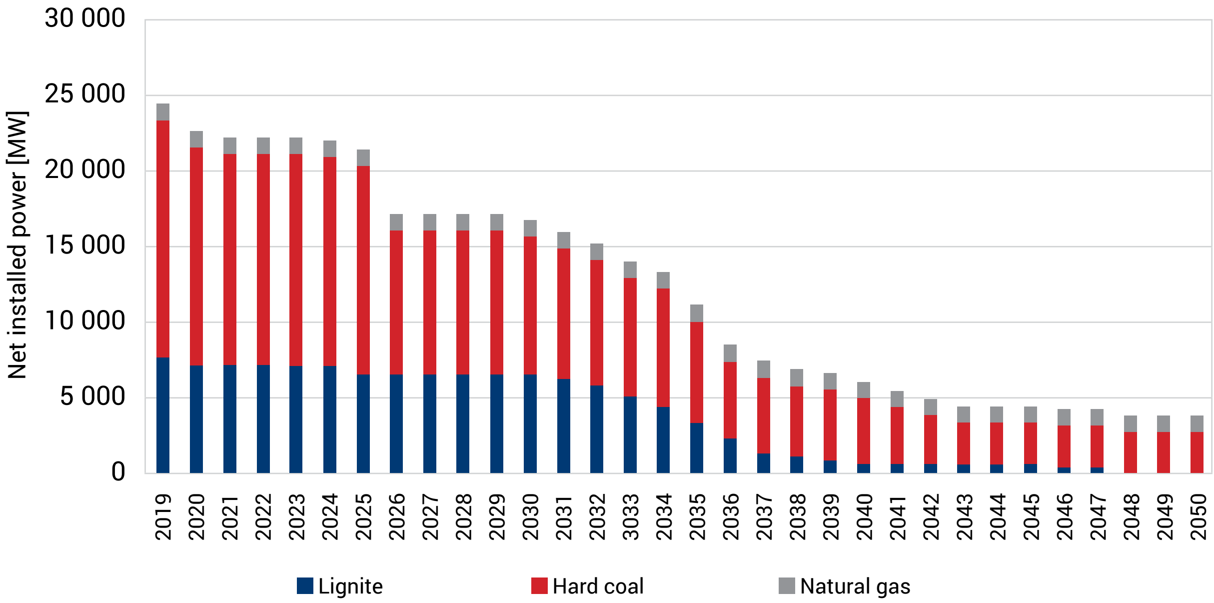
124 Engel H., Purta M., Speelman E., Szarek G., van der Pluijm P., *Emission neutral Poland 2050. How to turn a challenge into an opportunity*, McKinsey & Company 2020, https://www.mckinsey.com/pl/our-insights/carbon-neutral-poland-2050#.

125 *Energy Data Platform in Poland*, http://energy.instrat.pl/

126 *Development Plan for Meeting Current and Future Electricity Demand in the Years 2021-2030*. Polskie Sieci Elektroenergetyczne, Konstancin - Jeziorna 2020, https://www.pse.pl/documents/20182/21595261/Dokument_glowny_PRSP_2021-2030_20200528.pdf.

Forecasts will not be credible unless they are verified to answer the question of whether the projected total capacity installed in individual technologies will be able to meet electricity demand, both globally (on an annual basis) and in each hour of the year, or even more precisely, in each quarter of an hour, as this is the resolution with which balance analyses are made in practice. In this context, plans related to decommissioning of thermal power units as a natural consequence of the decarbonization process and suspension of investments in this sector (except for natural gas-fired power plants, referred to as "transitional fuel") are of particular importance. Forecasts in this respect presented by PSE S.A.[126] are shown in Fig. 5.3 and Fig. 5.4.

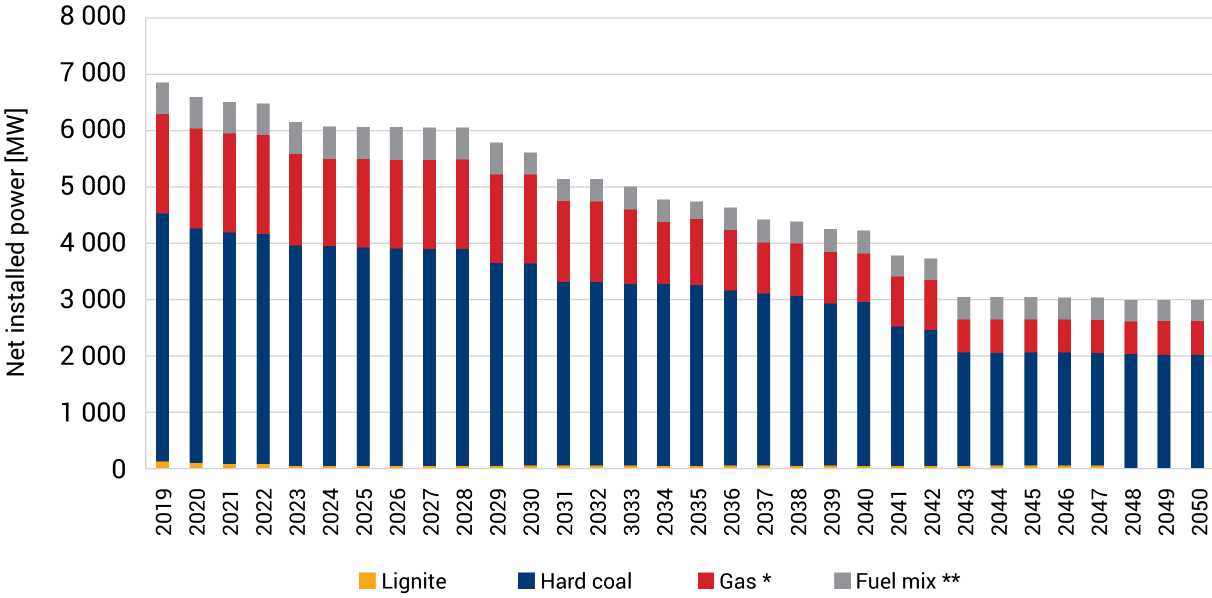
Figure 5.3. Installed capacity of thermal CUs in the absence of a capacity mechanism after 2025 (CDU - centrally dispatched generation unit)



Source: [127]

127 *Development Plan for Meeting Current and Future Electricity Demand in the Years 2021-2030*. Polskie Sieci Elektroenergetyczne, Konstancin - Jeziorna 2020, https://www.pse.pl/documents/20182/21595261/Dokument_glowny_PRSP_2021-2030_20200528.pdf.

Figure 5.4. Installed capacity in thermal nCDUs (gas units without hydrogen)



Source: [128]

Although work on nuclear power in Poland is still preliminary, its presence in the energy mix in 2040 should be considered highly probable with an installed capacity of 4000-5000 MW. Bearing in mind the objective of this study which is to determine the role of wind generation in the process of building a hydrogen economy based on green hydrogen, a simplified balancing analysis of generation sources for 2030 and 2040 was carried out using data from Tab. 5.1 and Tab. 5.2 (PEP2040 data - A, author's own forecast - B, forecast[129] - C) and data from PSE S.A. regarding CDGU and nCDGU[130] retirements. The results are presented in Tab. 5.3 and Tab. 5.4.

Table 5.3. Lists of installed capacities in the Polish Power System - forecast for 2030 (with respect to RES variants A, B, C) along with the expected energy production

Generation type	Installed capacity [GW]	Rated power usage time [h]	Electricity per year [TWh/a]
Thermal CDUs	16.5	5000	82.5
Thermal nCDUs	5.5	5000	27.5
Nuclear power	0	8000	0
A. onshore WF	9.5	2800	26.6
B. onshore WF	12	2800	33.6
C. onshore WF	18	2800	50.4
A. offshore WF	6	4800	28.8
B. offshore WF	8	4800	38.4
C. offshore WF	10	4800	48

128 *Development Plan for Meeting Current and Future Electricity Demand in the Years 2021-2030*. Polskie Sieci Elektroenegetyczne, Konstancin - Jeziorna 2020, https://www.pse.pl/documents/20182/21595261/Dokument_glowny_PRSP_2021-2030_20200528.pdf.

129 H. Engel, M. Purta, E. Speelman, G. Szarek, P. van der Pluijm, *Emission-neutral Poland 2050...*

130 *Development plan for meeting current and future electricity demand for 2021-2030...*

Generation type	Installed capacity [GW]	Rated power usage time [h]	Electricity per year [TWh/a]
PV	7	1100	7.7
PV	12	1100	13.2
PV	17	1100	18.7

Source: author's own study based on forecasts[131, 132,133].

Total electricity: variant A - 173 TWh, variant B - 195 TWh, variant C - 227 TWh. Balancing the electricity demand (190 TWh) requires, for Option A, electricity generation of about 20 TWh in gas-fired peaking units.

Table 5.4. List of installed capacities in the Polish Power System - forecast for 2040 (with respect to RES Options A, B, C) along with the expected energy production

Generation type	Installed capacity [GW]	Rated power usage time [h]	Energy during the year [TWh/a]
Thermal CDUs	6	5000	30
Thermal nCDUs	4	5000	20
Nuclear power	4	8000	32
A. onshore WF	9.5	2800	26.6
B. onshore WF	16	2800	44.8
C. onshore WF	28	2800	78.4
A. offshore WF	11	4800	52.8
B. offshore WF	20	4800	96
C. offshore WF	29	4800	139.2
A. PV	16	1100	17.6
B. PV	20	1100	22
C. PV	25	1100	27.5

Source: author's own research based on forecasts[131,132,133].

Total energy: Option A - 179 TWh, Option B - 244 TWh, Option C - 327 TWh (the balancing calculations do not take into account new natural gas units, whose construction is not certain due to climate policy, although it seems necessary). The analyses presented show that balancing electricity generation (in the energy sense) requires installed capacity of at least 12 GW onshore wind, 8 GW offshore wind, 12 GW PV, and for 2040 - 16 GW onshore wind, 20 GW offshore wind, 20 GW PV (Option B). Option A corresponding to the projections[131] does not balance demand already in 2030 and the deficit to be covered by new gas, biogas and biomass units, hydroelectric plants, imports, DSR mechanisms (in134 rightly

131 Announcement by the Minister of Climate and Environment on the National Energy Policy until 2040. Monitor Polski 10.03.2021, item 264.

132 Engel H., Purta M., Speelman E., Szarek G., van der Pluijm P., *Emission neutral Poland 2050. How to turn a challenge into an opportunity*, McKinsey & Company 2020, https://www.mckinsey.com/pl/our-insights/carbon-neutral-poland-2050#.

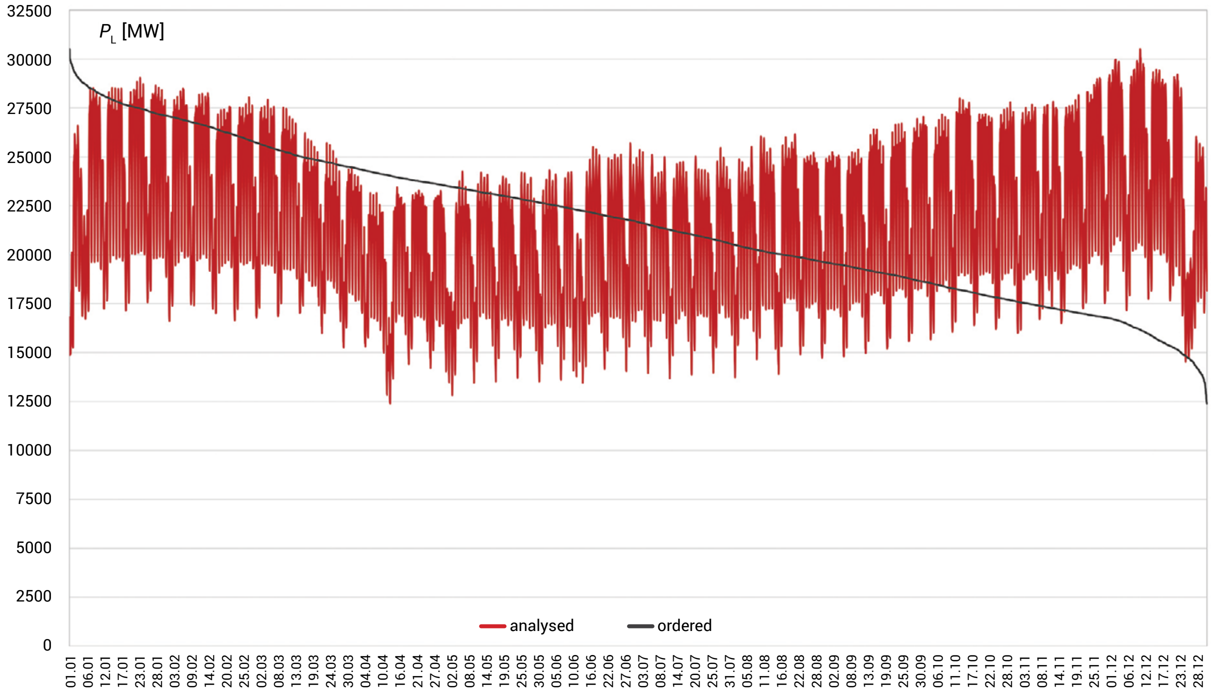
133 *Development Plan for Meeting Current and Future Electricity Demand in the Years 2021-2030*, Polskie Sieci Elektroenergetyczne, Konstancin - Jeziorna 2020, https://www.pse.pl/documents/20182/21595261/Dokument_glowny_PRSP_2021-2030_20200528.pdf.

134 *How to close the carbon gap, 43% RES in 2030.*, 2020 Report ...

called the carbon gap) may reach as much as 60-70 TWh in 2040. Obtaining such additional balancing possibilities is unrealistic. Option B gives a much better chance of balancing demand, but only Option C offers the possibility of creating significant energy surpluses which can be converted into green hydrogen and supply a developed hydrogen economy. Similar conclusions were reached in [135] and [136].

The nature of variable generation (VR) makes it highly unreliable to assess the ability to meet demand based on energy annual balances. As already mentioned, it is necessary to carry out verification for power with a resolution of not less than one hour, i.e. for 8760 cases. Such an analysis was carried out by assuming that the annual electricity demand pattern for 2030 is as given in Fig. 5.5. For such course, annual electricity demand is 190 TWh and peak capacity 30.5 GW.

Figure 5.5. The course of electricity demand variability in the NPS in 2030



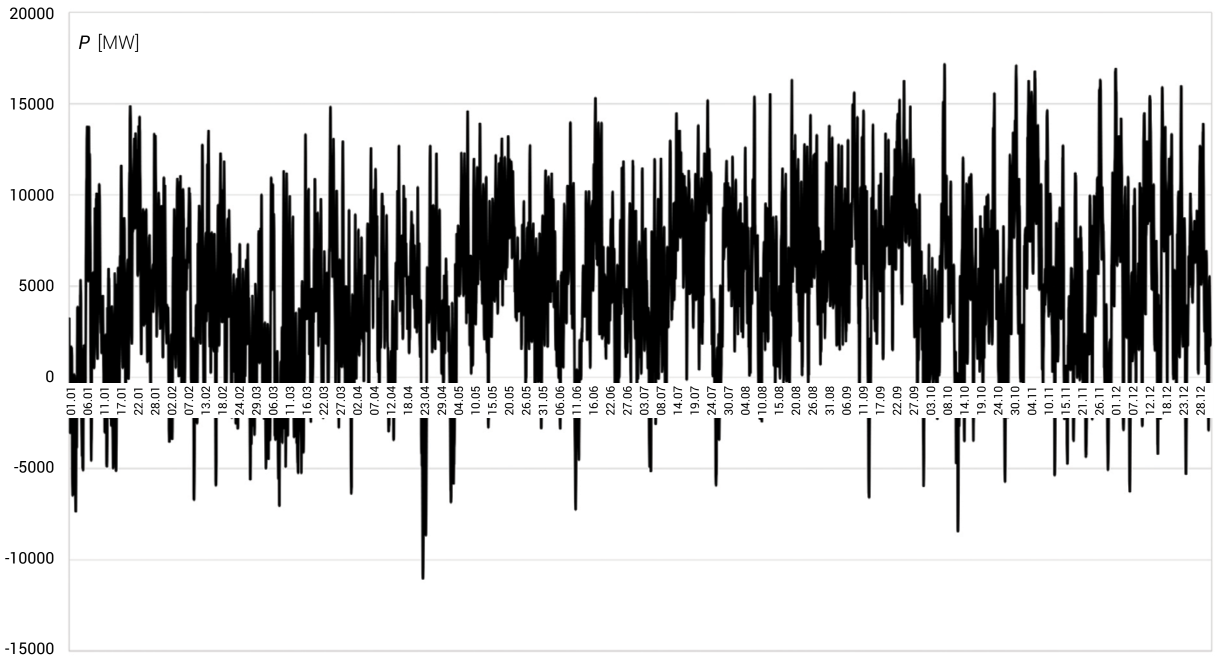
Source: own research according to Polskie Sieci Elektroenergetyczne S.A., "System Data" tab, https://www.pse.pl/dane-systemowe.

For the presented form of annual demand changes the generation structure was assumed according to Table 5.4, Option B (Onshore WF - 12 GW, OWF - 8 GW, PV - 12 GW, demand 190 TWh). For the CDU and nCDU thermal units (together 22 GW), 9 GW were assumed to operate in the base load (forced generation) and 13 GW remained for balancing purposes. With the above generation structure, it will not be difficult to achieve balancing in terms of power output for every hour of the year. Fig. 5.6 shows the output to be balanced and Fig. 5.7 its ordered graph. Short-term (less than 500 hours per year) demand for more than 13 GW can be covered by various interventions and imports, while the excess of RES generation is of symbolic importance.

135 T. Adamczewski, M. Jedra, *Zielone gazy ...*

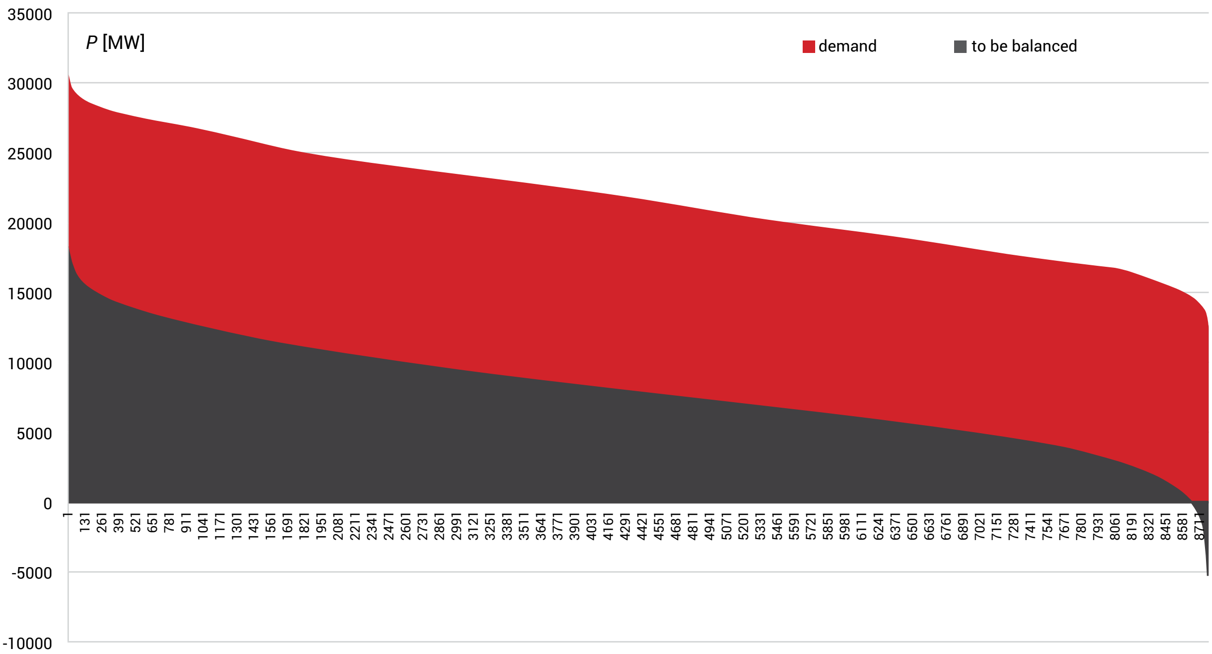
136 H. Engel, M. Purta, E. Speelman, G. Szarek, P. van der Pluijm, *Emission-neutral Poland 2050...*

Figure 5.6. The course of variability of balancing power in the national power system in 2030 (generation structure indicated above, according to Option B), negative values indicate power surplus



Source: own study.

Figure 5.7. Ordered annual graphs of: load, baseload generation, PV generation, onshore and offshore wind generation in 2030. Assumption for generation mix as for Fig. 5.6



Source: own study.

On the other hand, despite the assumption of a significantly higher installed capacity in RES than in PEP2040, the surplus of green generation is 'only' 3 TWh. In terms of value, this is approximately 1 billion PLN worth of energy, but it will be difficult to obtain due to the fact that the surplus periodically appears in the form of characteristic 'peaks' with large amplitudes (Fig. 5.5 and Fig. 5.6).

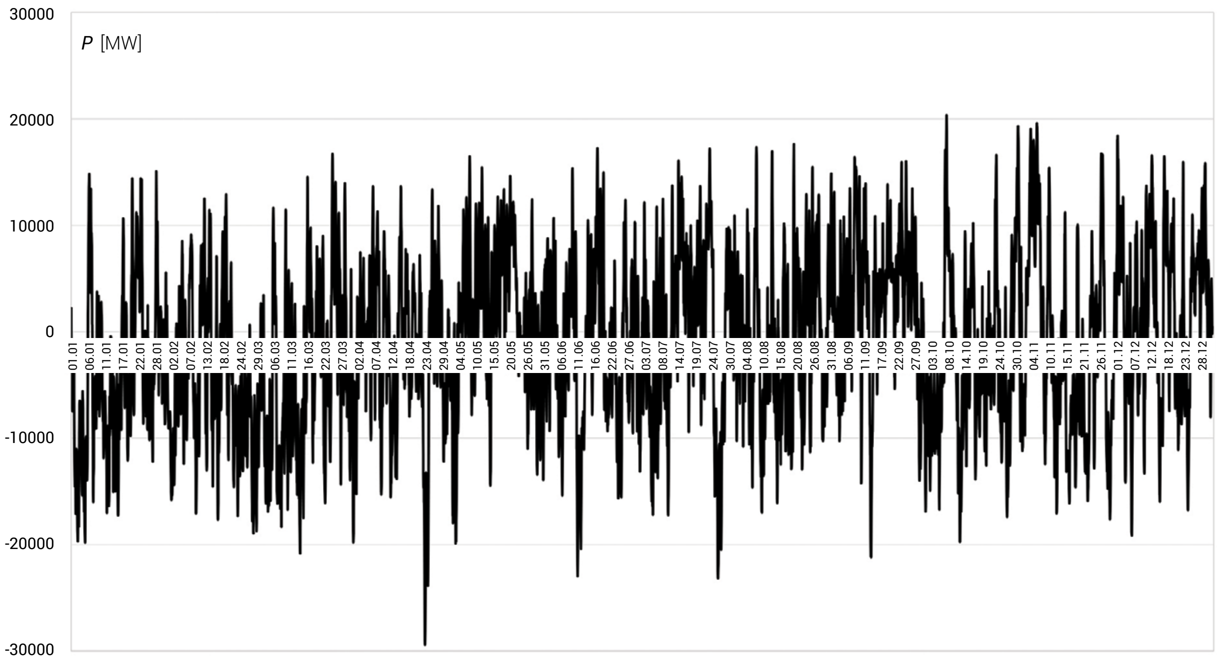
Analysis of the year 2030 for the forecast data of McKinsey[137] and the Energy Forum[138] (RES generation according to Option C, very high increase in demand) indicates a worse balance situation, because the "missing" capacity of over 13 GW is present for more than 2000 hours a year. The surplus of RES generation increases compared to Option B only to 4 TWh. Thus, the predictions determining the possibilities of hydrogen generation from surplus contained in[138] estimating it at 1.5-2 TWh (energy contained in gas) are convergent with the results obtained in the presented analysis.

Much higher capacity of RES generation and much higher balancing requirements are provided by the analysis for the year 2040. Demand, with the annual developments in accordance with the rescaled Fig. 5.4, was assumed at the level of 215 TWh (peak capacity: 34.5 GW). For such a form of annual demand variations, the generation structure was assumed according to Fig. 5.6, Option B (onshore WF - 16 GW, OWF - 20 GW, PV - 20 GW). For the CDU and nCDU thermal units (together 10 GW), 5 GW were assumed to operate in the base load (forced generation) and 5 GW remained for balancing purposes. Nuclear units with a total capacity of 4 GW were also assumed to operate all year round. With such a generation mix, it is a major challenge to balance power output for every hour of the year. Fig. 5.8. shows the output to be balanced and Fig. 5.7 shows its ordered graph. The balancing power above 7 GW occurs for more than 2,000 hours a year (total balancing power is 24 TWh). At the same time the RES-E surplus (86% from wind) is as high as 34 TWh and the maximum RES-E capacity is 29 GW. The annual pattern of this surplus is shown in Fig. 5.9. Assuming a surplus of 10 GW (yellow), as much as 30 TWh of energy would be available to power electrolysers and produce green hydrogen. Thus the energy needed to balance the system is roughly equivalent to the 'excess' energy from RES.

137 H. Engel, M. Purta, E. Speelman, G. Szarek, P. van der Pluijm, *Emission-neutral Poland 2050...*

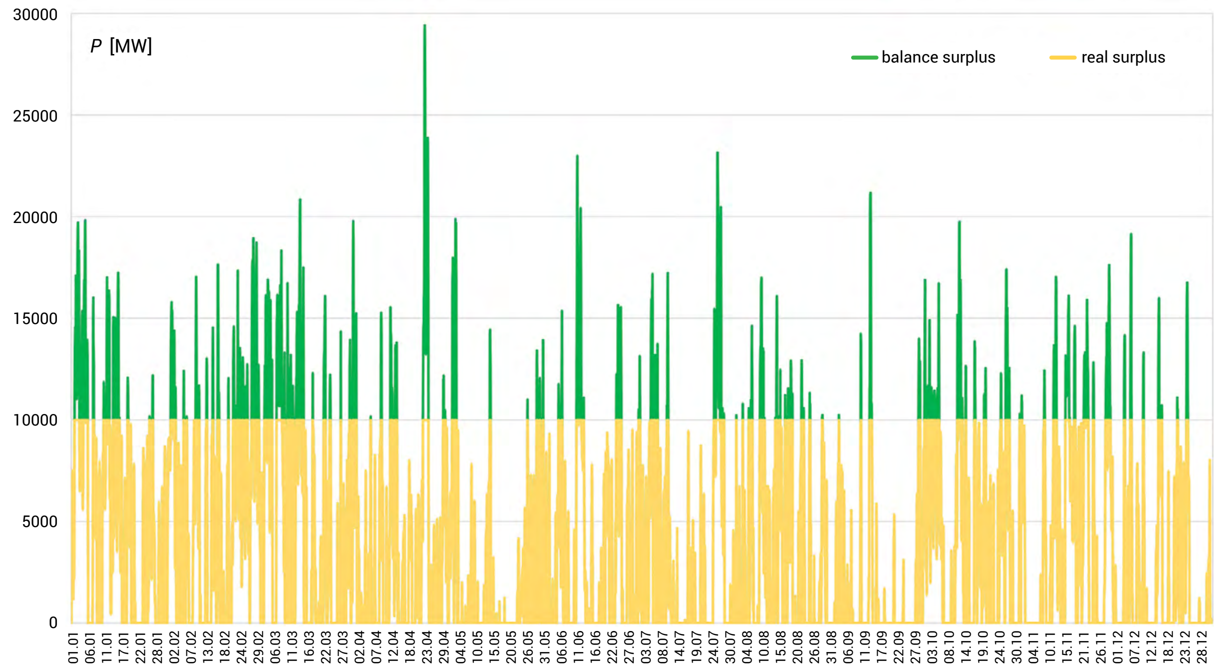
138 T. Adamczewski, M. Jedra, *Zielone gazy ...*

Figure 5.8. The course of variability of balancing power in the National Power System in 2040 (generation structure indicated above, according to Option B), negative values indicate power surplus



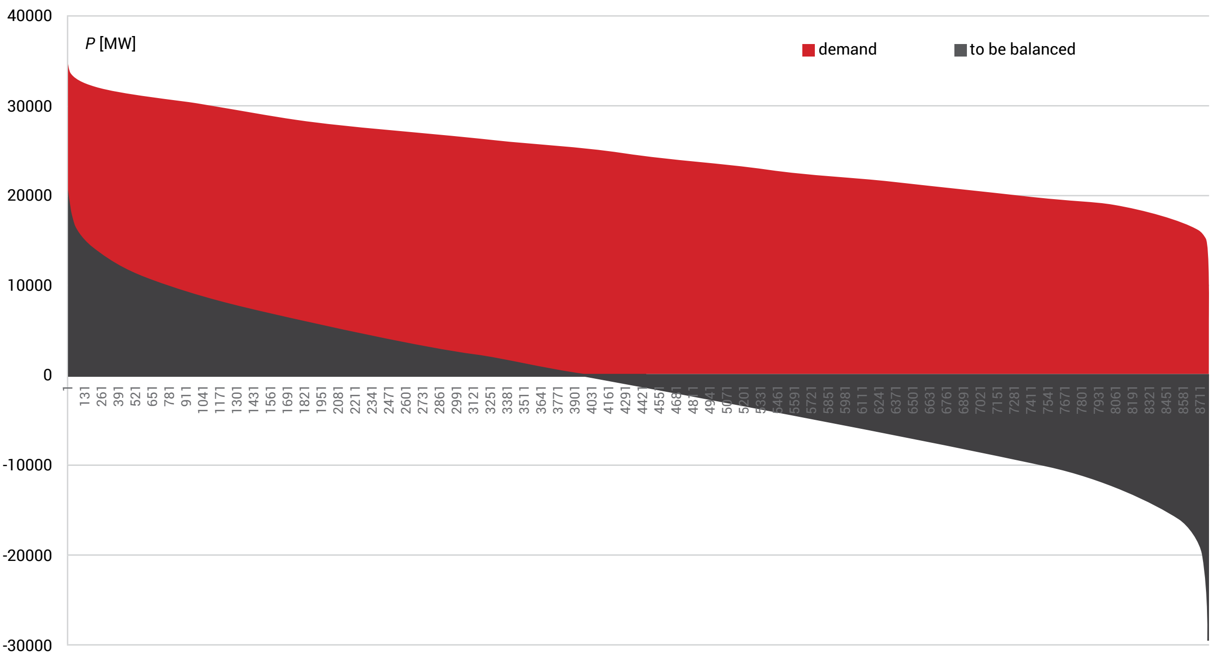
Source: own study.

Figure 5.9. Course of RES power surplus in the National Power System in 2040 (generation structure indicated above, according to Option B), yellow colour indicates values to be used, assuming the capacity of facilities to absorb the surplus amounts to 10 GW



Source: own study.

Figure 5.10. Ordered annual graphs of load, baseload generation, PV generation, onshore and offshore wind generation in 2040. Generation structure assumption as for Fig. 5.8



Source: own study.

The analysis presented here, particularly for the year 2040, shows a picture of the Polish power system in which only with the installation of really large wind capacity (16 GW onshore, 20 GW offshore) will there be a chance of balancing demand with a small contribution of the remaining coal-fired generation (10 GW) and new gas-fired peaking units. The prerequisite for meeting this challenge is the possibility to manage the RES surplus, which will appear in significant amounts (about 20% of the total energy produced).

5.2 Energy storage - a prerequisite for electricity security in systems based on renewable sources

Bearing in mind the inevitable need to increase the capacity installed in RES in 2030-2040, analyses should be carried out to study the actual needs for storage systems for the electricity produced by these sources. With the ability to operate in charging and discharging mode at different times, these systems can lead to conditions for balancing the operation of SEE. This is a well-known fact, publicized in the media and socially accepted. The key task of the analyses is to determine the power and capacity of energy storage facilities in such a way that all the energy coming from RES is used. It can be concluded *a priori* that backyard battery storage facilities are unable to meet this challenge.

At present, electricity storage projects in Poland are at different stages of advancement. In 2020, two battery storage projects were completed, located in Puck and Bystra. The total power and capacity of these installations is 6.75 MW and 28.5 MWh, respectively. Additionally, about 7 battery storage projects are currently being planned[139]. Without underestimating their significance for the NPS, it should be stated, however, that this significance is rather symbolic and the projects under consideration should be regarded as technology demonstrators, which is, of course, also important in terms of the prospects of development of the hydrogen economy and its wide use. However, it is difficult to give these projects a key importance from the point of view of the global needs of the electricity system.

Of practical importance at present are pumped storage power plants (PSPPs), the total capacity of which (in pumped storage mode) exceeds 1,600 MW in Poland and the capacity of about 16 GWh. The share of PSPPs in shaping the daily demand is noticeable and significant[140]. Unfortunately, the prospects for the completion of the construction of the 750 MW Młoty PSPP, which started more than 40 years ago, are rather dim.

Energy storages can have many different functions in the power system, which should be determined at the planning stage for the construction of such an installation. First of all, the main function and purpose of connecting such a device to the power grid should be determined. These functions are applicable both within the generation and transmission sector and include: commercial operation related to daily electricity trading (revenues from the difference in purchase and sale prices) and impact on the system as part of services or system obligations (the list of these is broad).

Identification of revenues from commercial activities is straightforward - the higher the daily price variation in the balancing market, the higher the revenue. However, the calculation of revenues from system services is currently difficult, as according to the directive[141] they must become a separate segment of the balancing market which will make their valuation. However, it can be said that the value of these services in financial terms is currently far less than the core commercial activities of energy storage and economic arbitrage. The said directive also prohibits (with some exceptions) grid operators from owning energy storage facilities.

To help understand the variation in the characteristics of electricity storage technologies, Fig. 5.11 presents a summary of them according to[142].

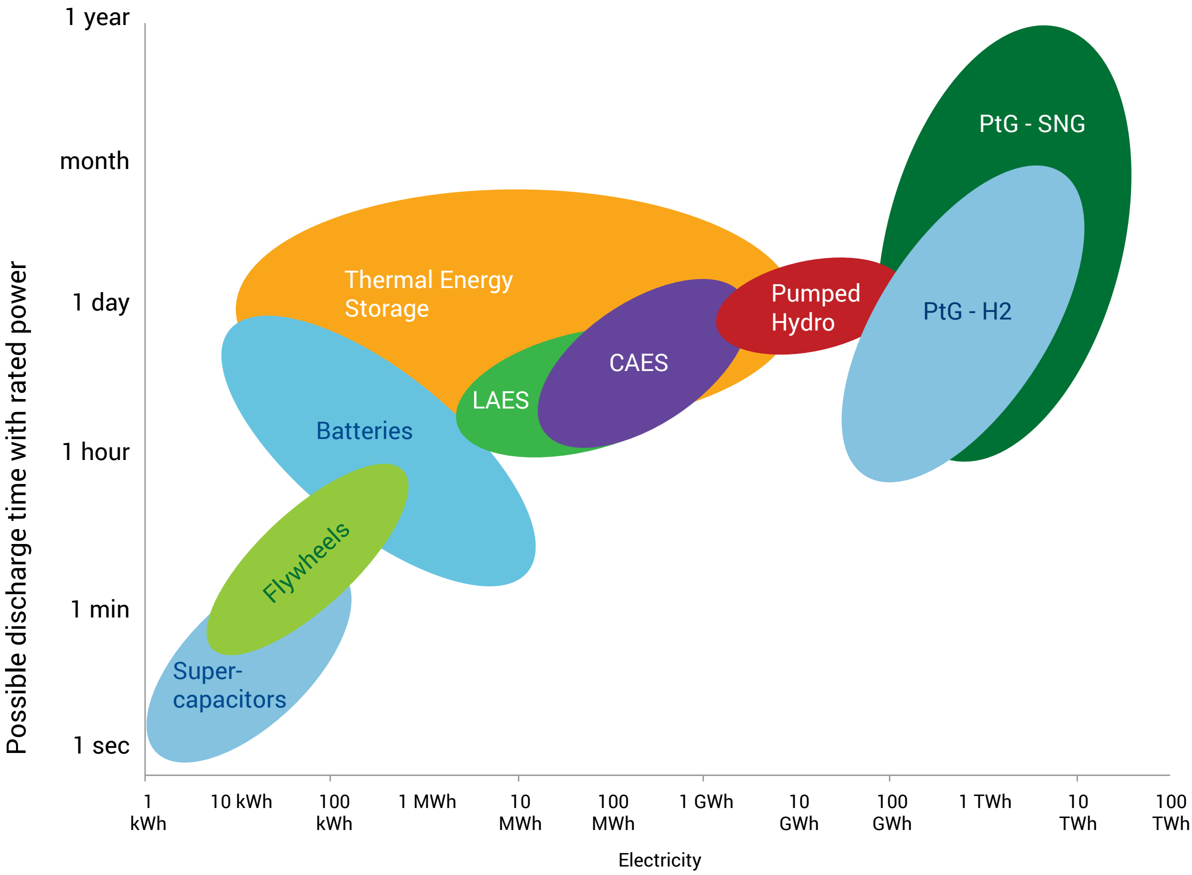
139 R. Raczkowski, *Zwiększenie udziału generacji wiatrowej w systemie elektroenergetycznym poprzez optymalizację systemu magazynowania energii [Increasing the share of wind generation in the power system through optimization of the energy storage system]*, PhD dissertation, Warsaw University of Technology, Warsaw, 2021.

140 Polskie Sieci Elektroenergetyczne S.A., "System Data" tab, https://www.pse.pl/dane-systemowe

141 Directive (EU) 2019/944 of the European Parliament and of the Council of 5 June 2019 on common rules for the internal market in electricity and amending Directive 2012/27/EU (Official Journal of the EU L 158/125, 14.6.2019.

142 J. Paska, *Electricity reservoirs in the power system - applications and solutions*, "Electrotechnical Review" 2012, 9a(88).

Figure 5.11. Energy storage technologies in combination with storage capacities and discharge times



Source: J. Paska, *Electric energy storage in the power system...*

When considering the necessity of using surplus RES generation on the scale of the national power system, one has to consider energy storage capacities on the level of terawatt-hours (TWh), as demonstrated in the previous section. As can be seen in Fig. 5.11, this only involves gas-based solutions: hydrogen or synthetic SNG.

Returning to the analysis of the NPS in 2040 (Option B for RES development), storage capacities of 1 TWh and 10 GW were considered. From today's perspective these volumes seem unusually large. It is worth noting, however, that the document[143] sets the rated capacity of electrolysers operating in the European Union in 2030 at 40 GW and the draft Polish Hydrogen Strategy[144] sets the capacity of electrolysers installed in Poland in 2030 at 2 GW. The assumed values of total hydrogen storage capacity (1 TWh, 10 GW in 2040) are therefore not abstractly excessive. The storage operation algorithm was considered, which consists in accumulating the surplus generation until its capacity is completely filled.

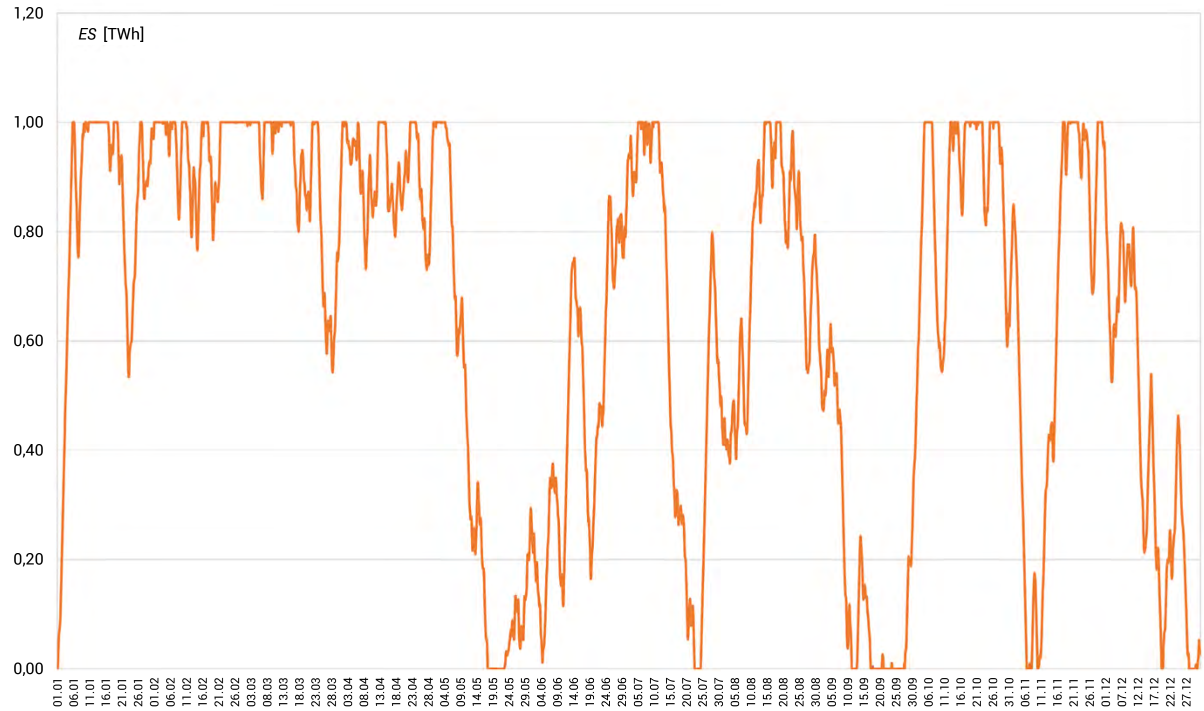
143 European Commission, Communication From The Commission To The European Parliament, The Council, The European Economic And Social Committee And The Committee Of The Regions. A hydrogen strategy for a climate-neutral Europe, Brussels, 8.07.2020. COM (2020) 301 final.

144 *Polish Hydropower Strategy until 2030 with an Outlook until 2040* (draft)...

It then discharges according to demand in the system, but if there is surplus generation before it is fully discharged, charging resumes. Assuming hypothetically for research purposes that the conversion efficiency of P2-G-2P is 100% (unfortunately, as for today, it does not exceed 30%), a very interesting effect of the impact of the "global storage of large capacity" on the balancing capability of the Polish power system is obtained. It is presented in the following figures.

Fig. 5.12 shows the annual cycle of storage charging and discharging. It can be seen that the state of full charge is reached as early as the first days of January. The high state of charge lasts until spring but drops to zero during a few windless days. In summer, the state of charge is reached considerably less frequently, and a full double discharge also takes place. In autumn, the storage facility also recharges to its maximum value several times.

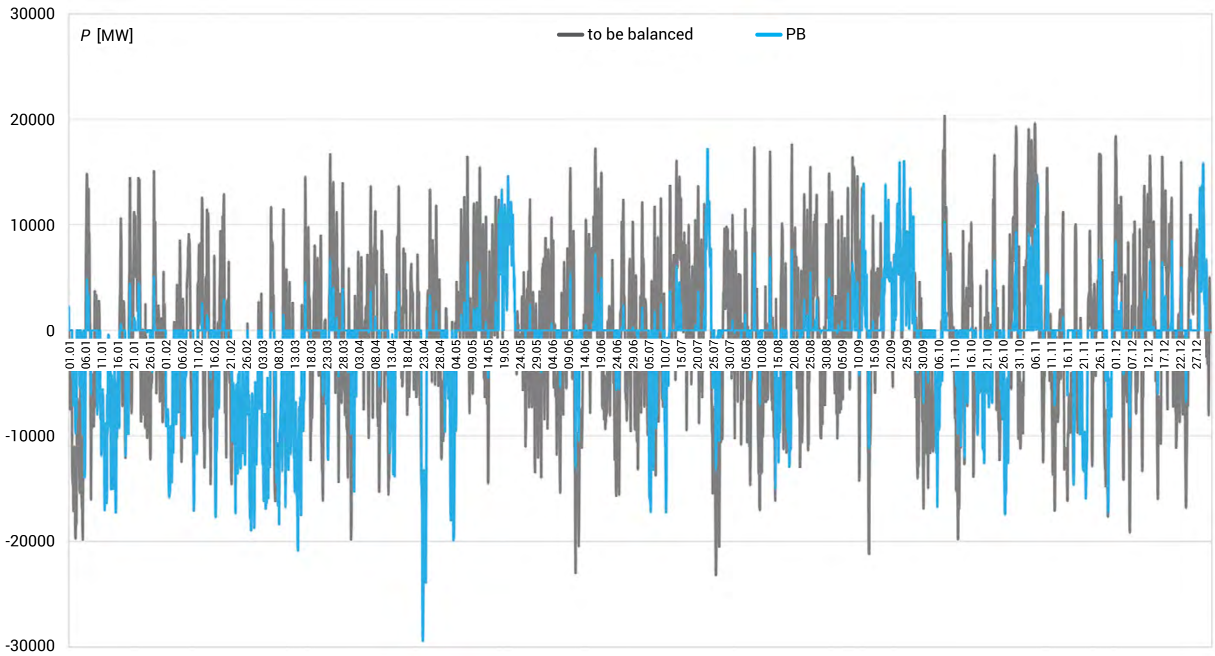
Figure 5.12. Annual pattern of charging and discharging of global storage managing surplus from RES in the National Power System in 2040



Source: own study.

Despite such a large capacity and power of the global storage, it is not possible to completely balance the demand of the NPS. Fig. 5.13 shows the flows of power to be balanced before and after the storage application. In the winter period, there is still surplus generation from RES that remains unutilised, while in the summer period, there is the power to be balanced in the state of depletion of the storage resources. However, the impact of global storage on meeting the balancing needs of the system is very significant.

Figure 5.13. Power flows to be balanced in NPS (year 2040, Option B), grey colour without energy storage, blue colour after storage (1 TWh, 10 GW)

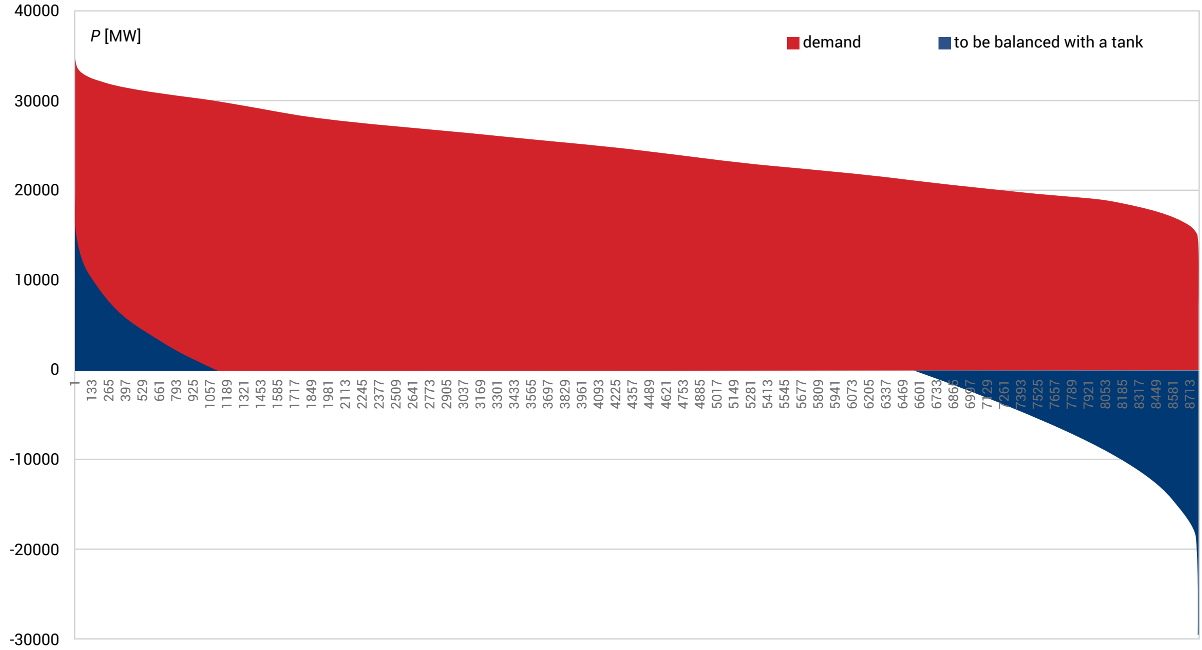


Source: own study.

This is confirmed by the ordered diagram in Fig. 5.14. For more than six thousand hours in a year, the storage facility completely satisfies the demand of the NPS for power (balancing needs are zero). In the remaining periods of the year, the balancing capacity is on the level of 6 to 9 GW and its duration does not exceed one thousand hours. The previously assumed rated power of the remaining CDU's and nCDU's of 5 GW plus DSR operations supported by PSPP facilities, biogas and imports will be able to fulfil this task.

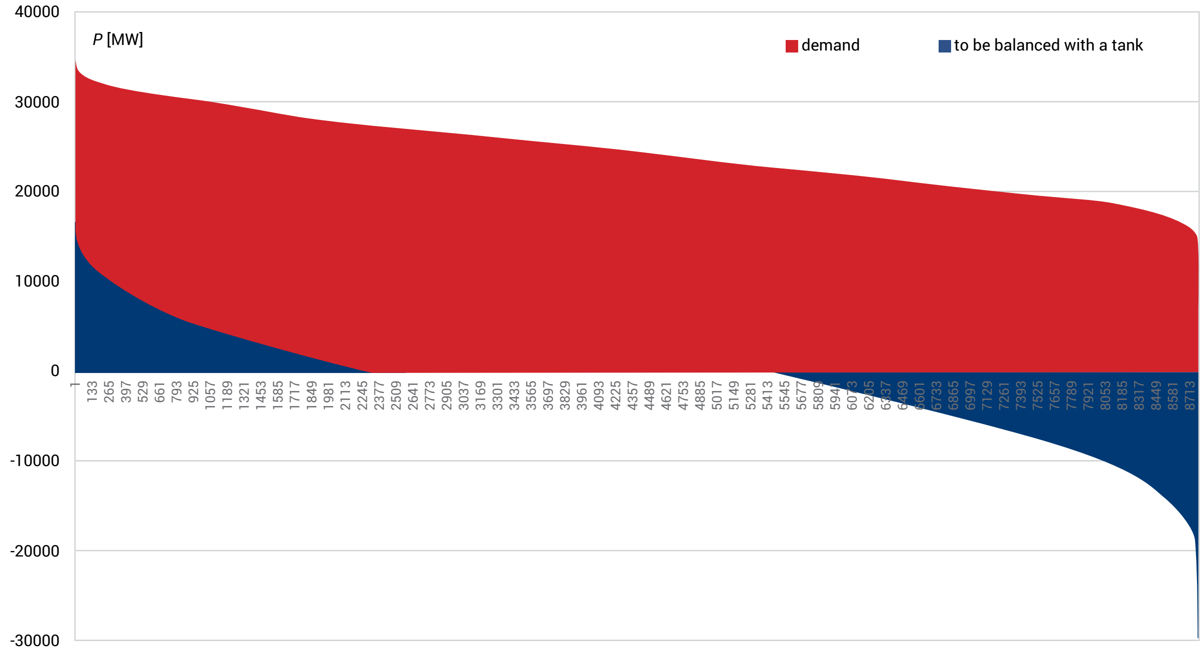
For comparison, Fig. 5.15 shows an analogous diagram but for half the global storage capacity and power (0.5 TWh, 5 GW). Admittedly, the number of hours with zero demand is reduced to four thousand, but even for such parameters, the balancing requirements are much easier to meet than those shown in Fig. 5.10 (without any storage).

Figure 5.14. Ordered annual graphs of load, baseload generation, photovoltaic generation, onshore and offshore wind generation in 2040, using 1 TWh, 10 GW global storage



Source: own study.

Figure 5.15. Ordered annual graphs of load, baseload generation, PV generation, onshore wind generation, and offshore wind generation in 2040 using 0.5 TWh, 5 GW global storage



Source: own study.

5.3 Wind and hydrogen power in the Polish Power System, a 2030-2040 perspective

It follows from these considerations that in view of the process of withdrawal of conventional coal-fired units from service in the NPS and the suspension of construction of new ones (with the exception of gas-fired units), with their generating capacity limited to 10 GW in 2040 and their share in energy production below 20% of demand, the power system must operate on the basis of other, alternative energy sources. Since, in addition to nuclear power, these will primarily be variable generation (VR) RES sources, their operation must be supported by energy storage facilities. Such an opinion is, of course, well-known and does not raise any doubts. However, it seems that the scale of needs in this respect has not been realised so far. These needs, compared to the present state, can be summarised as follows, using the letter abbreviations used in the first part of the paper (the last two symbols stand for energy storage capacity and power):

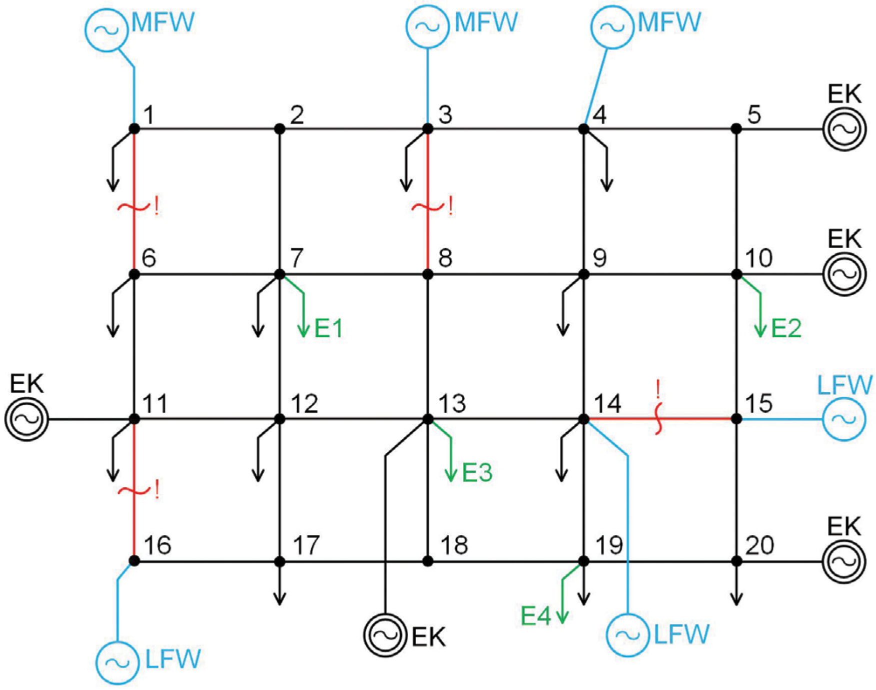
- Currently: onshore WF: 6.5 GW, OWF: 0 GW, PV: 5 GW, ES: 0.02 TWh, PS: 2 GW,
- in 2040: onshore WF: 16 GW, OWF: 20 GW, PV: 20 GW, ES: 1 TWh, PS: 10 GW.

These numbers may seem shockingly large, but there is another, qualitative aspect to the challenge outlined above - the indicators needed for 2040 will not be achieved without a large-scale approach. With all the support and understanding for the prosumer, distributed, civic and cooperative energy movement, it will not be possible to achieve global coverage of consumer demand in the future using these solutions and to provide power to energy storage devices based on the hydrogen economy. The above position does not deny the important role of distributed generation in the operation of the NPS but the analyses carried out make it clear that the role of large-scale energy and of the transmission system (both in electricity and in gas) will still have a strategic significance for Poland's energy security.

Fig. 5.16 illustrates symbolically the power system, which for the transmission grid and 110 kV can be treated as a multiple closed system. In selected nodes, conventional (CE) and wind (onshore WF and offshore WF) energy sources are connected. Prosumer photovoltaic systems are connected at the low voltage level and are not shown in the figure. It can be expected that large-scale hydrogen production will take place in electrolyser systems with a capacity of up to several hundred megawatts (in the EU hydrogen strategy, a 100 MW unit is to be the standard[145]) connected to the transmission grid (marked with the letter E). Injecting power from large groups of offshore and onshore farms into the grid will pose a risk of overloading high-voltage lines, especially if a nuclear power plant is located near the coastal town of Żarnowiec. Overloads are possible and are indicated in red in Fig. 5.16.

145 European Commission, Communication From The Commission To The European Parliament, The Council, The European Economic And Social Committee And The Committee Of The Regions. A hydrogen strategy for a climate-neutral Europe, Brussels, 8.07.2020. COM (2020) 301 final.

Figure 5.16. Schematic illustration of a closed-loop network structure of a NPS with conventional, onshore and offshore wind power and electrolysers connected deep inside the grid; conspicuous overloads on some lines (red)



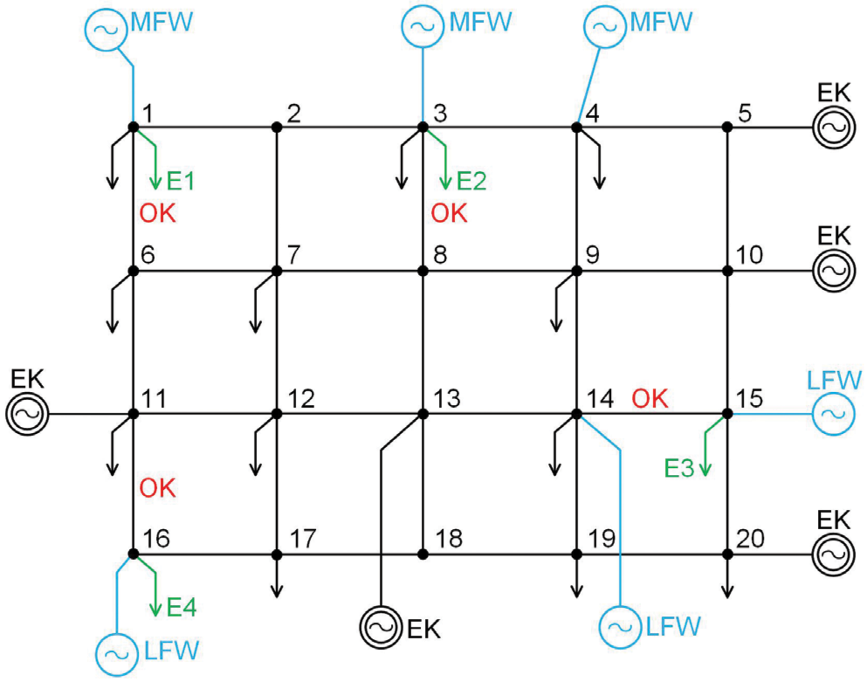
Source: own study.

The issue of electrolyser location is worth noting at this point. It can be imposed by gas infrastructure and environmental constraints. It can also result from the location of hydrogen storage facilities (salt caverns). It should be emphasized that even the location of electrolysers far from RES generation sites allows them to interact with these sources, in particular, to operate at full capacity in order to manage the excess generation and to shut down under high demand conditions. Even now it is fully possible to create appropriate group control systems of "RES - electrolysers" systems. It is argued in the literature[146] that the cost of feeding electrolysers from the grid will also include a high distribution charge. This conclusion is premature, as it is based on the current distribution charge system, which in the future may change fundamentally, so that hydrogen production as a strategic energy conversion may not be covered by such a charge at all. It appears that in many opinions there is an established view of the distribution charge as a 'postage stamp method', whereby a 100 m supply of energy is valued in the same way as a 100 km supply. Meanwhile, this fee can be determined in many other ways (e.g. nodal prices). The idea of integrating wind farms with hydrogen production facilities also appears in the literature. Moreover, for example, there is a discussion[147] about electrolysers integrated with nuclear power plants. These visions are only partly feasible. It is, of course, possible to integrate a RES source and an electrolyser plant within a single grid infrastructure and, moreover, to introduce a control system that strictly regulates the level of power flowing into and possibly out of the system. Such a solution can provide a number of technical (overload elimination) and economic benefits, see Fig. 5.17.

146 T. Adamczewski, M. Jedra, *Zielone gazy ...*

147 *Polish Hydropower Strategy until 2030 with an Outlook until 2040* (draft)

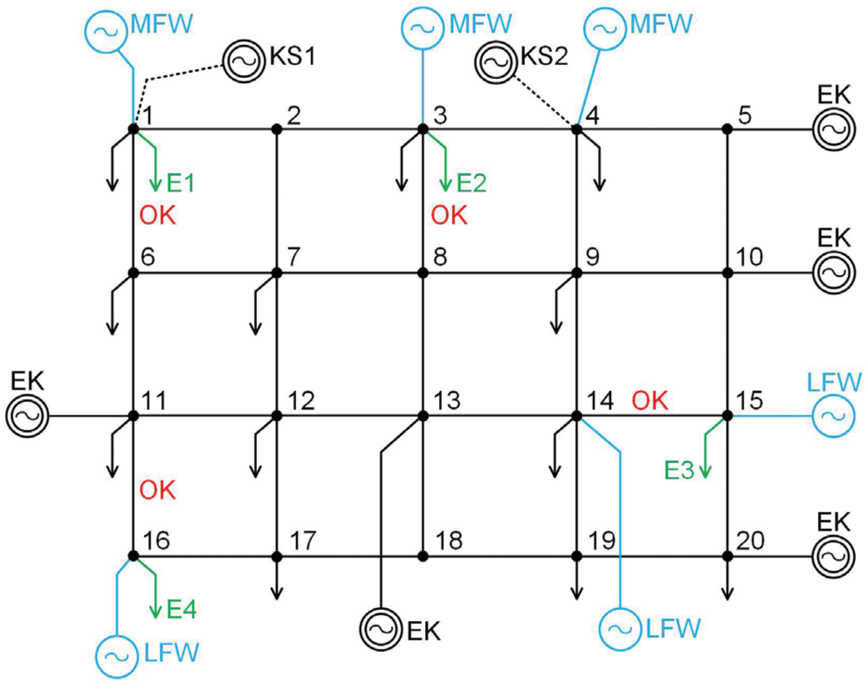
Figure 5.17. Schematic illustration of a closed grid structure of a NPS with conventional power, onshore and offshore wind as well as electrolysers integrated in wind farms; the elimination of line overloads is visible



Source: own study.

However, this does not eliminate the system requirements for each of these devices. Both wind turbines and electrolysers must operate, according to today's standards, in a grid with a specific "voltage rigidity". The measure of this feature (defined here in a very simplified way) is a parameter called short-circuit power determined for the place of connection (a farm set, an electrolyser set). Already today, due to too low values of short-circuit power in the nodes considered for connection of offshore wind farms in the north of Poland, the necessity of installing special devices called synchronous compensators (SC) is being considered, which complicates the entire network system and increases its costs, see Fig. 5.18.

Figure 5.18. Schematic illustration of a closed NPS grid structure with conventional power generation, onshore and offshore wind power as well as electrolysers integrated with wind farms; one can see the need to install synchronous compensators to increase the voltage rigidity of the grid in the connection nodes



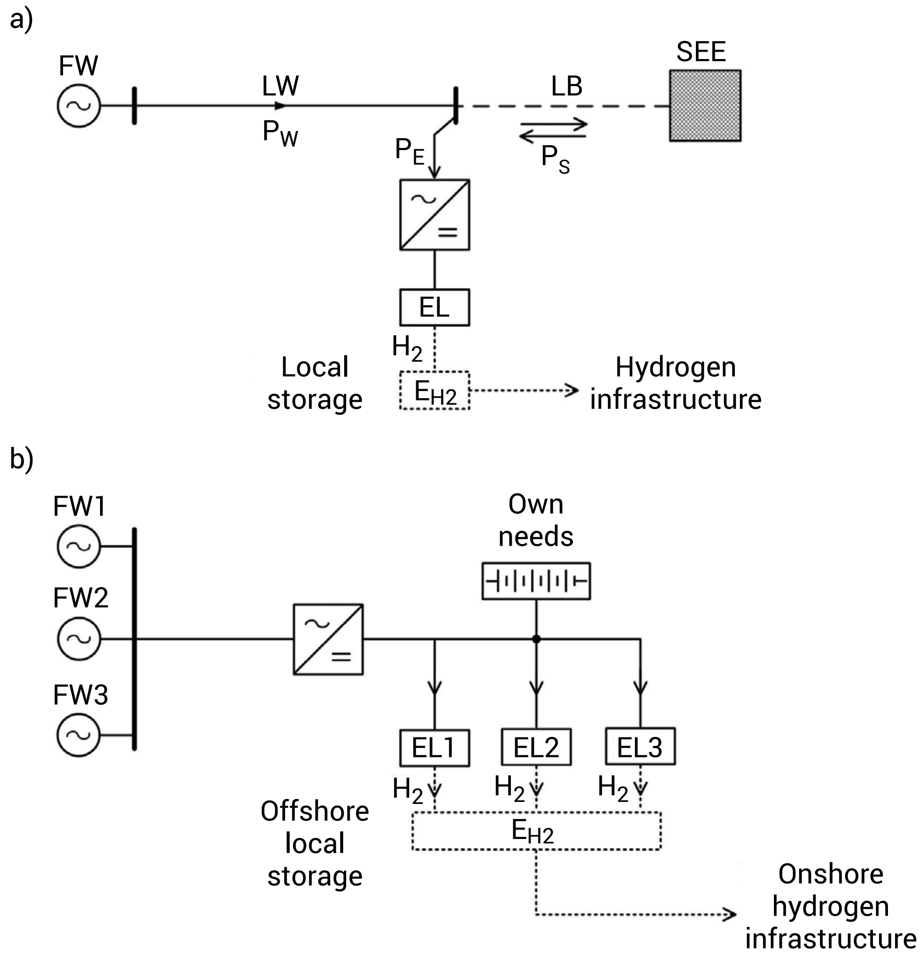
Source: own study.

Therefore, the concept of systems with a separate line between a wind farm and an electrolyser (or a set of farms, a set of electrolysers) operating completely outside of the power system should be approached with caution (but also hope). Currently neither wind turbines nor electrolysers (except for very small power units) are able to work individually. The reason is the lack of any voltage rigidity in such a system. It is necessary to interconnect the wind farm-electrolyser set with the power system (SEE) via a block line, as illustrated in Fig. 5.19 (the block line is marked with a dashed line). However, it can be expected that power electronic solutions will emerge that will allow wind farms to operate without a connection to the power system, directly on a set of electrolysers located on floating platforms, Fig. 5.19b[148.] While the first solution offers flexibility in terms of electricity (electrolysers can be fed from wind farms or from the grid), the other solution allows for feeding the hydrogen system (gas pipelines, storage facilities) and using hydrogen for purposes other than electricity production (G2P transformation). A radical alternative solution may be the construction of (one or several) direct current lines (HVDC). In view of the very high concentration of generation in northern Poland (offshore and onshore farms, a nuclear power plant), such a solution should not be considered just a futuristic vision of system development. One must bear in mind the limited possibilities of transmitting power by means of alternating current[149] resulting from elementary electrical engineering theory.

148 G. Calado, R. Castro, *Hydrogen Production from Off Shore Wind Parks: Current Situation and Future Perspectives, Applied Sciences* No. 11(12)/2021; *RWE Hydrogen Business*, RWE AG Germany, July 2021.

149 J. Machowski, Z. Lubośny, *Stabilność systemu elektroenergetycznego [Stability of the Power System]*, WNT, Warsaw 2018.

Figure 5.19. Separated systems: a) wind farm with electrolysis installation, visible separated line (LW) and the necessary block line (BL) and connection to the SEE system b) offshore wind farm complex with an electrolyser set located at sea; connection to the hydrogen infrastructure through a gas pipeline

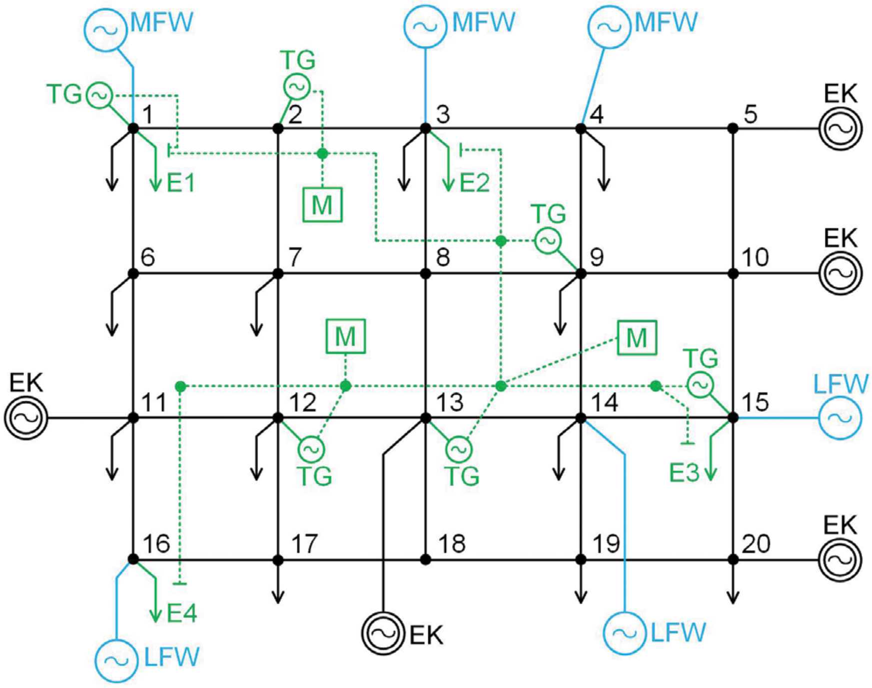


Source: own study.

Fig. 5.20 gives an example of the locations of electrolysers in the aggregate option with generation. Of course, it is necessary to mention the location of devices for G2P reverse transformation realized on a large scale through OCGT or CCGT turbines[150]. Here, too, there are visions of their integration with the RES - electrolyser component and creation of systems called energy hubs with additional support of BESS battery storage facilities. This concept may be implemented, but with such a large scale of the problem in terms of energy (using almost 30 TWh of energy contained in gas), a more realistic vision is to build a network of hydrogen storage facilities and gas pipelines and to locate G2P generating facilities in places resulting from system needs and infrastructural capabilities. Again, the spatial dispersion of gas generation will not be a barrier to subjecting the power regulation process to the algorithms resulting from the overarching goal of a global storage facility.

150 T. Chmielniak, T. Chmielniak, *Energetyka wodorowa [Hydrogen power generation]*, PWN, Warszawa 2020.

Figure 5.20. Schematic illustration of a closed grid structure of a NPS with conventional power, onshore and offshore wind, and electrolysers integrated with wind farms; hydrogen infrastructure (grids, storage facilities) is visible, together with turbines (TG) performing G2P functions



Source: own study.

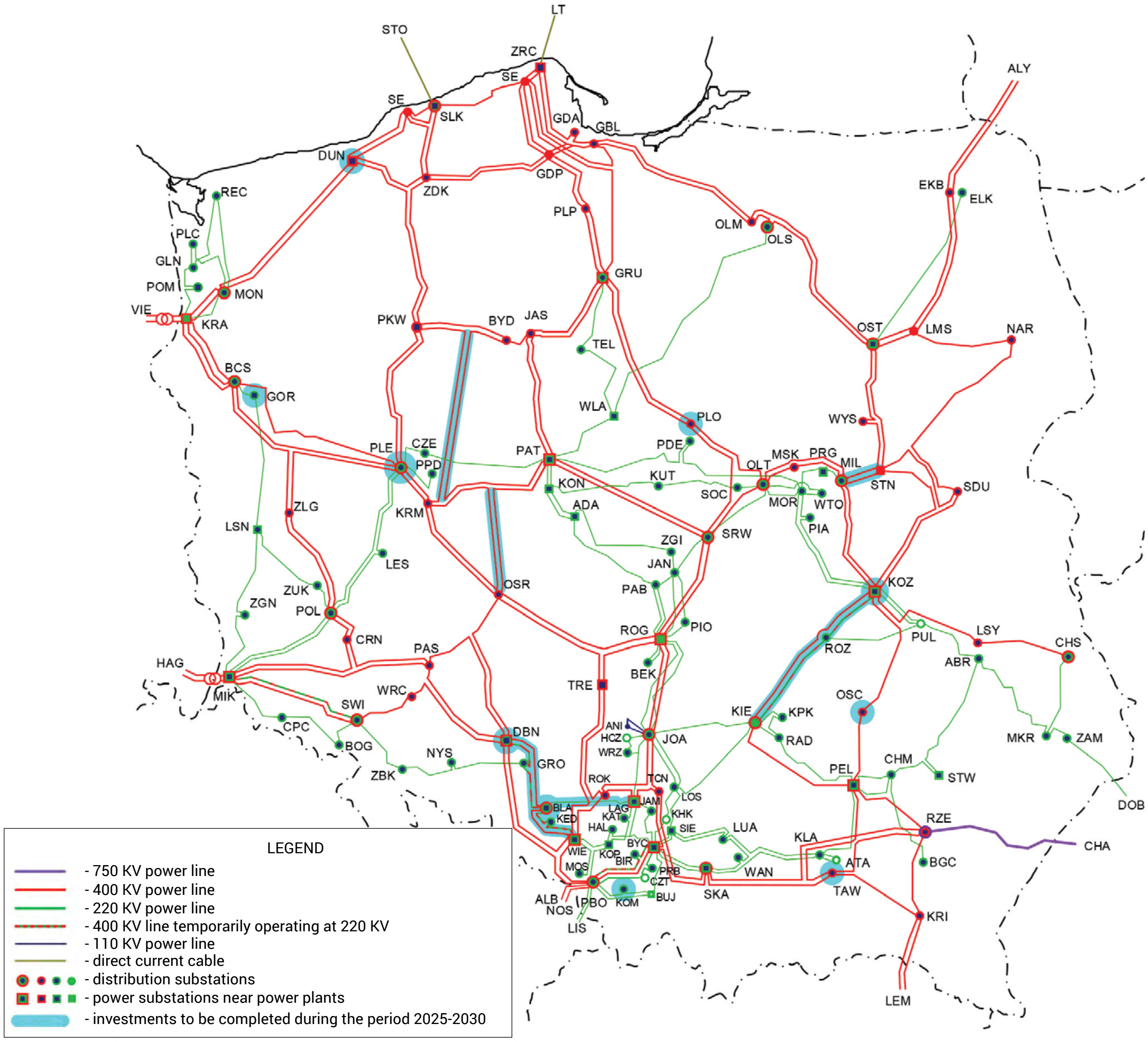
The NPS development plans until 2040, prepared in multiple options by PSE S.A. (Fig. 5.21),[151] include offshore wind generation and a nuclear power plant, so the greatest intensity of new line construction is seen in the north. However, does it also include the forecast defined as onshore WF: 16 GW, OWF: 20 GW, PV: 20 GW, ES: 1 TWh, PS: 10 GW, let alone the visions contained in the studies[152] and[153]? Probably not, hence the need for further revision of transmission grid development plans, following the revision of official concepts of power sector development in Poland. Determination of the plans of PSE S.A. regarding the connection possibilities in 2040 in the light of the demonstrated need to increase the capacity of wind farms will have an impact on the selection of alternative solutions: hydrogen transmission through a north-south gas pipeline, construction of HVDC lines, etc.

151 *Development plan for meeting current and future electricity demand for 2021-2030...*

152 H. Engel, M. Purta, E. Speelman, G. Szarek, P. van der Pluijm, *Emission-neutral Poland 2050...*

153 *Energy Data Platform in Poland*, http://energy.instrat.pl/

Figure 5.21. Development plants of the Polish Power System until 2040, adjusted to the needs indicated in[154]



Source: [155]

The discussion held so far has focused on the global problems of the Polish power system. It has been shown that only with the development of renewable energy (mainly onshore and offshore wind power) at a significantly higher level than assumed in the government document PEP 2040[154] and with the development of energy storage capabilities on an unprecedented scale and the application of P2G2P gas solutions, it is possible to ensure the balancing of needs and power generation capabilities, with a share of conventional thermal power generation of less than 20%.

154 Announcement of the Minister of Climate and Environment on the National Energy Policy until 2040 ...

155 *Development Plan for Meeting Current and Future Electricity Demand in the Years 2021-2030*, Polskie Sieci Elektroenergetyczne, Konstancin - Jeziorna 2020, https://www.pse.pl/documents/20182/21595261/Dokument_glowny_PRSP_2021-2030_20200528.pdf.

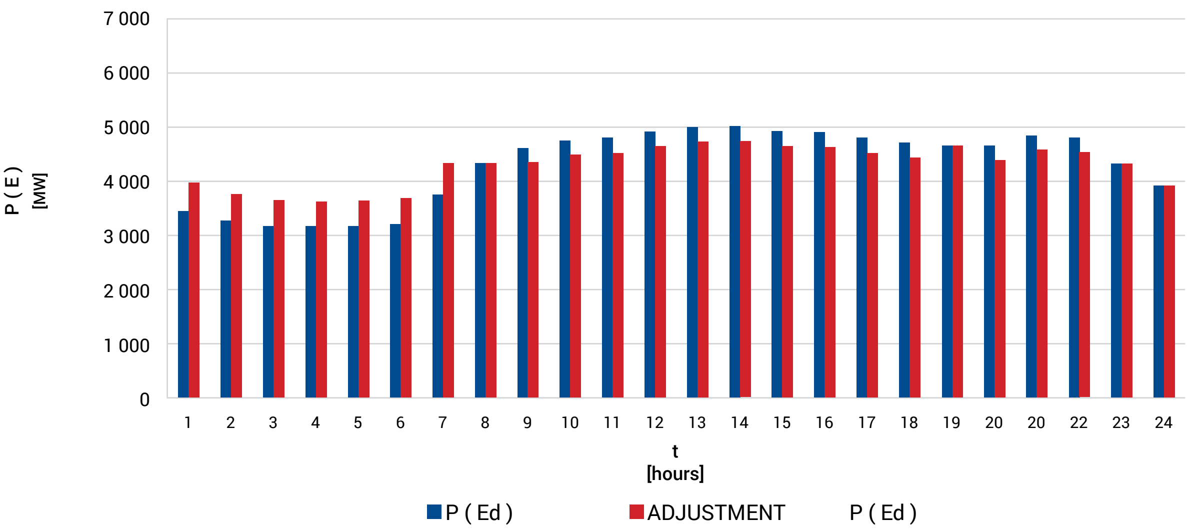
Storage of electric energy in green hydrogen and its recovery in emission-free conversion processes is, due to the technological conditions, long-term storage (for the global storage considered, the capacity related to the rated power is one hundred hours). However, in addition to the basic balancing purpose, other applications of the green hydrogen production process in cooperation with variable RES power generation are possible.

Three such applications are presented and discussed below. The first concerns increasing the load on the system by switching on electrolysers, not only during periods of excess generation from RES, but also during periods of low demand (in Fig. 5.22, this is the period from 1 to 7 o'clock). The production of hydrogen here does not lead to short-term storage for energy recovery during the peak of the same day, but to an indirect effect of reducing demand at other times by replacing electricity-based technologies with green hydrogen. Determining the effectiveness of such indirect conversion requires detailed atud, but its effectiveness is highly probable.

The analysis shows that in 2040, for approximately 2500 hours, the RES will require less than 4 GW of balancing power. This means that on average, 2-3 GW of power can be added to the system per hour, so 5-7.5 TWh of additional energy can be allocated to hydrogen production.

As already stated, produced hydrogen can contribute indirectly to reducing peak load demand, particularly under conditions of balancing difficulties. If one assumes the possibility of using hydrogen produced in this way over a period of a thousand hours, this would give a balancing capacity of 2-3 GW, extremely valuable in view of the results of the analyses shown in Fig. 5.14 and Fig. 5.15.

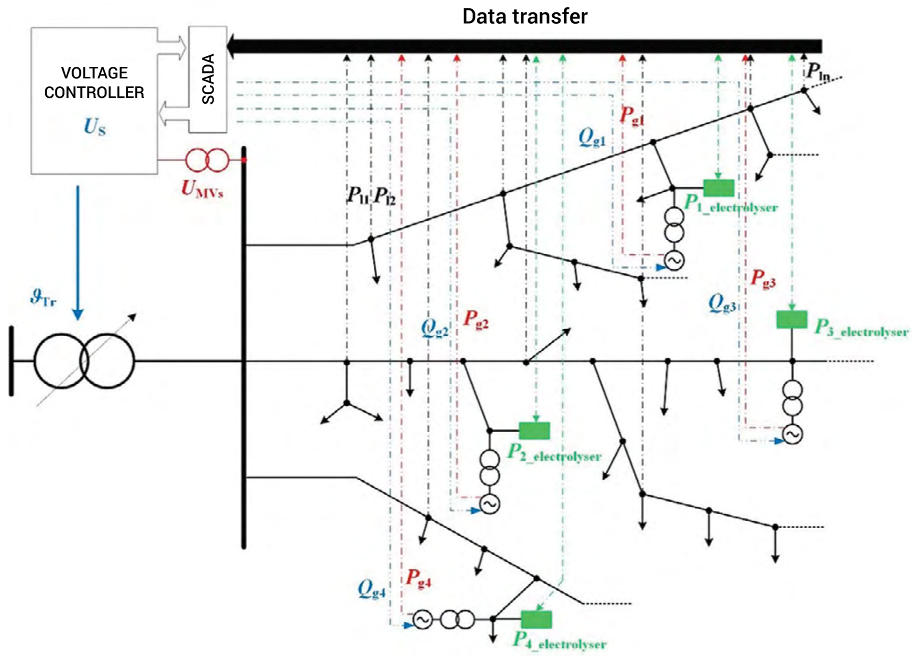
Figure 5.22. Illustration of load increase in the night demand valley (by 15%) and intermediate compensation of this increase in the day peak



Source: own study.

The production of hydrogen considered in the analyses included its large-scale segment, which will be of key importance for ensuring a balanced operation of the power system in the future. In parallel, a local segment of hydrogen production will develop, including electrolysers with a capacity of 100 kW, 0.5 MW, 2 MW or 10 MW. Apart from its significance for the development of a broadly understood hydrogen economy, it may also have an impact on the improvement of grid operation conditions at the medium voltage level. Fig. 5.23 illustrates the concept of the voltage regulation system in such a network, where RES sources integrated with electrolysers operate together with a traditional transformer equipped with a on-load tap changer[156]. As a result of the variability of the generated power, the voltage values in the grid also change, deteriorating the quality of power supply to other consumers. Controlling the power output of local electrolysers with a regulator that cooperates with the transformer significantly improves the quality of this voltage and cancels out any variations caused by local wind generation, as shown in Fig. 5.24.

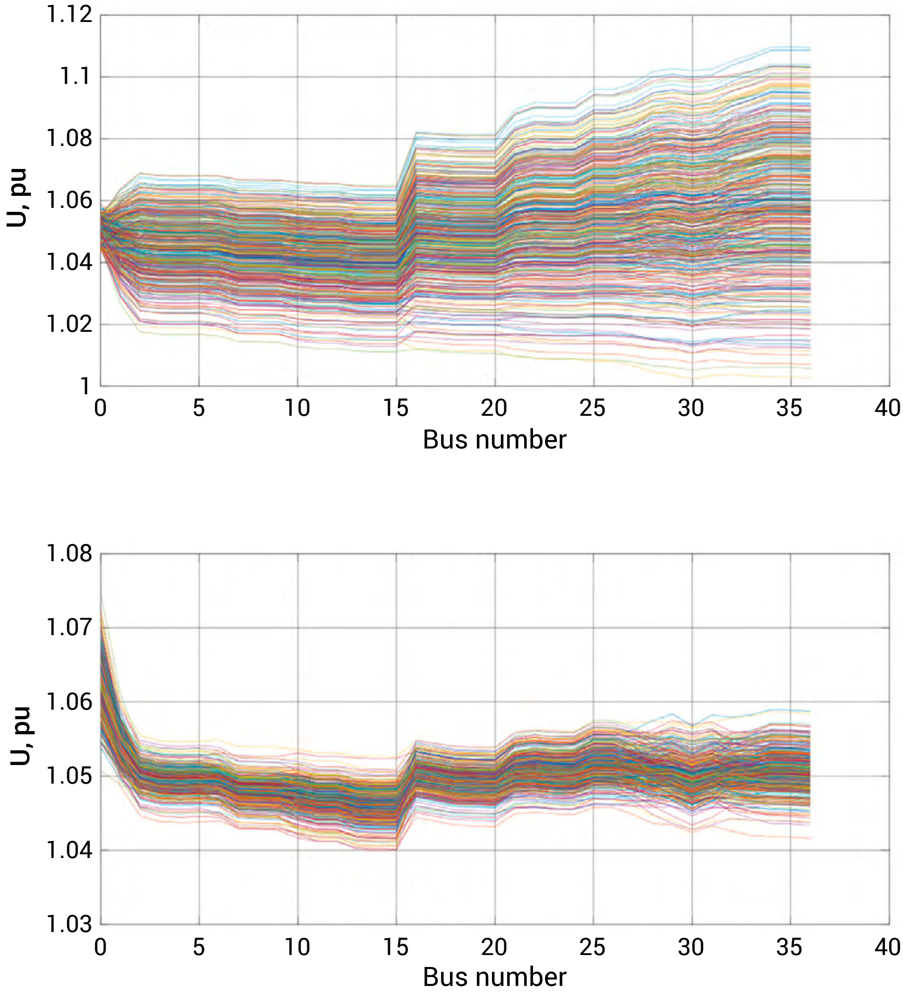
Figure 5.23. Concept of voltage regulation system in MV network with connected RES sources integrated with electrolyser power control



Source: P. Pijarski, P. Kacejko, *Voltage Optimization in MV Network with Distributed Generation...*

156 P. Pijarski, P. Kacejko, *Voltage Optimization in MV Network with Distributed Generation Using Power Consumption Control in Electrolysis Installations*, "Energies" 2021, 4(14).

Figure 5.24. Effect of power regulation of electrolysers connected to the MV grid reducing voltage changes in the network nodes caused by RES generation



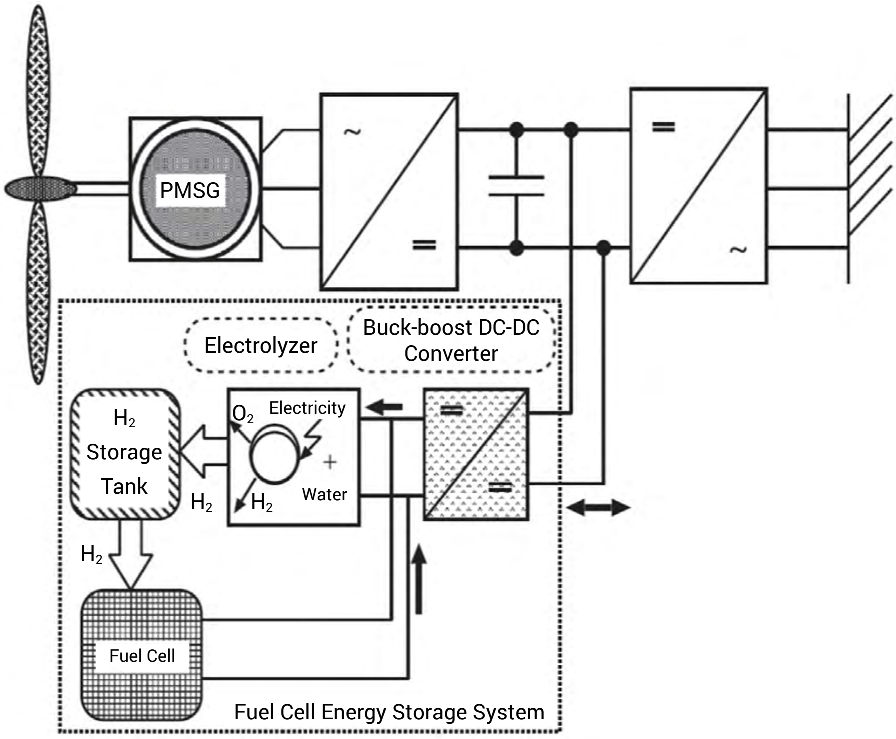
Source: [157]

The literature presents many other measures related to RES sources commonly referred to as "power stabilization" or even "smoothing"[158] or "ramping", in which electrolysers can play an important role as regulated variable power loads storing energy in hydrogen. All in all, these actions lead to a certain limitation of the output of RES sources, although they give it the expected shape, thus supporting the operation of the power system. In case of single turbines, additional power generation can be provided by fuel cells fuelled by stored hydrogen. Systems such as those shown in Fig. 5.25 are not designed to provide full generation in case of low wind speed or lack of wind for a few hours, but to eliminate interference components in the power output (e.g. 50 kW fuel cell power, 200-300 kWh hydrogen storage capacity, 3 MW turbine).

157 P. Pijarski, P. Kacejko, *Voltage Optimization in MV Network with Distributed Generation Using Power Consumption Control in Electrolysis Installations*, "Energies" 2021, 4(14).

158 A.M. Howlader, N. Urasaki, A. Yona, T. Senjyu, A.Y. Saber, *A review of output power smoothing methods for wind energy conversion systems, Renewable and Sustainable Energy Reviews* 2013, 26.

Figure 5.25. Concept of using a hydrogen storage tank and a fuel cell to "smooth" the output power waveform of a wind turbine



Source: A.M. Howlader, N. Urasaki, A. Yona, T. Senjyu, A.Y.. Saber, *A review of output power smoothing methods....*

5.4 Other selected problems and possibilities of applying green hydrogen in electric power engineering

5.4.1 Electricity generation using hydrogen

Medium- and large-scale power generation: in medium power gas technology hydrogen can be used for peaking power (gas technology combined systems using doped hydrogen or synthetic fuel). The green hydrogen produced can be used as a fuel for power generation as gas turbines can run on hydrogen to support a variety of industrial applications including steel mills, refineries and petrochemical plants where the hydrogen doping in gas turbine operation is no less than 50%[159]. These are potential elements where primarily doped hydrogen may be applied (the scale will depend on the technical efficiency of the processes and the ratio of performance to the price at which a given level of performance is obtained).

The use of hydrogen as a fuel for a classical gas turbine operating in an open circuit, drawing air for combustion from the environment and discharging exhaust gases into the environment, leads to their evolution from the beginning of hydrogen co-combustion with a small share of energy up to the com-

159 J. Goldmeer, *Power to Gas: Hydrogen for Power Generation. Fuel Flexible Gas Turbines as Enablers for a Low or Reduced Carbon Energy Ecosystem*, General Electric Company, 2019, pp. 13-14, https://www.ge.com/content/dam/gepower/global/en_US/documents/fuel-flexibility/GEA33861%20Power%20to%20Gas%20-%20Hydrogen%20for%20Power%20Generation.pdf

bustion of pure hydrogen in air. In this situation, the combustion products of the hydrocarbon fuel with carbon dioxide and an additional amount of water vapour appear in the exhaust gas stream. In contrast, when burning pure hydrogen, only water vapour will be a by-product. The possibilities of using hydrogen both as doped fuel and as pure hydrogen will depend on adjusting the production of large power gas turbines, but also smaller ones, to the possibilities of using hydrogen. Manufacturers declare that it will be possible to achieve this capacity at the turn of 2023-2030.

To illustrate the scale of an electrolysis plant preparing hydrogen for gas turbines, the following example calculation is given. This is an option of using only 4% of hydrogen to power a 385 MW gas turbine operating in a simple system, the demand for this gas is over 1100 kg/h. Achieving the required amount of hydrogen will be possible with the use (depending on the type of electrolyser used) of an electrolysis installation with a capacity in the range of 45-60 MW. This type of installation should be located close to the gas turbine, thus avoiding hydrogen transport (while maintaining higher installation peformance)[160].

Table 5.5. Example scale of hydrogen consumption for combustion in a gas turbine, for the options of using pure hydrogen and doped in 5%

Capacity MW	Consumption GJ/h	Hydrogen demand m^3/h (100%H_2)	Water demand m^3/h (100%H_2)	Hydrogen demand m^3/h (5%H_2)	Water demand m^3/h (5%H_2)
11.2	129	11 700	10	190	0.2
34.3	350	31 800	27	510	0.4
44.0	473	43 000	37	690	0.5
288.0	2 677	243 500	212	3 930	3.2

Source: Team for Development of the RES Industry and Benefits for the Polish Economy, Team Report No. 4, *Hydrogen economy,* May 2020, p. 28.

Low-power cogeneration systems,[161] including hybrid systems: fuel cells (possible implementation of hydrogen technologies today); hybrid systems in the form of a gas turbine coupled with a fuel cell (hydrogen when commercial installations become available). Usually cogeneration processes are based on natural gas. Assuming that hydrogen is today a more expensive fuel than natural gas, and OPEX is the dominant cost in the operation of cogeneration systems, the condition for choosing hydrogen over natural gas as the fuel source for a cogeneration unit will be to achieve better energy efficiency or a competitive price. For hydrogen cogeneration units to be a viable technology, it is required that the demand for heat increases along with the demand for electricity, then hydrogen cogeneration units will be able to create a niche where combined heat and power generation will be more beneficial, compared to high efficiency electric heat pumps[162].

160 Renewable Energy Industry Development and Benefits to the Polish Economy Team, Team Report No. 4, "Hydrogen Economy," May 2020, pp. 26-28, https://klasterwodorowy.pl/images/zdjecia/Gospodarka%20Wodorowa.%20Rekomendacje%20grupy%204.pdf

161 Cogeneration (CHP) is the simultaneous production of electricity and useful thermal energy (heating and/or cooling) from a single energy source.

162 Australian Government, *Australian hydrogen market study. Sector analysis summary*, Advision, 24 May 2021, pp 70-71.

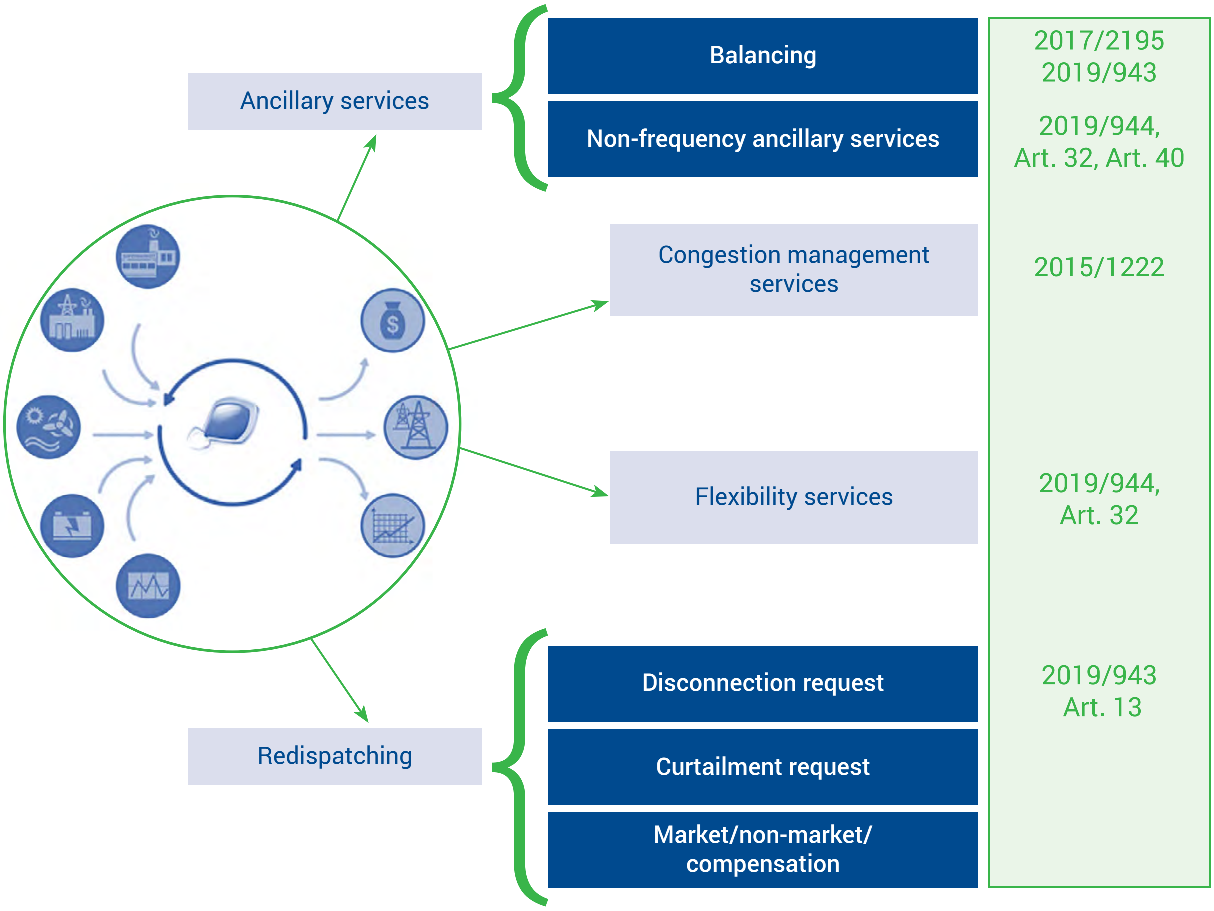
5.4.2 Application of hydrogen in the transmission and distribution of electricity

In order to indicate the possibility of using the processes related to hydrogen production in the electricity transmission and distribution subsector, the whole system for hydrogen production, transport and storage should be connected to the electric energy system, i.e. in the scheme with the RES source and with the electricity grid (or a transmission grid depending on the connection power of the source) of the local distributor. Only then will it be possible for the owner of the hydrogen system to provide additional services to electricity grid operators[163].

In such a model it can be assumed that the production of hydrogen for commercial purposes will be the primary goal (also using the possibility of storage). On the one hand, such a solution gives more possibilities to develop various business solutions, but, on the other hand, it brings additional costs related to the necessity of paying network fees as well as the cost resulting from the purchase of electricity during periods of zero production from the RES source. With such a solution, the carbon footprint of the hydrogen must be taken into account. In other words, it is not possible to talk about renewable hydrogen without obtaining guarantee certificates of origin for the electricity taken from the grid and used to produce hydrogen.

163 An example of a service catalogue resulting from a project investigating the applicability of electrolysers to the needs of system operators can be found in the study: Project 735485 - QualyGridS, *Standardized qualifying tests of electrolysers for grid services*, Table 5-2 Service catalogue for electrolysers, pp. 37-38.

Figure 5.26. Possibilities of using hydrogen for transmission and distribution in the power system



Source: own study based on EU Directive 2019/944 and EU Regulation 2019/943, EU Regulation 2017/2195[164], EU Regulation 2015/1222[165].

Moreover, a complementary element in this scheme may be the provision of non-frequency ancillary services by the owner of an installation/system (RES + electrolyser + storage) to a transmission or distribution system operator, flexibility services to a distribution system operator, or not being obliged to comply with the RES source capacity reduction when requested by an operator, or in extreme cases not being obliged to completely cease production of energy from RES when requested by an operator. As of today, due to the lack of comprehensive regulations for distribution system operators, system services can only be provided to the transmission system operator, whereas as regards flexibility services no regulations have been introduced in Poland (date: 31 July 2021).

164 Commission Regulation (EU) 2017/2195 of 23 November 2017 establishing balancing guidelines, Official Journal of the European Union L 316/6, 28.11.2017.

165 Commission Regulation (EU) 2015/1222 of 24 July 2015 laying down guidelines on capacity allocation and congestion management, Official Journal of the European Union L 197/24, 25.7.2015.

According to the current definition in EU Directive 2019/944[166], ancillary services[167] include balancing services, for which there are many legal provisions both at EU and national level, and non-frequency ancillary services. The main provisions on balancing services are found in the balancing network codes, but also in EU Regulation 2019/943[168]. At the national level, the most relevant are the guidelines provided in the Balancing Conditions described by PSE SA and accepted by the NRA[169].

Balancing services, although related to the entire power system, should only be understood from the perspective of responsibilities assigned to the transmission operator with respect to maintaining an appropriate level of frequency in the power system and ensuring an ongoing balancing of demand with generation. Similar responsibilities in ensuring technical balancing of the grid (in this case not related to frequency) are assigned to electricity distribution operators, however, this obligation is fulfilled without the possibility of purchasing additional services from the market.

As is well known, renewable sources such as wind and solar are characterized by fluctuating output power. This fluctuation puts additional load on the power system, which can result in problems in achieving a balance between generation and load, which can lead to frequency instability[170]. In the current energy market, the transmission system operator uses the ancillary services market to procure frequency containment reserve (FCR), which stops unwanted frequency fluctuations within the first few seconds after an imbalance occurs and provides satisfactory primary frequency regulation. In addition, this operator also acquires a frequency restoration reserve (FRR), which helps to restore the frequency to its nominal value[171]. Electrolysers can manage their power demand for hydrogen production (fuel cells and PEM-based electrolysers are able to quickly change the power setting to increase or decrease the demand or power generation accordingly), moreover, it is possible to store the generated hydrogen for a long time[172]. The stored hydrogen can be used to provide electricity back to the power system when needed[173]. However, it should be remembered that offers of this kind will be attractive to the transmission system operator if they are large enough in volume or power. At the current level of development of hydrogen systems, their use as balancing services is not to be expected, but this does not mean that locally they will not be able to provide flexibility services to distribution system operators in the future.

166 Directive (EU) 2019/944 of the European Parliament and of the Council of 5 June 2019 on common rules for the internal market in electricity and amending Directive 2012/27/EU, Official Journal of the EU L 158/125, 14.06.2019.

167 EU Directive 2019/944 Article 2 point 48) an ancillary service is a service necessary for the operation of a transmission or distribution system and includes balancing services and non-frequency ancillary services, excluding congestion management.

168 Regulation (EU) 2019/943 of the European Parliament and of the Council of 5 June 2019 on the internal market in electricity, Official Journal of the European Union L 158/54, 14.06.2019.

169 *Conditions Concerning Balancing,* pursuant to: Commission Regulation (EU) 2017/2195 of 23 November 2017 establishing balancing guidelines approved by the decision of the NRA, ref. no. DRR.WRE.744.35.2019.PSt of 5 March 2020, https://www.pse.pl/dokumenty

170 M.S. Alam, M.A. Alotaibi, M.A. Alam, M.A. Hossain, M. Shafiullah, F.S. Al-Ismail, M.M.U. Rashid, M.A. Abido, *High-Level Renewable Energy Integrated System Frequency Control with SMES-Based Optimized Fractional Order Controller*. Electronics 2021, 10, 511, https://doi.org/10.3390/electronics10040511

171 ENTSO-E, *Balancing Report*, 2020, p. 9.

172 *Deliverable Report. Electrical Grid Service Catalogue for Water Electrolyser*, Project 735485 - QualyGridS Standardized qualifying tests of electrolysers for grid services, 21.11.2017. pp. 27-35, www.qualygrids.eu

173 The efficiency levels (losses) of hydrogen use in different processes are indicated in the barriers chapter.

Another set of available services that can be seen from the perspective of new opportunities for hydrogen development are non-frequency ancillary services[174] (e.g. services for voltage control or islanding). Such services are currently used by the electricity transmission system operator. For electricity distribution system operators, opportunities for future use of such services have emerged with the publication of EU Directive 2019/944 (Article 31)[175]. The introduction of this element to the basket of tools at the disposal of the distribution system operator is extremely important in an era of rapid development of distributed energy sources, most of which are and will be connected to the distribution network. In order to ensure local needs to cope with network problems, cooperation of new, distributed energy sources (also P2G systems, electrolysers, energy storages) with the power system operator will play an important role.

Another basket of potential services in which sources of hydrogen production from RES could be involved in the future are flexibility services[176]. Flexibility services should be approached from the perspective of customer activation, but also the use of new opportunities such as electrolysers to support the system at a local level (medium and low voltage electricity grids). It is assumed that flexibility services will take the form of market services available on flexibility platforms, for an appropriate remuneration[177]. This remuneration can be understood as an additional alternative to achieve the benefits of green hydrogen production. If there is too much electricity generated in the system, then hydrogen production can be started, while if there is a shortage of electricity in the system to meet demand, then hydrogen production can be stopped, diverting all electricity production to the electricity grid. Of course, all of these processes require proper synchronization and a calculation of the profitability of the various forms of involvement and a clear definition of the business model for the parties involved.

In addition, in accordance with the applicable law under EU Regulation 2019/943[178], calls to reduce or completely abandon the production of electricity by a RES source will be subject to compensation from the operator who gives such an order. In this case, also depending on the amount of compensation paid, instead of reducing the amount of produced electricity fed into the grid, the excess can be redirected to the production of hydrogen (with a suitably adapted installation).

174 EU Directive 2019/944 Article 2 point 49) non-frequency ancillary services is a service used by a transmission system operator or distribution system operator to regulate steady-state voltage, rapidly inject reactive current, provide inertia to maintain local network stability, short-circuit current, stand-alone start-up capability and island operation.

175 These provisions have not yet been implemented in Poland, so it is difficult to conclude when, to what extent and in what manner users of the electricity system will be able to provide additional services to electricity system operators (as of 30 July 2021).

176 They were introduced by EU Directive 2019/944 Article 32 as a tool for the electricity distribution network operator to increase efficiency in the operation and development of the distribution system. Regulations should allow distribution system operators to procure such services from suppliers of distributed generation, demand response or energy storage.

177 *An integrated approach to active system management. With the focus on TSO-DSO cooperation in congestion management and balancing*. CEDEC, E.DSO, ENTSO-E, eurelectric, GEODE, 2019, pp. 28-41.

178 EU Regulation 2019/943, Article 13 Redispatching.

06

ECONOMIC ANALYSIS OF HYDROGEN PRODUCTION FROM RENEWABLE ENERGY SOURCES

This chapter presents estimates of the costs associated with the production of hydrogen from water electrolysis using different forms of renewable electricity. To compare the costs of hydrogen production from the technologies under consideration, the levelized cost of hydrogen (LCOH) production, was used, an index analogous to that used to compare the costs of electricity production from different sources, LCOE. The input assumptions on which the calculations were based rely on the analysis of technical and economic parameters presented in various publications of recognized national and international research centres. They have been described in detail in this part of the report along with the methodology used for the calculations. Determinants of reaching business viability and necessary steps to be taken to enable the development of hydrogen technologies based on RES are also indicated.

6.1 Description of technical solutions for the use of green hydrogen

In the context of a zero carbon economy, green hydrogen is the most desirable of all hydrogen options available. It can be obtained from electrolysers working with renewable energy sources such as wind, solar or hydropower plants. An important criterion for the development of RES-based hydrogen technologies is the cost of its production.

Estimates of these costs under Polish conditions has been presented for the following three technological options:

- an electrolyser integrated with an onshore wind turbine,
- an electrolyser integrated with an offshore wind turbine,
- electrolyser integrated with a photovoltaic power plant.

The term "integration" of an electrolyser with a RES source is in this case imprecise. There are possibilities of real technical integration of an electrolyser with a wind turbine or a PV installation at DC level, even "before" the transformation to AC level. However, these are not currently widespread and technologically mature solutions. In the economic sense, integration can be said to take place when a wind farm (PV farm) is connected to a single PCC (Point of Common Coupling*)*, so that the energy used to power the electrolyser is not charged a supply (distribution) fee. However, as stated in Section 5.4, this may change in future. It will then be possible to speak of virtual integration despite the physical distance of the objects under consideration. For the purposes of this report, the term "integration" will be used, which should be understood with the above remarks in mind.

Onshore wind generation of hydrogen through electrolytic processes is associated with the lowest lifecycle GHG emissions of any hydrogen generation pathway currently available[179]. In addition, onshore wind energy has one of the lowest averaged electricity LCOEs. Therefore, it represents a very promising opportunity for cost-effective, environmentally benign hydrogen production and GHG emission mitigation. In Poland, the market potential of onshore wind power plants is estimated at 22-24 GW in the 2050 perspective according to the Polish Association of Wind Energy (PAWE)[180]and at 35 GW by McKinsey[181].

179 C. Koroneos, A. Dompros, G. Roumbas, N. Moussiopoulos, *Life cycle assessment of hydrogen fuel production processes*, "International Journal of Hydrogen Energy" 2004, pp. 1443-1450; K. Hacatoglu, M.A. Rosen, I. Dincer, *Comparative life cycle assessment of hydrogen and other selected fuels*, "International Journal of Hydrogen Energy" 2012, pp. 9933-9940; V. Utgikar, T. Thiesen, *Life cycle assessment of high temperature electrolysis for hydrogen production via nuclear energy*, "International Journal of Hydrogen Energy" 2006, pp. 939-944; B. Olateju, A. Kumar, M. Secanell, *A Techno-Economic Assessment of Large Scale Wind-Hydrogen Production with Energy Storage in Western Canada*, Donadeo Innovation Centre for Engineering, Department of Mechanical Engineering, University of Alberta, Edmonton, Alberta, Canada 2016, p. 3.

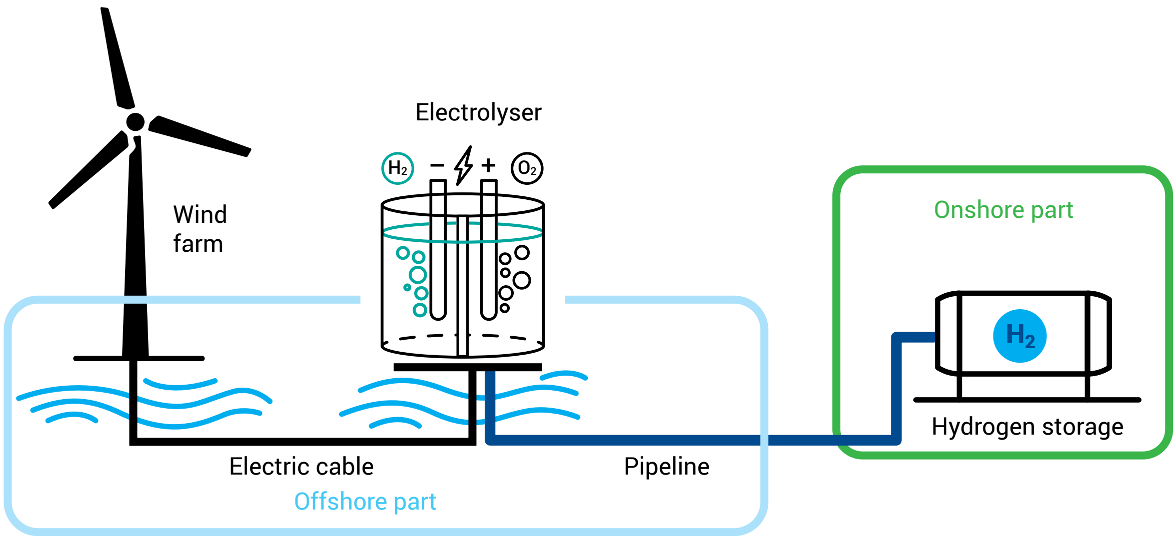
180 *Lądowa Energetyka Wiatrowa in Poland*, Polish Wind Energy Association, Report 2021.

181 *Carbon neutral Poland 2050. How to turn a challenge into an opportunity*, McKinsey & Company, 2020.

It is expected that such amounts of installed capacity will generate surplus electricity to enable the use of electrolysers and large-scale hydrogen production.

Another option are electrolysers integrated with offshore wind turbines. According to PAWE estimates the potential of offshore wind farms in the Polish part of the Baltic Sea in the 2050 perspective is 28 GW[182], while McKinsey determines this potential to be even higher: 45 GW. Electrolysers integrated with offshore farms will play an important role in the development of hydrogen economy. There are several technical solutions for connecting offshore wind turbines, electrolysers, transport pipelines, storage facilities and other structural components of the installation. As mentioned in Section 5.4, two basic system configurations can be distinguished: the first consists of an offshore wind farm, an offshore electrolyser and an onshore hydrogen storage facility (Fig. 6.1), while in the other system the electrolyser and the hydrogen storage facility are located on land. The first system is called the centralised system and the hydrogen acquisition costs included in the study were calculated for that system. Transmission of energy from offshore windmills converted into hydrogen is a more cost-effective form of long-distance energy transport than transmission of electricity via HVDC or HVAC lines. This type of project has been announced by the German energy group RWE[*].

Figure 6.1. Diagram of an offshore wind turbine integrated with an electrolyser - centralized system



Source: own study.

182 *Vision for the Baltic Sea. Vision for Poland*, Polish Wind Energy Association, 2020.

* The initiative is part of a project called AquaVentus in the North Sea, which will deploy 10 GW of green hydrogen-producing electrolysers which will be powered by offshore wind farms

In this study, LCOH calculations were also performed for a stand-alone electrolyser system driven by a PV photovoltaic power plant (option no. 3), which could be installed in remote locations without grid connection. This mode of operation has the significant disadvantage of reducing the utilization factor of the installed electrolyser capacity, but the advantage is that it allows large systems to be installed in remote locations that have no connection to the power system. The economics of such a solution can be improved by connecting to the grid, which will enable higher use of the electrolyser, especially under conditions of high RES share in the system, where emerging surpluses will cause a decrease in electricity prices on the wholesale market.

6.2 Technical and economic analysis of the green hydrogen production installation

6.2.1 Key assumptions

The cost of producing green hydrogen generally depends on the following factors, which will be described in detail later in this chapter:

- installation type,
- investment costs (CAPEX),
- operating costs (OPEX),
- efficiency,
- installation lifetime,
- capacity factor (CF),
- electricity costs (in case of stand-alone, non-grid-connected installations, this will be the levelized cost of electricity (LCOE) for a given source).

Type of installation

Electrolysers currently available on the market differ in their technical and economic parameters. The most promising types of electrolysers are considered to be:

- Alkaline Electrolyser (ALK).
- Polymer Electrolyte Membrane Electrolyser (PEM).
- Solid Oxide Electrolyser (SOE).

The average capital expenditure (CAPEX) is currently lower for ALK electrolysers than for PEM. However, it is anticipated that PEM electrolysers will soon become cheaper and absolutely unrivalled in the long term compared with ALK electrolysers. SOE electrolysers are both currently and for the foreseeable future the most expensive option. In addition, their disadvantage is the high operating temperature, which has a significantly reduced lifetime. However, high temperature electrolysis is more advantageous when an external heat source is available.

Calculations concerning electrolyser costs assume that the cheapest electrolyser option is selected for the analysed period of time. That is, for the units commissioned at present the technical and economic parameters of the ALK electrolyser were assumed, and for subsequent periods the PEM electrolyser. An important aspect in the process of selecting an electrolyser must be its flexibility. In this element PEM electrolyser performs better than ALK because it can be started in less than a minute. The start-up time for alkaline electrolysers ranges from 20-60 minutes, although some companies claim to be able to significantly reduce the start-up and response time in the 10-100% load change range to as little as a few seconds. This is a very important factor in the context of the role to be played by electrolysers in the future in electric power systems (as a practical way of converting surplus electricity into energy and stabilizing the operation of variable RES sources). Another important factor is the lifetime of electrolysers. In this aspect the best properties are characterized by ALK electrolysers, although for PEM electrolyser Siemens company also declares high operating life (even up to 45 years). Specifications of the discussed electrolyser types are presented in Table 6.1. It should be noted that individual parameters will be subject to changes over time, due to the rapid progress in the technology of production of these devices.

Table 6.1. Technical specification of electrolysers with different technologies

Electrolyser type:	ALK	PEM	SOE
Maturity of technology	Advanced	Demo	R&D
Operating temperature [ºC]	25–100	50–80	700–1000
E.g. to HHV conversion efficiency [%].	60–85	50–70	80–90
Hydrogen production [Nm³/h]	<1000	<400	<10
Service life [years]	20–30	10–45	10–20
Max stack life [h]	50 000–90 000	30 000–50 000	10 000–20 000
Hydrogen purity [%]	99,800	99,999	99,999

Source: own compilation based on PIE[183], STORE&GO[184].

CAPEX investment costs

Table 6.2 presents estimates of current and future CAPEX for the discussed electrolyser types. Fig. 6.2 illustrates the expected trends in the decrease of these costs, which will significantly affect the economics of Power-to-H_2 projects. The costs shown are for units of 5 MW reference capacity. According to these predictions, CAPEX has a high potential to decrease due to the technology learning curve and the scaling of production.

183 Maj M., Szpor A., *Kierunki rozwoju gospodarki wodorowej [Directions of development of hydrogen economy]*

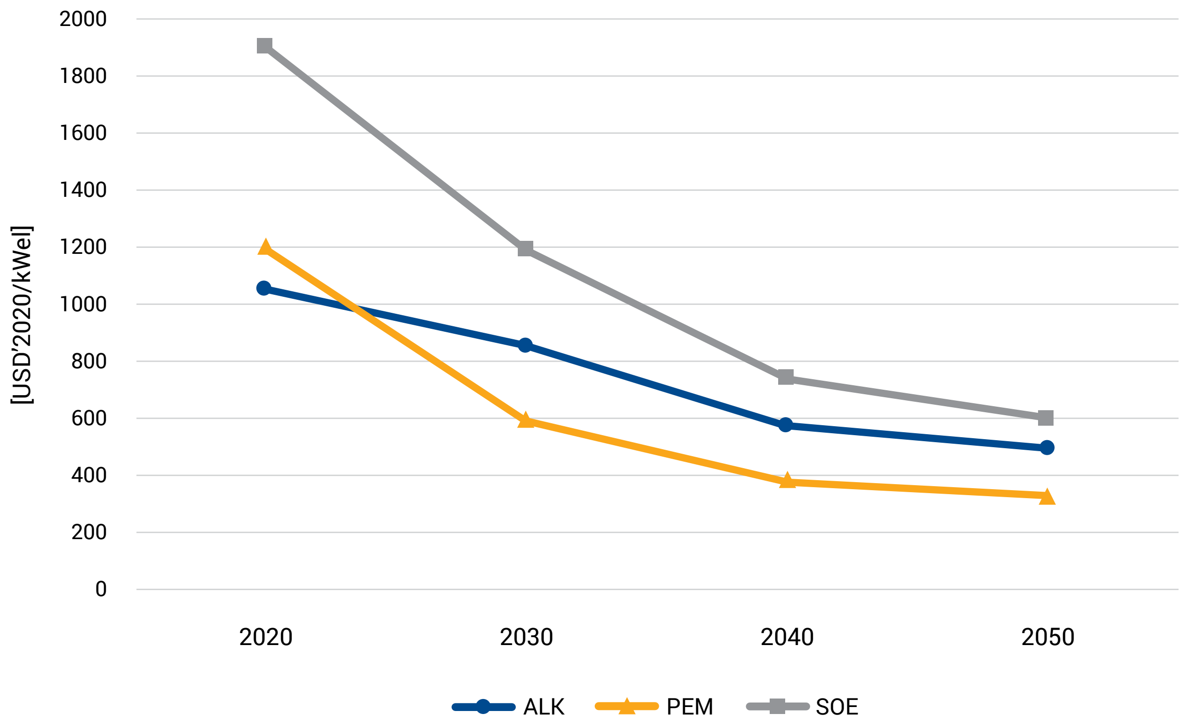
184 A. Zauner, H. Böhm, D. Rosenfeld, R. Tichler, *Innovative large-scale energy storage technologies and Power-to-Gas concepts after optimization*, STORE&GO, February 2019.

Table 6.2. Capital costs of electrolysers (CAPEX) [USD'2020/kW$_{el}$]

Electrolyser type:	ALK	PEM	SOE
2020	1050	1200	1900
2030	850	590	1190
2040	570	380	740
2050	490	320	590

Source: own study based on: A. Christensen[185], STORE&GO[186].

Figure 6.2. Investment cost projections of electrolysers (CAPEX)

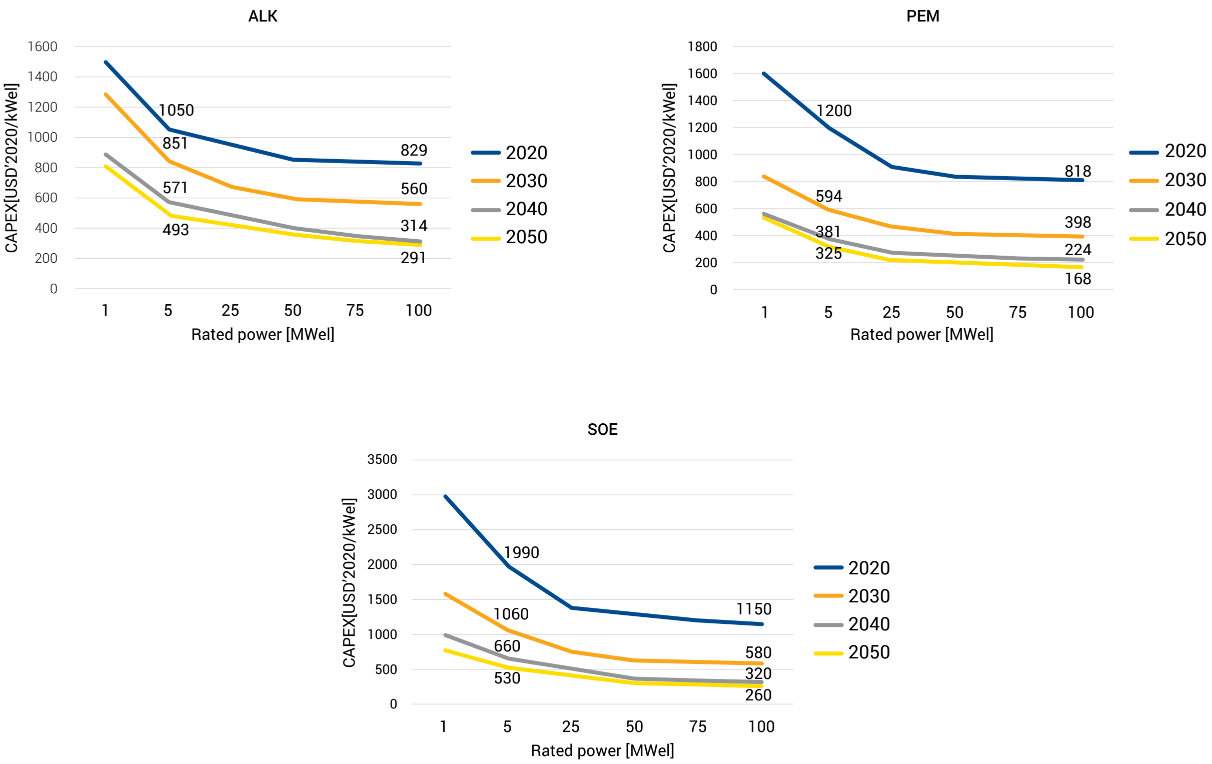


Source: own study based on: A. Christensen, STORE&GO.

A further reduction in investment costs can be achieved by exploiting economies of scale, i.e. by combining single electrolytic cells into large stacks. The possible scope of this reduction is illustrated in Fig. 6.3.

185 A. Christensen, *Assessment of Hydrogen Production Costs from Electrolysis: United States and Europe*, June 2020.
186 A. Zauner, H. Böhm, D. Rosenfeld, R. Tichler, *Innovative large-scale energy...*

Figure 6.3. Impact of economies of scale on investment costs (CAPEX)



Source: own compilation based on STORE&GO.

Operating costs O&M

Operating O&M costs for PEM and ALK electrolysers are quite similar, averaging 2% of CAPEX per year and 5% for SOE. These values are not expected to change significantly in the near future, as indicated, among others, by the data provided by FCH 2 JU[187]. It should be added that these costs are very sensitive to the location and size of the unit. An important component of the variable operating costs of electrolysers is water, which is consumed in the amount of 9 to 11 [l/kgH_2][188]. For the purpose of the presented analysis, the costs of electricity necessary for the operation of the electrolyser and auxiliary equipment have been provided separately.

Efficiency

The efficiency of converting electrical energy to chemical energy of an electrolyser depends on the type of electrolyser. Currently, the efficiency of PEM electrolyser is slightly lower than that of ALK electrolyser. It is between 55-70% (calculated according to HHV), while for the ALK electrolyser, literature

187 *Fuel Cells and Hydrogen 2 Joint Undertaking*, Multi-Annual Work Plan 2014-2020, 2018, https://www.fch.europa.eu/

188 J. Yates, R. Daiyan, R. Patterson, R. Egan, R. Amal, A. Ho-Baille, N. Chang, *"Techno-economic Analysis of Hydrogen Electrolysis from Off-Grid Stand-Alone Photovoltaics Incorporating Uncertainty Analysis,"* Cell Reports Physical Science, Vol. 1, Issue 10, 21.10.2020.

sources quote between 62-85%. With the progress that is being made in PEM technology, it is expected that these differences will decrease in the future. The conversion efficiency directly affects the specific electricity consumption expressed in kWh/kgH_2 and, consequently, the economics of the whole project. The specific energy consumption values adopted in the calculations take into account the energy consumption for compressing the hydrogen produced in the electrolysis process and keeping the unit in hot standby mode. In order to allow a quick response to electrical power consumption, the electrolyser is partially operated in hot standby mode. It is assumed that if no power from a renewable energy source is available, the electrolyser will remain in hot standby mode for at least one hour. After this time, the electrolyser switches to cold standby mode. The additional energy consumption and associated costs are included in the hydrogen production cost calculation by selecting the efficiency values accordingly.

Installation lifetime

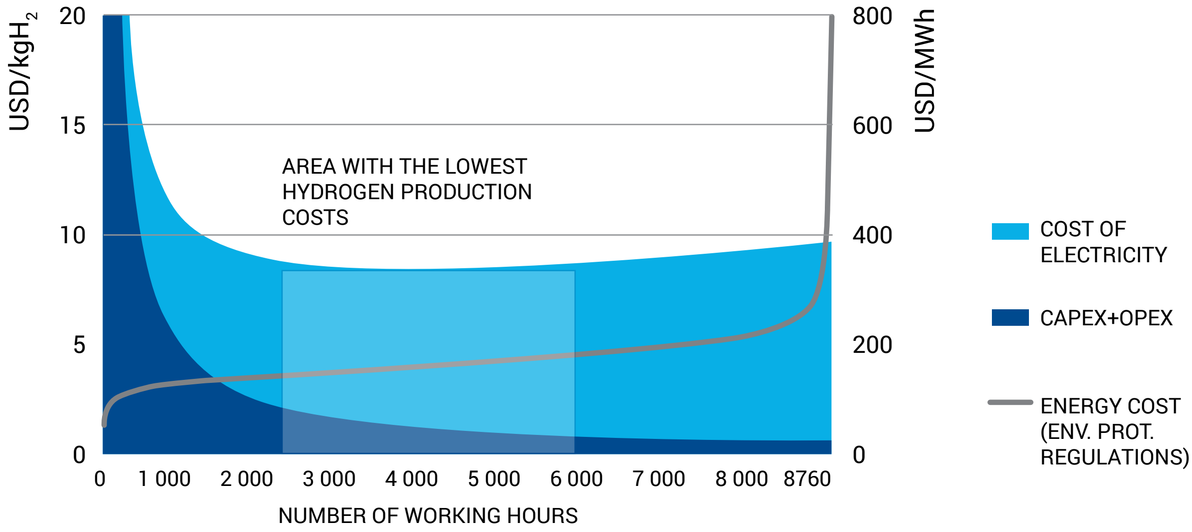
The life of the electrolyser stack is calculated by considering the maximum operating time of 40,000 h, 60,000 h and 140,000 h on average in 2020, 2030 and 2050, respectively, divided by the operating time. However, the lifetime of the electrolyser stack is limited by the maximum lifetime of the entire electrolyser system of 15, 20 and 30 years in 2020, 2030 and 2050, respectively. All the parameters given above vary depending on the type of electrolyser. The impact of the number of start/stop cycles on the life of the electrolyser stack cannot be considered because there is no reliable data on the maximum number of cycles that can be performed by the electrolyser stack during its life. In general, the impact of transient operation that occurs as a result of coupling to a wind farm or photovoltaic power plant on the lifetime of electrolyser stacks and systems is not sufficiently studied[189].

Installed capacity utilisation rates

The capacity utilization rate is directly related to the number of operating hours of the equipment. This indicator depends on the way the electrolyser is powered. If the electrolyser is fed from the grid, the value can range from 0 to 1. However, analyses by the International Energy Agency indicate that the most desirable value for the economics of electrolyser operation is between 0.3 and 0.7 (Fig. 6.4). These values are indicative and can vary depending on market conditions.

189 A. Zauner, H. Böhm, D. Rosenfeld, R. Tichler, *Innovative large-scale energy ...*

Figure 6.4. Influence of the number of hours of electrolyser operation on the cost of hydrogen production



Source: IEA - "The Future of Hydrogen. Technical Report," Paris, 2019, https://www.iea.org/reports/the-future-of-hydrogen.

For stand-alone units integrated with wind or PV power plants, the capacity factor is closely related to the source of electricity production. For onshore wind turbines, the capacity factor in Polish conditions will range from 0.25 to 0.35, for offshore wind turbines the range will be 0.35-0.55, and for photovoltaic turbines the range be will 0.1-0.25. Improvement of the economics of electrolysers integrated with sources characterized by low values of the capacity factor can be achieved by connecting them to the power grid and taking advantage of additional periods with low market prices when the RES source does not produce energy. Another solution is to connect an electrolyser to multiple RES sources with different profiles.

Electricity costs

The cost of electricity, in addition to investment costs, is one of the main components affecting the total cost of green hydrogen generation. For systems integrated with RES, it is closely related to the cost of generation from these sources. The LCOE for wind and photovoltaic power plants is expected to decrease significantly in the future, which will improve the economics of green hydrogen production systems. The decline in capital costs of wind and solar power plants is expected to continue (thanks to the increased efficiency of generating equipment and falling installation prices in line with the learning curve). Table 6.3 presents the McKinsey cost development forecasts for wind and solar-based power plants. Other assumptions used to calculate the LCOE for the RES technologies under consideration, adopted in the production cost calculation for Polish conditions, are also provided.

Table 6.3. Costs of basic RES technologies and key assumptions for LCOE calculations

Technology:	Parameter:	2020	2030	2040	2050
Onshore wind farm	CAPEX USD [thousand/MW_{net}].	1350	1200	1100	1000
	OPEX [USD/MW-yr].	28	25	22	20
	Life time [years]	25			
	Installed capacity utilisation rate	0,30	0,35	0,37	0,40
Offshore wind farm	CAPEX USD [thousand/MW_{net}].	2800	2000	1700	1600
	OPEX [USD/MW-yr].	82	78	72	67
	Life time [years]	25			
	Installed power factor	0,45	0,50	0,53	0,55
PV photovoltaic power plant	CAPEX USD [thousand/MW_{net}].	900	600	300	250
	OPEX [USD/MW-yr].	8,3	7,7	6,7	5,7
	Life time [years]	25			
	Installed power factor	0,12	0,14	0,16	0,18

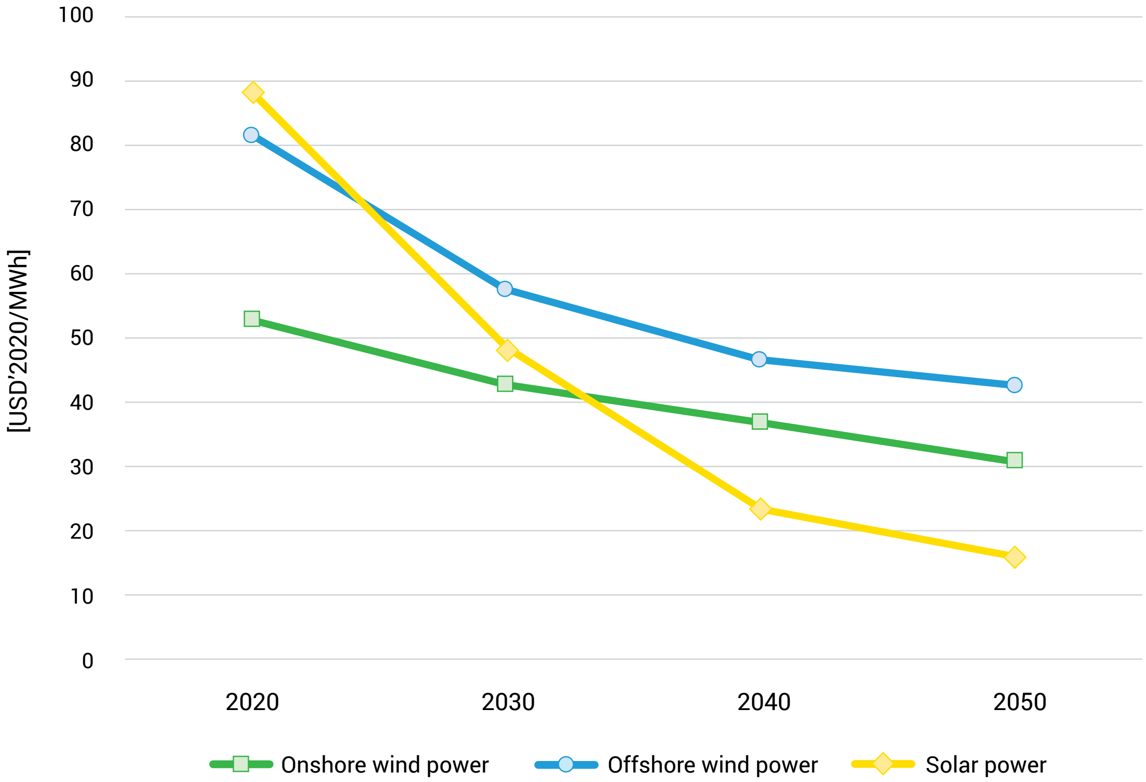
Source: own study based on McKinsey[190], IRENA[191].

The results of LCOE calculations based on the above assumptions indicate a significant decrease in electricity generation costs in key RES technologies (Fig. 6.5). This is possible due to the potential for technological development and improved generation efficiency. A decrease in electricity generation costs in the sources with which electrolysers can be integrated is one of the prerequisites for improving the economics of green hydrogen production and achieving the assumed market competitiveness. The calculations were carried out with the discount rate, which in the LCOE method equals the average real cost of capital, of 7%.

190 *Carbon neutral Poland 2050. How to turn a challenge into an opportunity*, McKinsey & Company 2020.

191 *Future of Wind. Deployment, investment, technology, grid integration, and socio-economic aspects*, International Renewable Energy Agency, October 2019.

Figure 6.5. LCOE for key RES technologies



Source: own study based on assumptions in[192].

Summary of assumptions used in the LCOH model

Table 6.4 summarizes the assumptions made in the LCOH model that were used to determine the hydrogen production costs for the three technology options considered. SOE electrolysers were not considered in the analysis because they represent the least mature of the electrolysis hydrogen generation technologies. To the total costs, the costs associated with replacing the stack after reaching the limiting number of operating hours were added at 35-45% of CAPEX[193]. The costs associated with transporting the hydrogen to land were also added to the CAPEX of the electrolysers integrated with the offshore wind turbine. Calculations were performed using a discount rate of 7%.

192 Yates J., Daiyan R., Patterson R., Egan R., Amal R., Ho-Baille A., Chang N., *Techno-economic Analysis of Hydrogen Electrolysis from Off-Grid Stand-Alone Photovoltaics Incorporating Uncertainty Analysis*, "Cell Reports Physical Science", Volume 1, Issue 10, p. 10, 21.10.2020.

193 Yates J., Daiyan R., Patterson R., Egan R., Amal R., Ho-Baille A., Chang N., *Techno-economic Analysis of Hydrogen Electrolysis from Off-Grid Stand-Alone Photovoltaics Incorporating Uncertainty Analysis*, "Cell Reports Physical Science", Volume 1, Issue 10, p. 10, 21.10.2020.

Table 6.4. Assumptions for the LCOH model

Electrolyser:	Parameter:	Unit:	2020	2030	2040	2050
ALK	Net power	[MW]	10			
	CAPEX	USD [thousand/MW].	1050	850	570	490
	OPEX calculated as %CAPEX	[%]	2			
	Electricity consumption	[kWh/kgH_2]	56	54	51	49
	Maximum number of working hours	[h]	75 000	90 000	110 000	125 000
	Lifetime	[years]	20			
	Stack replacement cost as % CAPEX	[%]	35			
PEM	Net power	[MW]	10			
	CAPEX	USD [thousand/MW]	1200	590	380	320
	OPEX as % CAPEX	[%]	40			
	Electricity consumption	[kWh/kgH_2]	66	62	57	53
	Maximum number of working hours	[h]	60 000	82 000	105 000	125 000
	Lifetime	[years]	20			
	Stack replacement cost as % CAPEX	[%]	40			

Source: own study based on: A. Christensen, STORE&GO.

As regards the cost of electricity necessary to power the electrolyser, it was assumed that for systems integrated with RES installations, the unit cost is equal to the LCOE of these sources (according to the calculation results presented in Fig. 6.5. For the option of the electrolyser connected to the distribution grid, the LCOH was calculated for three different price levels of 56, 73 and 90 USD/MWh. The CAPEX values given in Table 6.4 refer to both the costs of the electrolyser stack and auxiliary equipment.

6.2.2 Methodology

For the purposes of this study, the Levelized Cost of Hydrogen (LCOH) methodology was applied, which is analogous to the Levelized Cost of Electricity (LCOE) used in comparisons of costs of electricity generation technologies. This is the most frequently used index for comparing the costs of energy generation from various sources, which is used, inter alia, in the analysis of costs in OECD countries prepared periodically every 5 years for the IEA/NEA[194].

LCOH is the averaged unit cost of hydrogen, discounted for the first year of operation of the installation. By definition, it corresponds to the zero net present value (NPV) of assets, i.e. a situation in which an investment generates discounted revenues equal to the discounted costs. It is calculated according to the following formula:

194 *Projected Cost of Electricity Generating*, International Energy Agency.

$$LCOH = \frac{\sum_{t=1}^{n} \frac{CAPEX_t + (O\&M)_t + E_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{H_t}{(1+r)^t}}$$

Where:
$CAPEX_t$ – capital expenditures in year *t*,
$(O\&M)_t$ – fixed and variable maintenance and operating costs in year *t*,
E_t – electricity costs in year *t*,
H_t – the amount of hydrogen produced in year *t*,
r – average real discount rate.

Unlike financial analysis, this method makes more simplifying assumptions and uses more average values for the economic and technical parameters of the technologies considered. LCOH also excludes hydrogen transport and storage costs, as well as taxes. These simplifications mean that the cost estimates are more generalised, but the inputs and outputs can be used for detailed, case-specific analyses if required.

6.2.3 Results

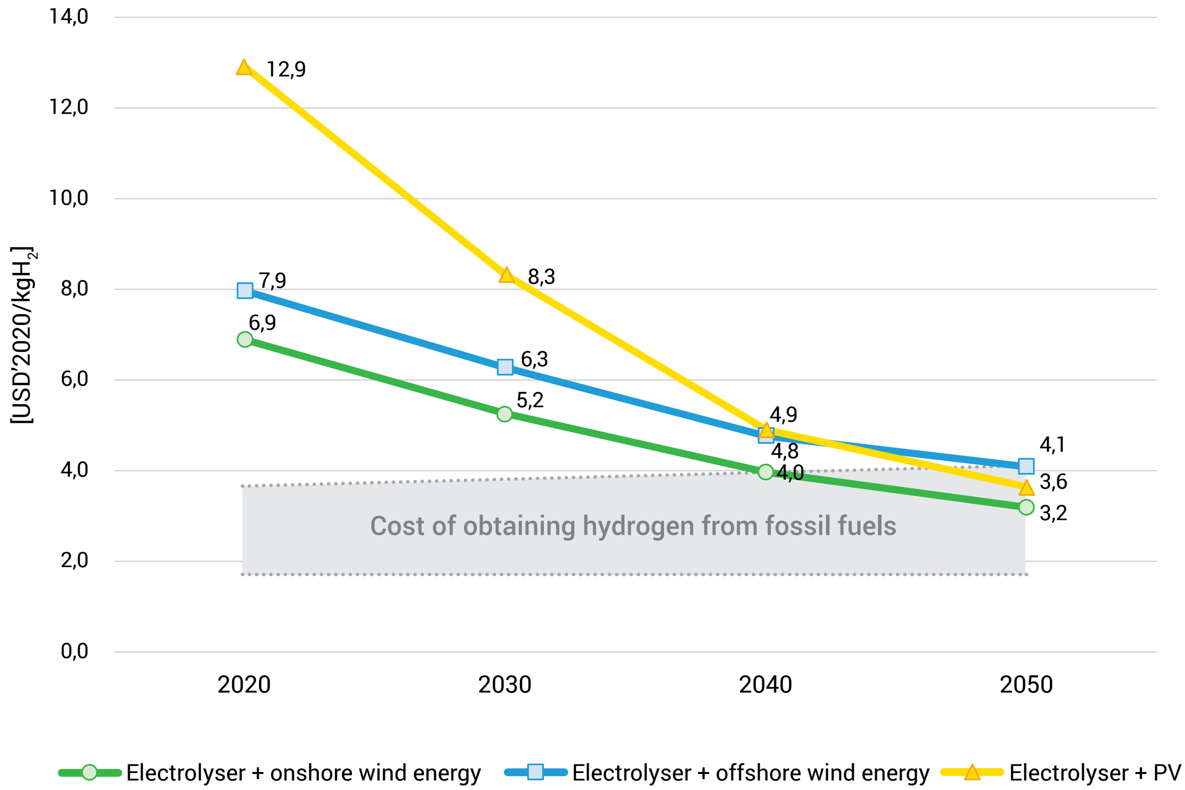
Fig. 6.6 and Fig. 6.7 show the results of modelling the cost of green hydrogen production for the three technology options considered in the analysis: electrolyser integrated with onshore wind farm, offshore wind farm and solar power plant.

For comparison purposes, the results of calculations for the electrolyser connected to the distribution network in three variants of electricity prices (low, middle and high) were also compared. Electricity prices assumed in the analysis include distribution charge rates.

According to the results obtained, the cheapest option for obtaining green hydrogen is an electrolyser integrated with an onshore wind farm. Currently, the cost of hydrogen production in this option is about 7 USD/kgH_2, while in the future it is possible to decrease it to about 3 USD/kgH_2. A slightly more expensive option is an electrolyser integrated with an offshore wind farm with costs in 2020 and 2050 of 8 USD/kgH_2 and 4 USD/kgH_2, respectively. The most expensive option at present, but with the greatest potential for decline, is option 3, an electrolyser integrated with a photovoltaic power plant. It is expected that the cost of obtaining hydrogen based on this technical solution will fall in the perspective of 2050 to about 3.5 USD/kgH_2.

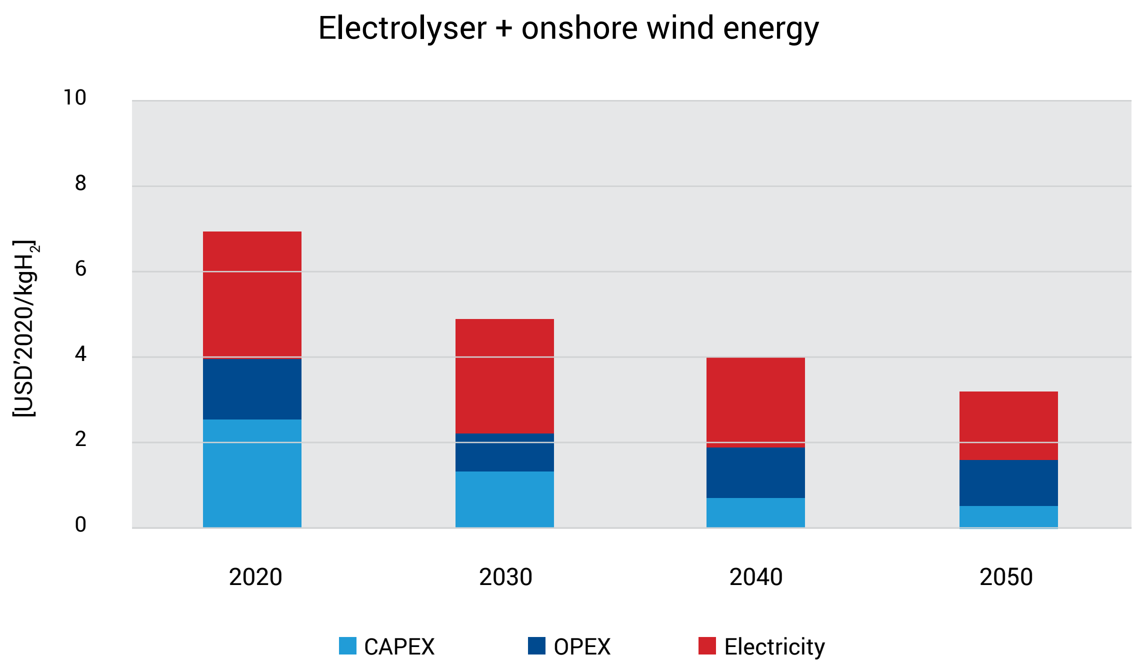
The results obtained for these sources are slightly less optimistic than those presented by various research centres in Europe and worldwide because of the lower values of the installed capacity indices of individual RES technologies that may be attained under Polish conditions. This particularly applies to photovoltaics because of worse insolation conditions compared to e.g. the southern European countries. The results of the analysis also indicate that technologies for obtaining green hydrogen in the future may become competitive compared to conventional methods of obtaining it from fossil fuels. The cost of producing hydrogen from fossil fuels is likely to increase in the future, due to the rising cost of purchasing CO_2 emission allowances. It should also be remembered that the results given in the analysis concern stand-alone systems, i.e. electrolyser + dedicated RES installation. Connecting them to the distribution grid will improve the utilization of electrolysers and, consequently, the overall economics of these projects.

Figure 6.6. Results of the economic analysis of hydrogen production from RES



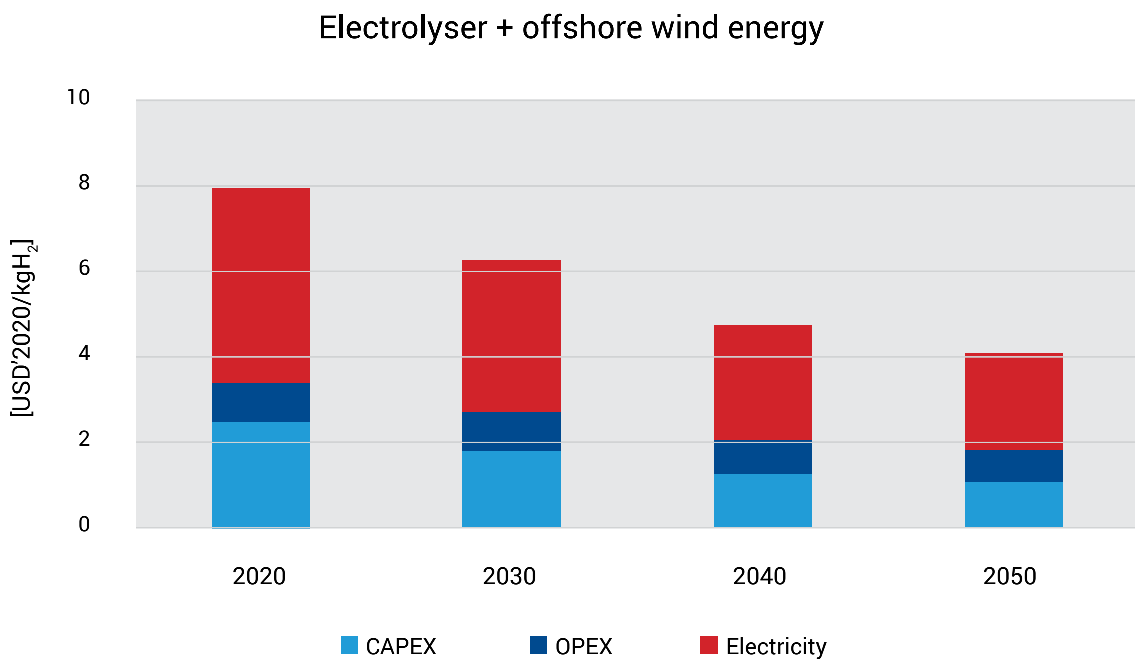
Source: own study.

Figure 6.7. Results of the economic analysis of hydrogen production from RES by kind (electrolyser + onshore wind power plant)



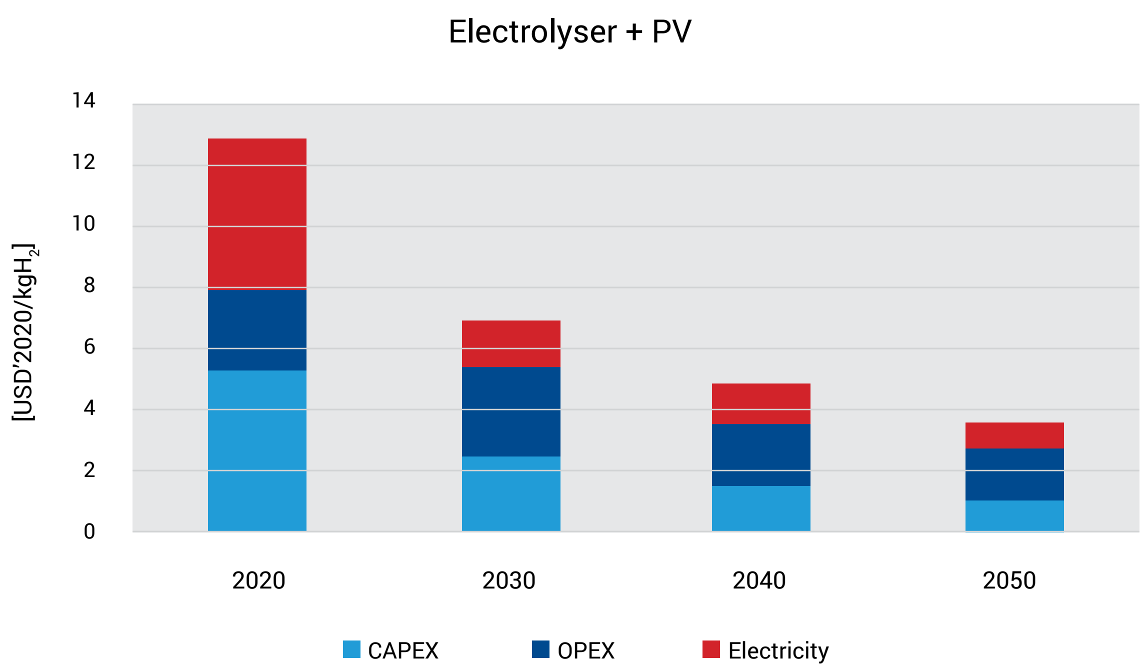
Source: own study.

Figure 6.8. Results of the economic analysis of hydrogen production from RES by kind (electrolyser + offshore wind turbine)



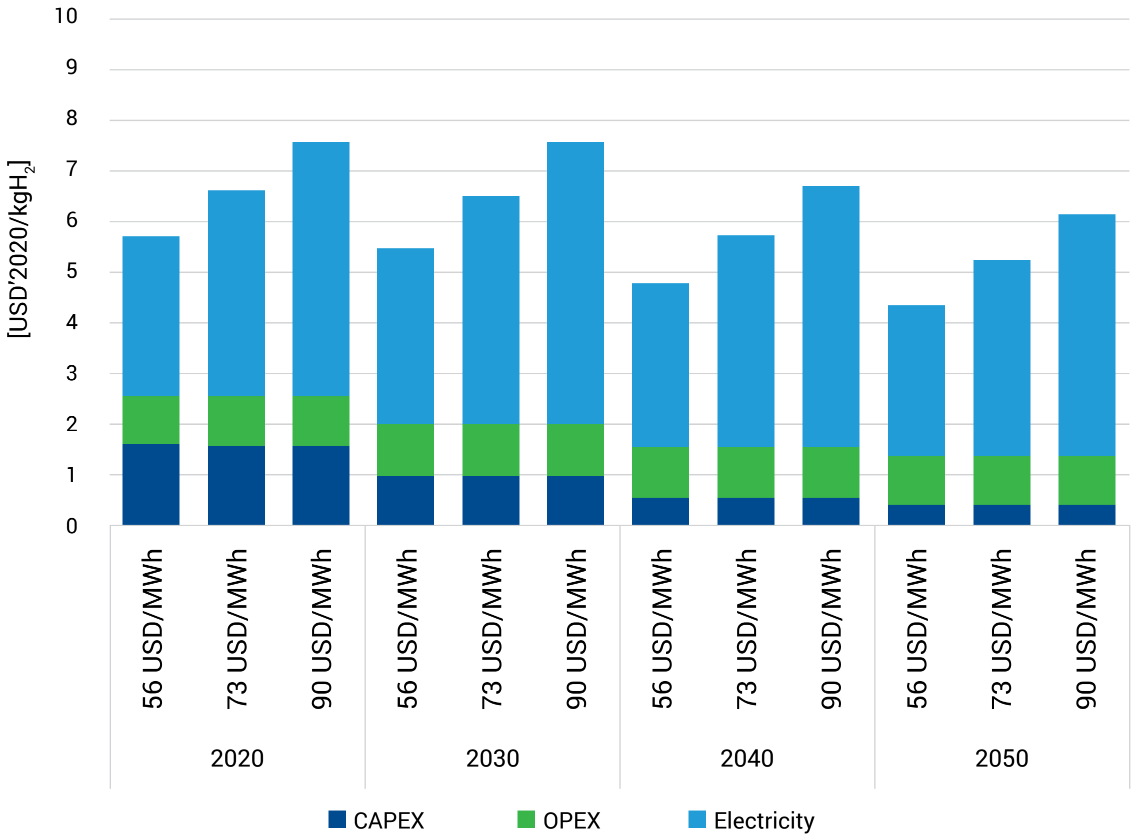
Source: own study.

Figure 6.9. Results of the economic analysis of hydrogen production from RES by kind (electrolyser + PV photovoltaic power plant)



Source: own study.

Figure 6.10. Costs of hydrogen production from a grid-connected electrolyser in three variants



Source: own study.

6.2.4 Determinants of achieving business profitability

The basic condition for achieving market competitiveness of green hydrogen is a significant reduction of unit production costs. For this purpose, the following two prerequisites must be met:

- the cost of electrolysers must be significantly reduced;
- the cost of electricity needed to power the electrolysers must also be significantly reduced.

The first condition can only be met if demand forces economies of scale. For the resulting potential to grow to cost-reducing levels, strong political support is needed in the early stages of development (including the creation of a stable regulatory environment in the first place). Demand for clean hydrogen needs to be generated, particularly in sectors where decarbonisation through electrification is technically difficult (power generation, transport, industry, district heating). Secondly, appropriate market support mechanisms for the hydrogen economy should be developed, e.g. contracts for difference, FIT (Feed-In Tariff), FIP (Feed-In Premium). In financing it is necessary to take into account not only capital costs but also operating costs, including the costs of transport, compression, storage and distribution of hydrogen. In some cases, the costs of technologies using hydrogen as a fuel should also be taken into account. The introduction of support mechanisms can be based, for example, on the difference between the price of grey hydrogen and green hydrogen[195]. A review and analysis of market support instruments

195 *Hydrogen economy in Poland*, Polish Economic Institute, *Policy Paper* 2020/5, p. 35.

abroad should facilitate the selection of the optimum solution. Subsidising hydrogen technologies will create appropriate incentives for companies in the sector and research centres to intensify their work on technology development, in exactly the same way as it was done in the case of RES technologies (these solutions resulted in a spectacular fall in costs in a relatively short time).

The second condition is the decrease in electricity costs from RES. This is possible due to the technical progress that is being made in these technologies. The greater the scale of RES technology application, the greater the decrease will be. Increasing the share of RES in the energy production structure (especially wind farms and photovoltaic power plants) is a key aspect in the context of developing the hydrogen economy. The greater the availability of cheap energy from RES, the lower the cost of obtaining green hydrogen will be. Large amounts of energy from RES will make it possible to generate surpluses, which will simultaneously influence the reduction of electricity prices on the wholesale market in periods of their occurrence.

Until the conditions described above are met, the development of hydrogen production technologies will have to be stimulated by subsidies in various forms, either at the investment stage or through support mechanisms at the operational level. For example, for technologies producing electricity from green hydrogen in the cheapest option, at current production costs and wholesale prices, the estimated financing gap is 800-900 PLN/MWh.

6.3 Description of available and planned resources for the development of green hydrogen projects

Bearing in mind, therefore, that green hydrogen production technologies are not yet commercially viable, it is necessary to support the development of these technologies. At present, however, there are not many support programmes dedicated to the development of this type of technology. However, taking into account that it is an emission-free source of electricity and heat and can serve as a fuel for transport, hydrogen technologies are eligible for support under programmes for renewable energy sources and the so-called clean transport. Taking into account the above, there are several support programs available and planned, both financial and substantive, for the development of the hydrogen economy in the EU. These include:[196]

- European Clean Hydrogen Alliance;
- Important Projects of Common European Interest (IPCEI);
- InvestEU;
- Clean Hydrogen for the Next Generation EU;

196 *Hydrogen in the EU's Economic Recovery Plans*, https://www.hydrogeneurope.eu/wp-content/uploads/2021/07/Hydrogen-Europe_EU-Recovery-Plan-Analysis_FINAL.pdf; Communication From The Commission To The European Parliament, The Council, The European Economic And Social Committee And The Committee Of The Regions. A hydrogen strategy for a climate-neutral Europe, Brussels, 8.7.2020 COM(2020) 301 final, p. 8-9, https://ec.europa.eu/energy/sites/ener/files/hydrogen_strategy.pdf; Communication From The Commission To The European Parliament, The Council, The European Economic And Social Committee And The Committee Of The Regions. A hydrogen strategy for a climate-neutral Europe, Brussels, 8.7.2020 COM(2020) 301 final, p. 8-9, https://ec.europa.eu/energy/sites/ener/files/hydrogen_strategy.pdf; *IPCEI on Hydrogen*, https://www.hydrogen4climateaction.eu/ipcei-on-hydrogen; *InvestEU*, https://ec.europa.eu/growth/industry/hydrogen/funding-guide/investeu_en; *Clean Hydrogen for the Next Generation EU*, https://www.fch.europa.eu/news/clean-hydrogen-next-generation-eu; *Innovation Fund*, https://ec.europa.eu/growth/industry/hydrogen/funding-guide/innovation-fund_en; Connecting Europe Facility - Energy, https://ec.europa.eu/growth/industry/hydrogen/funding-guide/connecting-europe-facility-energy_en; *European Regional Development Fund, Cohesion Fund and REACT-EU*, https://ec.europa.eu/growth/industry/hydrogen/funding-guide/european-regional-development-cohesion-fund-react-eu_en; *The Recovery and Resilience Facility*, https://ec.europa.eu/info/business-economy-euro/recovery-coronavirus/recovery-and-resilience-facility_en; LIFE, https://ec.europa.eu/gr.

- Horizon Europe;
- National Recovery Plans under the Recovery and Resilience Facility;
- Innovation Fund;
- Just Transition Fund;
- European Regional Development Fund, Cohesion Fund and REACT-EU;
- Connecting Europe Facility Energy;
- LIFE.

To a high extent, the funding mechanisms identified above are in the process of being established and the manner and extent to which funding can be allocated in the context of hydrogen is yet to be defined.

In the case of Poland, financing of hydrogen tasks was included in the draft Polish Hydrogen Strategy until 2030 with a perspective until 2040.

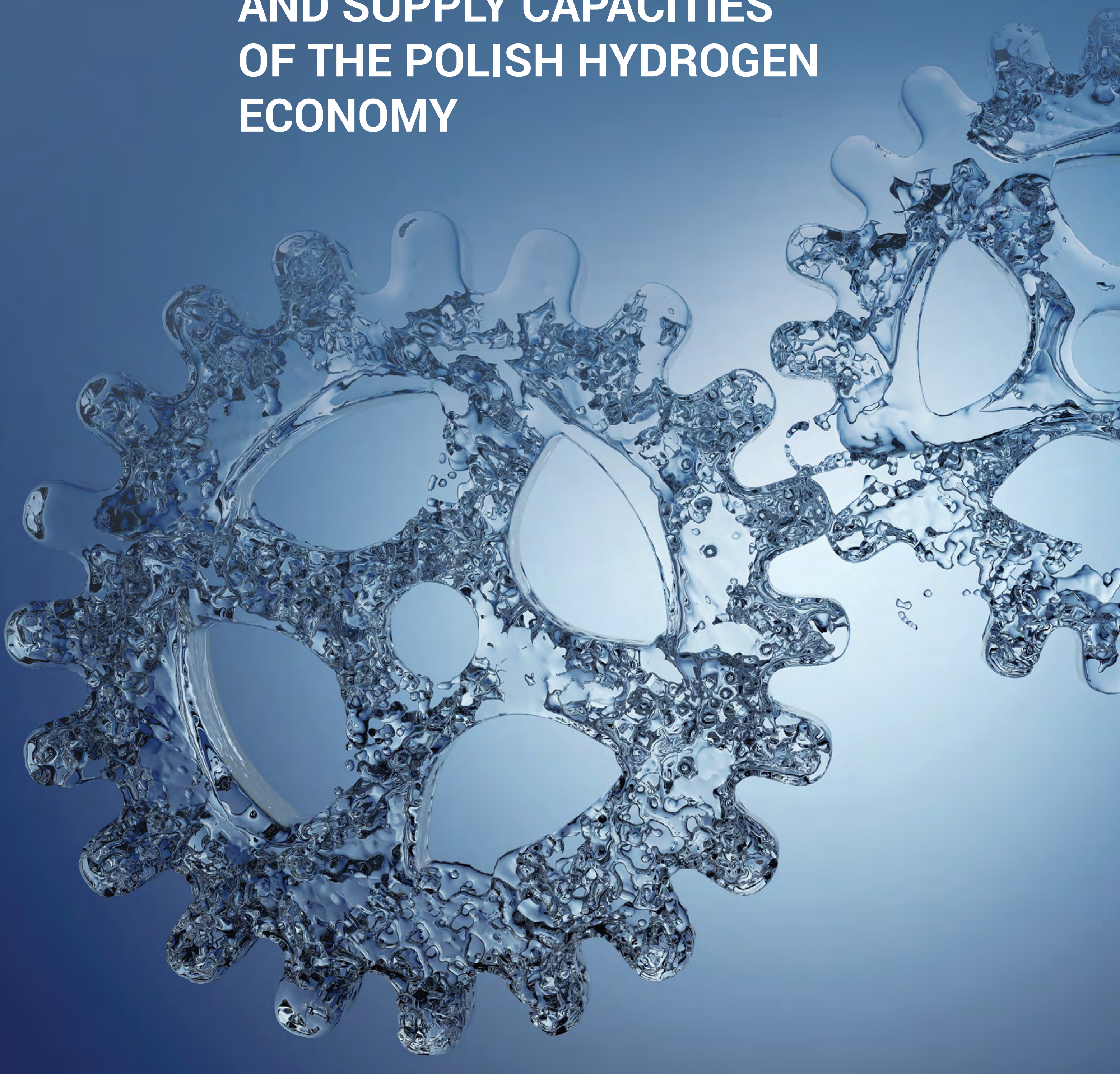
Table 6.5. National financial support programmes for green hydrogen envisaged in the draft NHP

No.	Programme	Purpose of support	Estimated fund value in billion PLN
1	Operational Programme Smart Growth + and national funds	Research in hydrogen management.	1.0
2	"New Energy" National Fund for Environmental Protection and Water Management (NFEP&WM)	Implementing technology for the production, transport, storage and use of zero-emission hydrogen.	0.6
3	"Green public transport" (Phase I)	Reducing the use of emission fuels in public collective transport. Addressed to public transport operators and organizers.	0.32
4	"Hydrogenization of the Economy" NFEP&WM	Implementation of innovative projects related to hydrogen technologies.	n.a.
5	Support for electric vehicle charging infrastructure and hydrogen refuelling infrastructure" NFEP&WM	Development of electric vehicle charging and hydrogen refuelling infrastructure	0.1
		Total:	**PLN 2.02 billion**

Source: Draft PHS, p. 29.

07

FINAL FORECAST OF DEMAND AND SUPPLY CAPACITIES OF THE POLISH HYDROGEN ECONOMY



7.1 Analysis of the projected demand for green hydrogen

Interest in hydrogen as a zero-emission energy source, which also has one of the highest energy densities per unit of mass, has been growing for a long time - between the mid-1970s and today the use of hydrogen has more than quadrupled[197]. Today's interest in this material is further justified by the search for applications for surplus electricity produced by renewable energy installations - primarily wind farms and photovoltaic installations. According to the BP report, hydrogen is expected to grow in importance after 2035, as falling costs of generation technologies combined with rising coal prices will allow hydrogen to increasingly compete with hitherto dominant fuels. As a result, it is estimated that by 2050 hydrogen will account for around 7-16% of total final energy consumption. In specific sectors, this will be about 10-18% in industry and about 7-10% in transport (especially long-distance trucking and aviation). Most hydrogen production by 2050 is to be a combination of green and blue hydrogen[198]. This means that even faster growth in wind and photovoltaic capacity will be required.

Today's use of hydrogen is dominated by industrial applications. The four most important applications of hydrogen (in both pure and mixed forms) in the world are those indicated in 2.4: oil refining (33%), ammonia production (27%), methanol production (11%) and steel production by direct reduction of iron ore (3%)[199]. In the future, chemical, iron and steel production will offer a significant potential for large-scale demand for low-carbon hydrogen. A single plant could provide the baseload demand for electrolyser plants and their capacities, enabling an overall increase in production for wider hydrogen economy[200]. Over 60% of the hydrogen currently used in refineries is produced using natural gas. It is generally believed that current global refining capacity is sufficient to meet the growing demand for crude oil, meaning that the majority of future hydrogen demand is likely to come from existing plants already equipped with hydrogen production units[201]. Demand for ammonia and methanol is expected to increase in the short to medium term, with new capacity providing an important opportunity to scale up low-carbon hydrogen production pathways. Increased efficiency may reduce overall demand levels, but this will only partially offset demand growth. In the longer term, steel production and high-temperature heat generation offer huge potential for hydrogen demand growth. Industrial heat is currently used in a variety of chemical processes: from melting to drying, and the use of hydrogen offers an opportunity to decarbonise this sector[202]. Assuming that the technological challenges that currently inhibit the uptake of hydrogen in these areas can be overcome, the key challenges will be to reduce costs and increase economies of scale. In the long term, it should be technically feasible to produce all steel using hydrogen, but this would require large amounts of low-carbon electricity: about 2500 TWh/year, or about 10% of today's global electricity production. Moreover, it would only be viable at very low electricity prices[203].

Beyond industry, hydrogen is promising in the long-term perspective in the transport, construction, and energy sectors. The competitiveness of hydrogen vehicles depends on the cost of fuel cells and the

197 *Global demand for pure hydrogen*, 1975-2018, IEA, https://www.iea.org/data-and-statistics/charts/global-demand-for-pure-hydrogen-1975-2018

198 *BP Energy Outlook 2020 edition*, pp. 102-103.

199 *The Future of Hydrogen. Seizing today's opportunities...*, p. 37.

200 A. Spyroudi, D. Wallace, G. Smart et al, *Offshore Wind and Hydrogen. Solving the Integration Challenge*, 2020, p. 38, https://ore.catapult.org.uk/wp-content/uploads/2020/09/Solving-the-Integration-Challenge-ORE-Catapultr.pdf

201 *The Future of Hydrogen. Seizing today's opportunities...*

202 A. Spyroudi, D. Wallace, G. Smart et al, *Offshore Wind ...*

203 *The Future of Hydrogen. Seizing today's opportunities...*

construction and use of refuelling stations. Reducing the cost of fuel cells and on-board hydrogen tanks is therefore a priority. This could make these vehicles competitive with electric cars and make them potentially attractive to consumers who prioritize long range. At the same time, for users of PCEVs, the priority is to reduce the price of delivered hydrogen[204]. It is estimated that the size of the PCEV market could be around 30,000 vehicles per year by 2030 and could grow to 500,000 vehicles per year by 2050[205]. In shipping and aviation, on the other hand, the availability of low carbon fuel solutions is limited, so hydrogen is an attractive option here. Ammonia and hydrogen have the potential to contribute to meeting environmental targets in shipping, but their production cost is high compared to petroleum-based fuels. Hydrogen-based liquid fuels are also a potentially attractive option for aviation, but again at the cost of higher energy consumption.

In the building industry, the greatest opportunities for hydrogen use in the near future lie with its blending with natural gas. It is estimated that hydrogen consumption for building heating could be up to 4 Mt (134 TWh) globally in 2030. This potential is greatest for multi-family and commercial buildings, especially in dense urban areas where conversion to heat pumps is more difficult than in suburban areas. Long-term prospects for heating could include the direct use of hydrogen in hydrogen boilers or fuel cells. However, both are dependent on the modernisation of infrastructure and the availability of public security measures.

Power generation also offers many opportunities for hydrogen and hydrogen-based fuels. In the near term, ammonia could be co-fired in coal-fired power plants to reduce CO_2 emissions. Hydrogen and ammonia can be flexible power generation options when used in gas turbines or fuel cells. With low power factors typical of flexible power plants, hydrogen costing less than 2.5 USD/kg offers great potential to compete in the fuel market[206]. The main low carbon competitors for such services are natural gas from CCUS and biogas. In the long run, hydrogen can play a role in large-scale and long-term storage to offset seasonal fluctuations.

7.2 Hydrogen demand forecast for 2030-2040, with a 2050 outlook

The considerations and information presented in this report indicate that the development of a hydrogen economy, despite the barriers defined and discussed above, is a natural consequence of the decarbonization process, and the widespread use of hydrogen and biomethane is the only (apart from nuclear energy) alternative for a fossil fuel free Poland.

When assessing the domestic demand for hydrogen in the perspective of 2030-2040 and further to 2050, it should be borne in mind that its current high consumption in the chemical industry, 33 TWh, is based, as widely discussed in this report, on steam reforming technology. Thus, projections for future years should take into account not only the use of hydrogen in new areas (electricity, heating, transport), but also the transition to low- or zero-emission technologies for producing this gas for industrial purposes.

The literature related to hydrogen demand forecasts along with the assessment of production capacity is relatively rich, especially for Europe as a whole and with respect to 2050, treated as the year

204 *Ibid.*

205 A. Spyroudi, D. Wallace, G. Smart et al, *Offshore Wind ...*

206 *The Future of Hydrogen. Seizing today's opportunities...*

of full decarbonisation[207, 208, 209, 210, 211, 212, 213]. In relation to Poland, the most comprehensive look is provided by the Energy Forum publication[210]. using analyses[207] and [213]. However, the problem is that the authors of these studies focus on 2050 (while ignoring the situation in 2040 and treating 2030 as a starting point with almost zero green hydrogen supply possibilities). Meanwhile, the year 2040 is the reference point for the forecasts and analyses covered by the government document PEP2040 and will mark the beginning of the period of final entry into the zero-carbon economy, after the decade-long offshore wind development, as well as the first stage of nuclear power construction, with conventional coal and natural gas units still in use. Therefore, it is very important from a forecasting point of view. Table 7.1 shows the path of domestic hydrogen demand in 2030, 2040 and 2050, developed on the basis of, including the author's assessment of the dynamics of development of individual areas of the hydrogen economy.

Table 7.1. Hydrogen demand forecast for Poland (in TWh) including all economy sectors

	2021	2030	2040	2050	Notes
Industry	33	33	30	28	The reduction in demand from 33 TWh to 28 TWh will be accompanied by a shift to green or, to a limited extent, blue hydrogen.
Transport	0	2	23	33	FE forecasts are very high demand (36 TWh) for jet fuel production, these have been reduced to 18 TWh given current production levels.
Heating	0	2	12	15	Various forms of obtaining thermal energy from hydrogen.
Electricity	0	3	24	36	Balancing SEE needs requires efficient use of surplus RES converted to hydrogen.
Total	33	46 (7)	89 (59)	112 (84)	Quantitative increase in demand with qualitative change in hydrogen production technology for the chemical industry; in parentheses demand is given without taking into account industry needs.

207 Kielichowska I., Staschus K., Leun Kees van der, et al. *Polska neutralna klimatycznie 2050. Elektryfikacja i integracja sektorów [Climate neutral Poland 2050. Electrification and sector integration]*, ed. by K. Błachnio, Energy Forum, p.54, 2020.

208 *Opportunities for Hydrogen Energy Technologies Considering the National Energy & Climate Plans*, Trinomics and LBST, p. 24, 2020.

209 Pyrka M., Jeszke R., Boratyński J., et al. *Polska Net-Zero 2050. Mapa Drogowa Osiągnięcia Wspólnotowych Celów Polityki Klimatycznej dla Polski do 2050 r. [Poland Net-Zero 2050. Road Map for Achieving Community Climate Policy Goals for Poland by 2050*. IOŚ-PIB, p. 113, Warsaw 2021.

210 Adamczewski T., Jędra M., *Green Gases. Biomethane and hydrogen in Poland*, edited by J. Zaleska, Energy Forum, 2021.

211 Peters D.,, Leun K., Terlouw W., *Gas Decarbonisation Pathways 2020-2050: Gas for Climate*, Guidehouse, p. 126, Utrecht 2020.

212 *Hydrogen Roadmap Europe. A Sustainable Pathway For The European Energy Transition*. Fuel Cells And Hydrogen Joint Undertaking, Bietlot, p.79, Belgium 2019.

213 Terlouw W., Peters D., Tilburg J., et al. Gas for Climate. *The optimal role for gas in a net-zero emissions energy system*, NAVIGANT, p. 223, Utrecht 2019.

It is obvious that the presented demand for hydrogen by industry (mainly chemical) will undergo a gradual conversion from grey hydrogen to green and blue hydrogen. Companies managing hydrogen-using plants are already interested in electrolysis plants, CO_2 capture plants, and interest in low-power nuclear SMRs is also moving in the direction of using them to produce hydrogen and abandoning the use of natural gas. There is also a trend to build our own RES sources designed to cooperate with electrolysers. It can be concluded that this process will occur naturally and that it will be stimulated primarily by economic and business calculations, in which the results of the considerations shown in Chapter 6 will undoubtedly play a role. State policy supporting these undoubtedly beneficial (from the point of view of the decarbonisation process and climate protection) processes comes down to the creation of an appropriate regulatory environment, discussed in Chapter 11. A much greater challenge is to create a hydrogen economy (both on the demand and supply side) in those areas where it does not currently exist. In terms of the demand side presented above, the report presented here has adopted the results of the work of institutions that appear to have thoroughly assessed the expected trends in hydrogen demand, assessing the growth in demand as real and significant. As far as the supply possibilities are concerned, the results of the analyses carried out as part of the report were confronted with the forecasts presented in the publications quoted above.

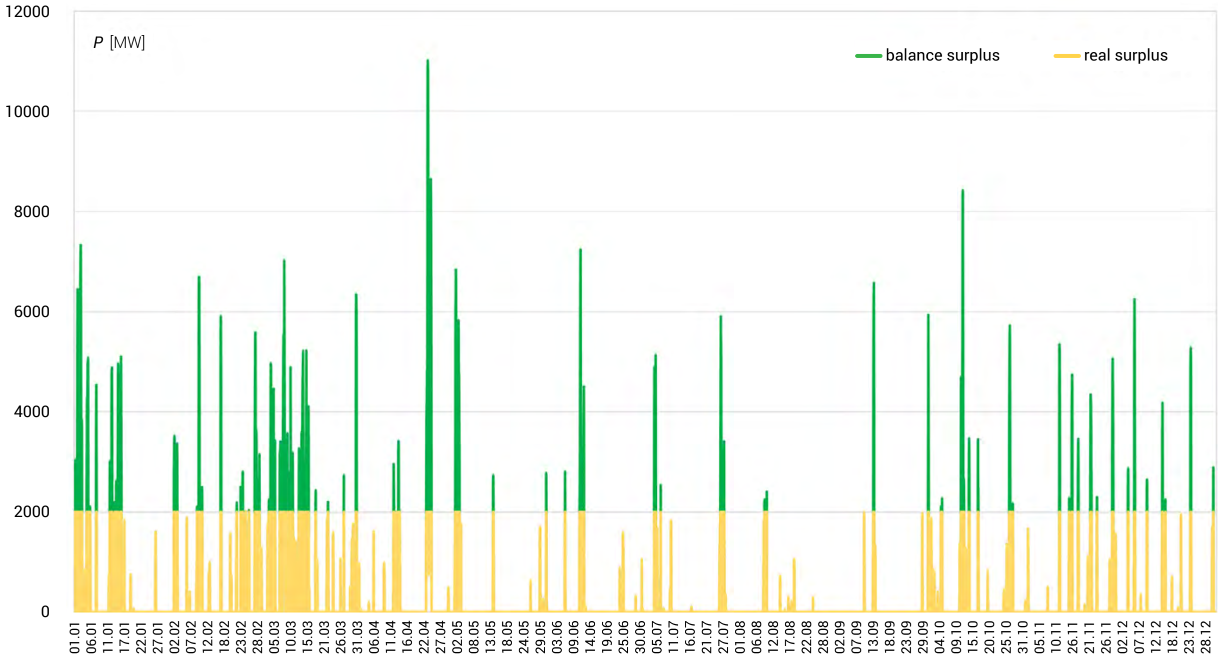
7.3 Assessment of green hydrogen supply opportunities in the context of onshore and offshore wind and photovoltaic development

7.3.1 Year 2030

As stated in Chapter 5, the balance of electricity generation and demand will not be particularly threatened (thanks to the conventional units kept in operation), but the volume and the predicted structure of RES generation (PV: 7.3 GW, onshore FW: 9.5 GW, OWF: 5.9 GW) give a chance for at most a symbolic value of energy surplus (0.3 TWh). Increasing the installed capacity of RES according to the author's option B (PV: 12 GW, onshore FW: 12 GW, OWF: 8 GW) allows to obtain a surplus of 3 TWh, although technically it will be difficult to fully use it, as shown in Fig. 10.1. This result is very similar to the one presented in[214], in which the volume of hydrogen obtained from RES surplus for the year 2030 was determined at 1.7 TWh. Both values do not ensure meeting the demand which (except for the chemical industry) is estimated at 7 TWh.

214 I. Kielichowska, K. Staschus, L. Kees van der et al, *Polska neutralna klimatycznie 2050...* , p. 54.

Figure 7.1. Expected generation surplus in RES sources for 2030 for the author's option B of their structure (PV: 12 GW, onshore WF: 12 GW, OWF: 8 GW)

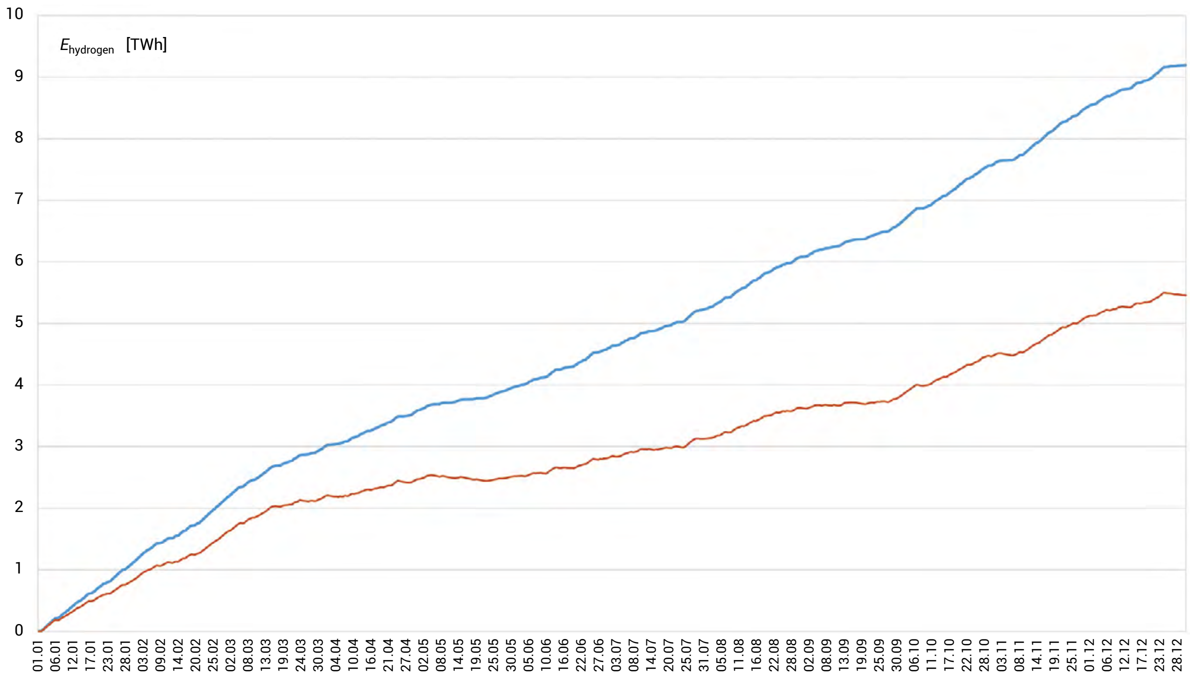


Source: own study.

It is also known from the draft document of the Polish Hydrogen Strategy[215] that the installation of electrolysers with a capacity of 2 GW is expected for the year 2030. There will be no business sense in their operation if the annual time of use of their rated capacity is less than 4000-5000 hours (see Chapter 6, Fig. 6.4, Fig. 6.4). Since powering the electrolysers from the planned RES installations would *de facto* force high-emitting sources to generate additional power (to replace the energy consumed by the electrolysers), the necessity of building additional 2 GW offshore wind facilities (possibly an onshore option) dedicated solely to powering the electrolysers should be considered (technically, a dedicated line or offshore production or a hydrogen pipeline). Obtaining more than 9 TWh of electricity in this way can be distributed between the needs of the electricity system and the introduction of hydrogen into the transmission and distribution system to meet the demand of other hydrogen economy entities.

215 *Polish Hydrogen Strategy until 2030 with an Outlook until 2040.* - draft, pp. 18-21, https://bip.mos.gov.pl/strategie-plany-programy/polska-strategia-wodorowa-do-roku-2030-z-perspektywa-do-2040-r/

Figure 7.2. Annual electricity generation from offshore wind farms (2 MW capacity, 9 TWh) - blue line; after a transfer of some part of energy to hydrogen production supporting the power sector, more than 5 TWh are left for hydrogen production for other sectors of the economy (brown line)



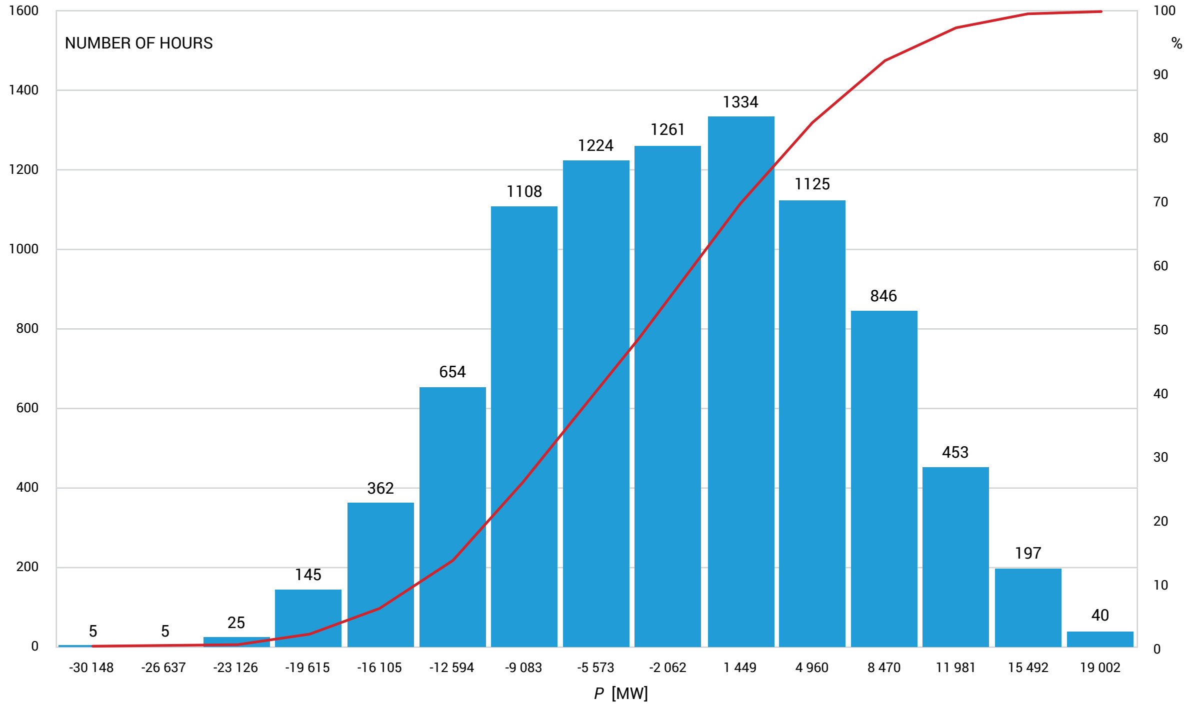
Source: own study.

As a result, electricity of a total value of about 12 TWh could be used to produce almost 8-9 TWh of green hydrogen, which, in view of the demand of 7 TWh shown above, can be considered a satisfactory supply level, particularly in the light of the initial development of the hydrogen economy. This value exceeds the forecast as the development option in Section 2.6.1.

7.3.2 Year 2040

In 2040, the decarbonisation process will be well advanced and a significant number of conventional power units - both CDGU and nCDGU - will be decommissioned. As indicated in Chapter 5, the chance for measurable values of RES generation surplus is only given by their perspective defined as variant B in Table 5.4 (PV: 20 GW, onshore FW: 16 GW, OWF: 20 GW). Below the results of analyses are presented, which put even more emphasis on RES development, this option has been called (referring to other EU actions for climate) 3x20 GW (PV: 20 GW, onshore FW: 20 GW, OWF: 20 GW). This option gives very clear values of RES generation surplus (41 TWh) without removing SEE balancing demand (21 TWh, 20 GW). These relationships are shown in the histogram in Fig. 7.3.

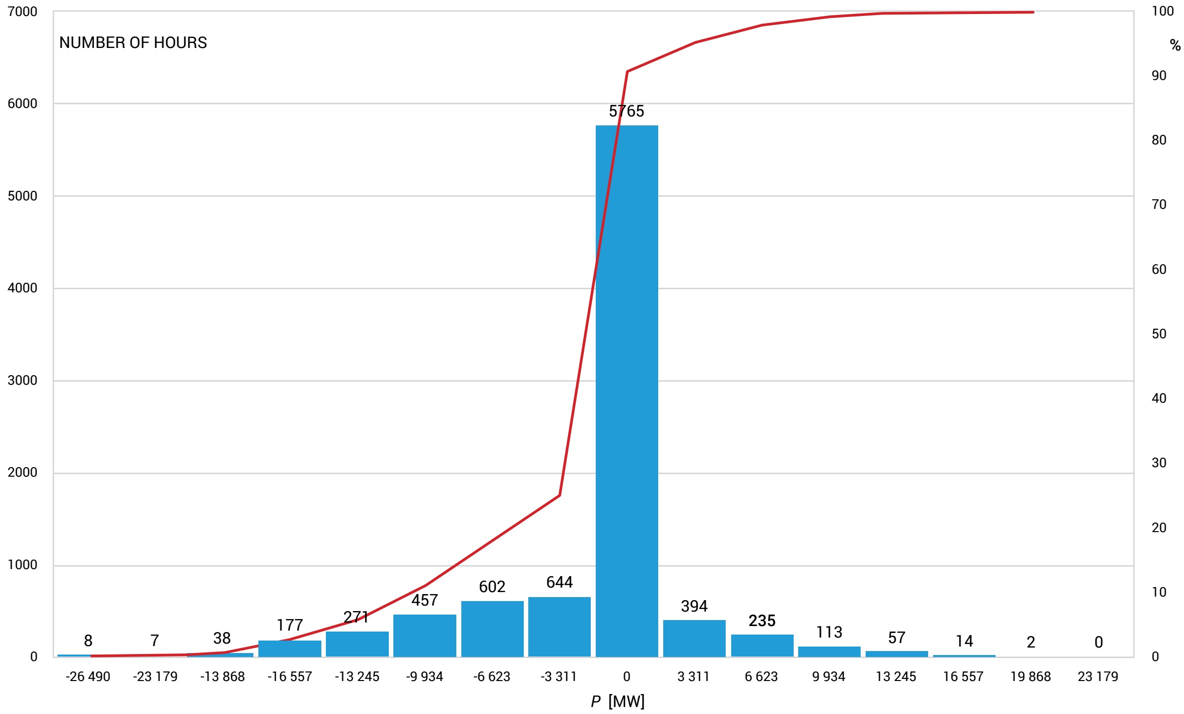
Figure 7.3. Histogram of balancing power values for SEE in 2040 for the 3x20 GW scenario



Source: own study.

Such a significant amount of surplus generation can be efficiently utilised by providing sufficiently large storage capacities in the form of hydrogen. With a global storage capacity of 1 TWh and a storage capacity of 10 GW, a very high utilisation rate of the RES surplus is achieved and the balancing requirement in the SEE is reduced to a small value of 3 TWh. These relationships are illustrated in Fig. 7.4 with a histogram of the balancing power in the SEE with global storage. As can be seen, for a period of more than 6000 hours per year, the system would be fully balanced (zero balancing capacity), positive balancing capacity values and unused surpluses occur for very short periods of time compared to operating conditions without the effect of energy storage.

Figure 7.4. Histogram of the power to be balanced for SEE in 2040 for the 3x20 GW scenario, including 1 TWh storage and 10 GW capacity

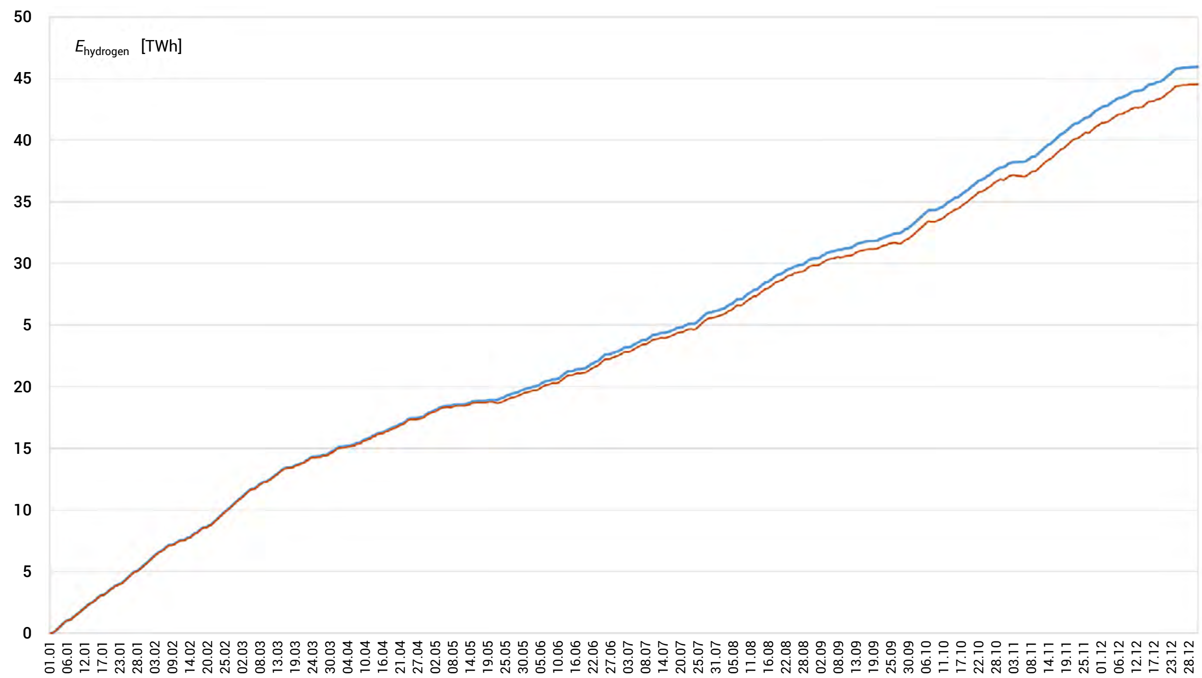


Source: own study.

The use of surplus electricity of 41 TWh will make it possible to produce hydrogen with an energy value of about 30 TWh. According to Table 7.1, this will meet the needs of the power sector projected for 2040. There are still other sectors that need to be satisfied, which even excluding the chemical industry is estimated at over 30 TWh, and including it 65 TWh. They can be met by offshore wind farms producing only for electrolysis, in electrolyser systems working offshore, using hydrogen pipelines or special type of tankers. With the capacity of such an additional 10 GW group of farms, the expected energy value is more than 45 TWh, from which hydrogen with an energy value of about 32 TWh can be produced.

Thus, the demand needs identified for 2040 in Table 7.1 in total at 89 TWh could be balanced to a significant extent taking into account the potential of hydrogen production from surplus RES amounting to about 30 TWh and from dedicated farms at 32 TWh. The missing part could be covered by internal activities of chemical industry companies (local electrolysers, blue hydrogen, imports).

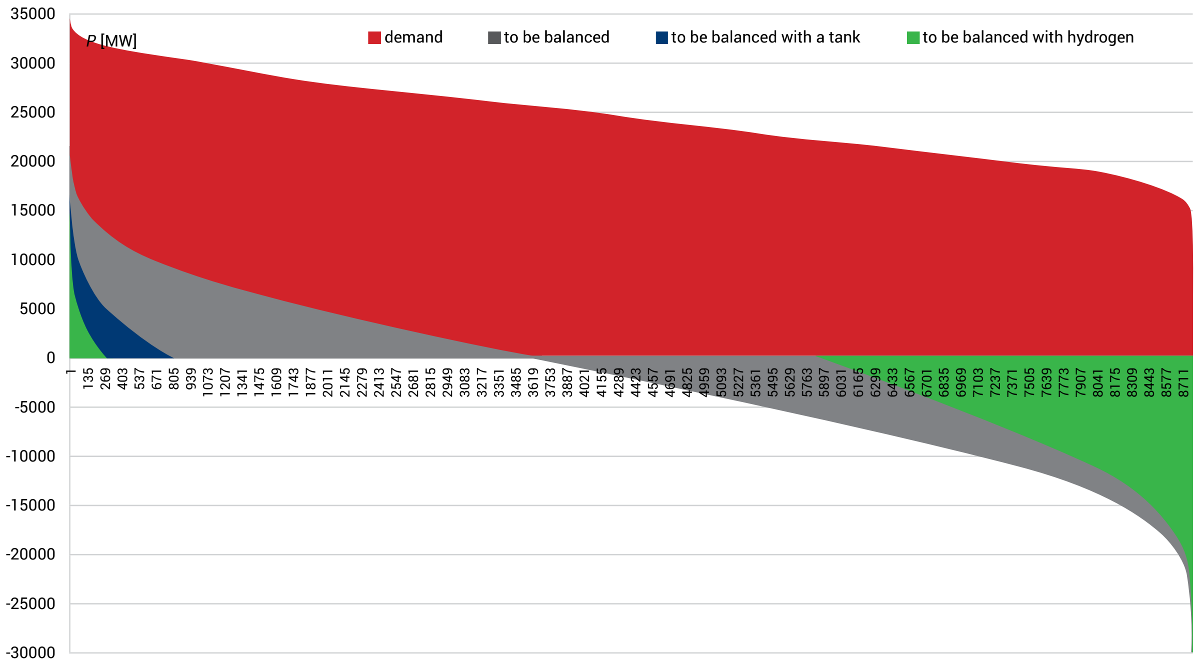
Figure 7.5. Annual energy generation from unbundled offshore windmills (10 MW capacity, 45 TWh) - blue line; after a part of the energy is transferred to the production of hydrogen supporting the electric power industry, more than 40 TWh remain for the production of hydrogen for other sectors of the economy (brown line)



Source: own study.

The overall positive picture of the SEE balancing situation and the existence of a high level of surplus with the adopted RES structure described as 3x20 GW + 10 GW is confirmed by Fig. 7.6, which presents an ordered diagram of demand and generation.

Figure 7.6. Ordered diagram of demand for power in the NPS for 2040; very small balancing needs (positive value - green) and surplus to be utilized after meeting the balancing needs (negative value - green) are visible



Source: own study.

7.3.3 Year 2050

While considering the 112 TWh of hydrogen demand projected for this year, it should be kept in mind that this will be the year of declared and expected full decarbonization of all areas of the Polish economy. Projections of electricity consumption and installed capacity in RES "soar" to over 300 TWh by 2050 in publications [D1], [D4] and installed capacity to over 160 GW. Regardless of the degree of uncertainty in the forecasting assumptions, it is certain that the prerequisite for the proper functioning of the power system in 2050 will be such a level of RES development and the possibility of associated energy storage that will ensure the system's ability to balance demand and generation at any time. However, one has to bear in mind limited connection and transmission capacities of the power system, which will result in the fact that the state of equilibrium possible for the balanced "copper plate" model cannot be achieved in reality. What is then left (in addition to the inevitable development of nuclear power) is the further exploration of offshore wind energy potential in the Baltic Sea and meeting the demand for green hydrogen through independent transmission systems (Fig. 5.19, Fig. 6.1).

7.3.4 Predicted shape of hydrogen economy in Poland - synthetic approach

Based on the analyses in this report, the following vision of Poland's hydrogen economy in the decarbonisation process emerges:

A. Ensure an adequate level of installed RES capacity (onshore and offshore wind and photovoltaics) to achieve a significant level of energy surplus in addition to the direct balancing of electricity demand;

B. Development of technologies to convert surplus electricity into energy stored in hydrogen with maximum efficiency of the process and minimum cost;

C. Allocation of a part of RES potential with the highest capacity utilization rate (offshore wind energy) for direct hydrogen production, without considering the balance needs of the power system and without the need to connect generation sources and electrolysers to the grid (off-grid operation);

D. Establishment of a hydrogen transmission, storage and distribution system to meet the balance needs of the electric power sector and to meet the growing demand for this gas in other areas of the economy;

E. Mastery of efficient techniques to convert hydrogen to electricity to balance demand during periods of insufficient generation from RES sources;

F. Development of distributed hydrogen generation and distribution systems, in various technical and business configurations in support of a global large-scale system.

08

OVERVIEW OF SELECTED GREEN HYDROGEN DEPLOYMENT STRATEGIES

8.1 Policy and legal tools related to the development of hydrogen production and renewable energy sources

The plan to develop renewable hydrogen, based on renewable energy sources including offshore wind power, is one of the cornerstones of the energy transition and the reduction of CO_2 emissions. The emissions reduction policy accelerated in 2018 with Ursula von der Leyen taking over the presidency of the European Commission. At that time, climate and energy policy was transformed into the European Green Deal, a grand economic and industrial strategy with climate protection at its core[216]. The planned reduction of greenhouse gases was raised to 55% in 2030, which was accepted by all Community countries in December 2020[217]. Shaping of policies, legal tools, normative system and financial support instruments for implementation of the European Green Deal has begun[218]. The actions taken will mobilise a stream of EUR 1 trillion for energy transformation until 2030[219]. Financial support at the level of 30% of the EU budget for the years: 2021–2027 has been allocated.

Another financial lever for the energy transition is the Next Generation EU Fund with over EUR 723 billion, from February 2021[220] (designed to stimulate economies after the crisis and recession caused by the COVID-19 pandemic - funds will be spent based on Green Deal priorities)[221]. In addition, the implementation of this policy will require multi-year investments in the annual amount of EUR 260 billion (1.5% of the 2018 GDP of the EU countries)[222]. This means that Poland will allocate 30% of EUR 170 billion to energy transition[223] and large support for renewable hydrogen by 2027. This sector is treated as an important subsystem for reducing GHG emissions in the EU.

8.2 European Union hydrogen strategy

The EU hydrogen strategy, already described in part under point 2.5, points to the widespread use of renewable or low-emission hydrogen as an energy carrier, fuel and energy storage. Hydrogen effectively eliminates emissions from industrial processes in those sectors of the economy which have hitherto used coal (the steel and chemical industries)[224] and achieves the social policy objective of creating new jobs[225].

216 U. von der Leyen, A *Union that aims higher, Political guidelines for the next term of the European Commission (2019-2024)*, https://ec.europa.eu/commission/presscorner/api/files/document/print/pl/ip_19_5542/IP_19_5542_PL.pdf (accessed 11.08.2021).

217 European Council Conclusions of 11 December 2020. EUCO 22/20 CO EUR 17 CONCL 8, https://www.consilium.europa.eu/pl/documents-publications/public-register/euco-conclusions/?year=2020 (accessed 10.08.2021).

218 European Green Deal, Communication from the Commission to the European Parliament, the European Council, the Council, the Economic and Social Committee and the Committee of the Regions, Brussels, 11.12.2019. Com(2019) 640 Final, https://eur-lex.europa.eu/legal-content/PL/TXT/?uri=COM%3A2019%3A640%3AFIN

219 *Ibid*, p. 7.

220 The EU's 2021-2027 long-term budget & NextGenerationEU. Facts and figures https://op.europa.eu/en/publication-detail/-/publication/d3e77637-a963-11eb-9585-01aa75ed71a1/language-pl

221 A Recovery Plan for Europe, https://ec.europa.eu/info/strategy/recovery-plan-europe_pl

222 The European Green Deal, Communication from the Commission to the European Parliament...

223 What is the National Reconstruction Plan, How the EU Reconstruction Fund came into being and what it has to do with the National Reconstruction Plan, https://www.gov.pl/web/planodbudowy/czym-jest-kpo2

224 Hydrogen Strategy for a Climate Neutral Europe, Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions, Brussels, 8.07.2020. Com(2020) 301 final, https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52020DC0301

225 *Ibid*, p. 2.

European companies can compete globally in clean hydrogen technologies and are prepared to participate in the development of the emerging industry. The aim is to become a world leader in renewable energy technologies. Forecasts indicate that in 2050, clean hydrogen will provide 22% of global energy demand with a market value of USD 700 billion[226]. In the EU, hydrogen will account for 24% of energy demand in 2050[227] if EU policies lead to a higher CO_2 reduction target than that committed to in the Paris Agreements[228] on global warming[229].

The hydrogen industry is expected to create 1 million new jobs and total investment in the EU has been estimated at between EUR 180-470 billion[230]. The lowest level of investment (EUR 180 billion) implies the implementation of a massive EU-wide industrial project,[231] but EU strategies will aim higher, resulting in investments closer to the EUR 470 billion ceiling.

8.2.1 European Union - hydrogen - draft support scheme - regulations

The EU hydrogen strategy indicates a priority for the production of renewable hydrogen from wind power and photovoltaics. The choice of renewable hydrogen is based on the fact that industrial concerns from EU countries have a strong position in the electrolyser manufacturing industry[232]. The following relationship can be expected: the launch of support for renewable hydrogen will be linked to the large-scale development of renewable energy. The system of development of the hydrogen sector is: state and European Union aid, financial instruments (subsidy measures, preferential credits), regulatory tools (legal solutions supporting the development of the industry sector). The analysis of EU announcements indicates that on the one hand a competitive hydrogen market will be built in the EU by 2030, with a mechanism for distributing hydrogen supplies among end users[233]. On the other hand, new guidelines and a legal framework defining the rules of support for renewable hydrogen and stimulation of demand and supply have been announced. Clean production and distribution technologies are to be strengthened. It has been announced that a certain proportion of energy from renewable sources will be allocated to the production of hydrogen and that a support system will be set up to ensure competitiveness with fossil fuels[234]. Financial support will also be given to hydrogen storage and bunkering as well as to industrial end products of the hydrogen industry. There will be incentives at the EU level, based, among other things, on a quota system (minimum levels of use of renewable hydrogen in the chemical industry and

226 Hydrogen Economy Outlook, Key messages, Bloomberg NEF, dated 30.03.2020, p. 8.

227 Hydrogen Roadmap Europe, A Sustainable Pathway for the European Energy Transition, Publications Office of The European Union, 2019, p. 8, https://www.fch.europa.eu/news/hydrogen-roadmap-europe-sustainable-pathway-european-energy-transition

228 Paris Agreement concluding the 21st UN Climate Change Conference. The agreement commits to present by 2020 long-term scenarios for reducing greenhouse gas emissions in accordance with the methodology adopted by the IPCC. The aim of the Agreement is to limit the average global temperature increase to well below 2°C over the period 1750-2100, and to aim to limit this increase to 1.5°C.

229 However, if the hydrogen industry were developed solely on the basis of the reduction targets adopted under the Paris Agreement, it would be sufficient for hydrogen to account for 8% of energy demand in 2050.

230 Hydrogen strategy for a climate neutral Europe..., p. 2.

231 It is worth recalling that the lower value of cumulative investments ensures the implementation of the Paris Agreement, which is to enable the implementation of the plan to reduce temperature to below 2°C. The objective of the Agreement - as already indicated - is to limit the average global temperature increase to well below 2°C in the period 1750-2100, and to strive to limit this increase to 1.5°C.

232 Hydrogen strategy for a climate neutral Europe..., p. 6.

233 *Ibid*, pp. 7, 8.

234 *Ibid*, p. 12.

in transport[235]). Common standards will be created for technologies and final devices, designed to eliminate production using carbon fuel (*de facto* this will create barriers for equipment from Asian countries). Renewable hydrogen certification is planned based on the EU ETS system. Guarantees of origin are envisaged for renewable hydrogen used in transport[236] and sustainable development certificates to improve the profitability of production and trade of this fuel on the Community market[237].

There will be contracts for difference for low-carbon hydrogen to eliminate high-carbon hydrogen in oil refineries, steel production, fertilizers, chemicals, synthetic fuels, hydrogen-derived fuels (ammonia)[238]. Direct support schemes and minimum production volumes were signalled. The EU hydrogen strategy assumes that by 2030 a large-scale hydrogen ecosystem ready for commercialization will be built[239]. Support will also be given to hydrogen production in industrial clusters, in coastal regions, in close proximity to the location of offshore wind farms. A law will be passed to facilitate the construction and operation of pipelines and direct power lines[240].

8.2.2 Renewable hydrogen - projected production volumes and financial support, end users

Renewable hydrogen produced by RES is seen as an energy carrier to replace fossil fuels (oil, petroleum-based fuels, coal). It is also set to become an energy store, and will play a key role in sustaining the gas industry, by supplementing and over time replacing natural gas in the gas fuel mix. An overhaul of the energy system is needed in three dimensions. The first, is to move towards a closed-loop operation of the electricity sector. The second is electrification of end-use sectors of the economy - based on RES. The third is broad use of renewable fuels, including renewable hydrogen where full electrification is not possible[241].

It is assumed that hydrogen will play a key role in modernizing the natural gas industry. High-methane natural gas is seen as a transitional solution because of its CO_2 emissions. This triggers a process of changing the composition of the fuel mix: replacing high-methane gas with carbon-free gas. In 2050, the mix is likely to contain: 20% natural gas and 80% renewable gases (primarily renewable hydrogen)[242].

Renewable energy is key for renewable hydrogen. Its share in power generation is expected to

235 *Ibid*, p. 14.

236 Directive of the European Parliament and of the Council (EU) on the promotion of the use of energy from renewable sources (recast) (text with EEA relevance), 2018/2001 of 11 December 2018. L 328/82, Article 19, https://eur-lex.europa.eu/legal-content/PL/TXT/?uri=CELEX%3A32018L2001 (accessed 11.08.2021).

237 Hydrogen strategy for a climate neutral Europe..., p. 15.

238 *Ibid*, p. 16.

239 *Ibid*, p. 17.

240 Art. 38 - containing description of facilitations and exemptions from legal regulation for direct pipelines in Directive 2009/73/EC of the European Parliament and of the Council of 13 July 2009 concerning common rules for the internal market in natural gas and repealing Directive 2003/55/EC https://www.ure.gov.pl/pl/urzad/prawo/prawo-wspolnotowe/dyrektywy/4350,Dz-U-UE-L-0921194.html (accessed 11.08.2021), Article 7 - direct lines, contains facilitations and exemptions for such investments, Directive (EU) 2019/944 of the European Parliament and of the Council of 5 June 2019 concerning common rules for the internal market in electricity and amending Directive 2012/27/U, https://eur-lex.europa.eu/legal-content/PL/ALL/?uri=CELEX%3A32019L0944

241 Impetus for a climate-neutral economy: An EU Strategy for Energy System Integration, Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions, Brussels, 8.7.2020. Com(2020) 299 Final, p. 3, https://eur-lex.europa.eu/legal-content/PL/TXT/?uri=CELEX%3A52020DC0299.

242 *Ibid*, p. 19.

double to 55-60% by 2030, and by 2050 it should cover about 84% of demand[243]. Offshore wind energy will be the most important. In 2050 the power installed in offshore wind farms in EU countries is to reach 300-450 GW (currently: 12 GW)[244]. If the installed capacity is 300 GW, it will increase 25 times; if 450 GW, it will increase more than 37 times. This shows the enormous scale of the expansion of wind energy - the production of hydrogen is expected to stimulate an increase in wind farm capacity[245].

After 2030, according to the EU strategy, a quarter of the electricity produced by RES should go to the production of renewable hydrogen[246]. This means its large-scale production. Investments in electrolysers will absorb between EUR 24 and 42 billion, according to estimates. Further spending of amounts: 220-340 billion will increase the scale of production and enable 80-120 GW of electrolysers to be connected to renewable energy sources using solar and wind power[247]. Another EUR 65 billion will be invested in hydrogen storage, distribution and transport.

8.3 Hydrogen strategies of the Federal Republic of Germany, Japan and the United States

8.3.1 Federal Republic of Germany

The Federal Republic of Germany, in the National Hydrogen Strategy of Germany (German: *Nationale Wasserstoffstrategie*) adopted in 2020, has set directions for the development of the hydrogen economy. The strategic goal is to replace liquid and gaseous fuels with green hydrogen, which is perceived as the only long-term option for sustainable hydrogen production.

It is assumed that in the perspective of 2023, the foundations of a national hydrogen market will be created, and in the following years the market will be stabilized and shaped not only on a national scale, but also on an international scale. The German hydrogen strategy indicates the areas which may have the greatest application for hydrogen and these are: transport, industry, heating and energy storage. The production of hydrogen will require the development of offshore wind energy and photovoltaics[248]. The production of synthetic fuels will promote the role of hydrogen in transport and the addition of min. 2% kerosene to aviation fuel[249].

Germany currently consumes about 55 TWh of hydrogen, by 2030 demand will increase to 90-110 TWh[250]. Production will be based on offshore wind and onshore photovoltaic power[251]. Own production of renewable hydrogen will meet 16% of needs - the rest will be imported[252].

243 *Ibid*, p. 9.

244 *Ibid*, p. 9.

245 An EU Strategy to harness the potential of offshore renewable energy for a climate neutral future, Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions, Brussels, 19.11.2020. COM(2020) 741 final, p. 15,

246 *Ibid*, p. 8.

247 *Ibid*, p. 9.

248 *The German Hydrogen Strategy*, Watson Farley & Williams, 2021, https://www.wfw.com/articles/the-german-hydrogen-strategy/

249 M. Kędzierski, *German Hydrogen Strategy: Green Hydrogen in Focus*, Centre for Eastern Studies, 2020, https://www.osw.waw.pl/pl/publikacje/analizy/2020-06-16/niemiecka-strategia-wodorowa-zielony-wodor-w-centrum-uwagi

250 *The National Hydrogen Strategy*, Federal Ministry of Economic Affairs and Energy of the Federal Republic of Germany, 2020, https://www.bmwi.de/Redaktion/EN/Publikationen/Energie/the-national-hydrogen-strategy.html

251 It is estimated that 20 TWh of renewable electricity will be needed to produce 14 TWh of green hydrogen. For: *The German Hydrogen Strategy*, Watson Farley & Williams, 2021, https://www.wfw.com/articles/the-german-hydrogen-strategy/

252 M. Kędzierski, *German hydrogen strategy...*

The backbone for developing a hydrogen economy will be the natural gas transmission and distribution system. Gas pipelines will be tested to make them suitable for hydrogen transmission, and upgraded natural gas pipelines will be verified to make them compatible with hydrogen[253]. Expenditures on the development of the German hydrogen economy will amount to EUR 7-9 billion, government investments will amount to another EUR 12 billion until 2026[254] and foreign investments e.g. in Africa will total another EUR 2 billion[255]. Green hydrogen development will be supported at the level of federal states with potential for renewable energy development[256].

The strategic goal of the Federal Republic of Germany is to become an international leader in the field of hydrogen economy and export of hydrogen technologies and solutions[257]. Germany aims to introduce hydrogen into global politics and has the ability to create new areas of political rivalry in the field of geo-economics. By creating new pieces of reality, it creates fields of competition and new forms of gaining sources of competitive advantage[258]. It strives to become the world leader in hydrogen technology. It is in the interest of the German economy that hydrogen plays a key role in the energy transition. In the first instance, an internal hydrogen market will be created within the European Union, with the ultimate goal of a global market.

Germany is seeking to establish certification standards for hydrogen production, which would increase the competitive advantage of the German economy over others and contribute to the use of international trade in hydrogen and related products for geopolitical purposes. The gas infrastructure consisting of transmission and distribution pipelines and gas storage facilities will be of key importance for building Germany's position within the global hydrogen economy.

Germany's objective is to expand electrolyser capacity to 5 GW by 2030 and to 10 GW by 2040[259]. In the perspective of 2030, the Federal Republic of Germany's goal is to expand its electrolyser capacity to 5 GW, and by 2040 to 10 GW. Domestic production will not meet demand, so additional hydrogen imports, mainly from Africa[260], the Netherlands, Norway and the Russian Federation, will be necessary[261]. The existing importers of natural gas to Germany will retain their position in the area of hydrogen supplies due to the network of gas connections with Germany.

253 *The National Hydrogen Strategy*, Federal Ministry of Economic Affairs and Energy of the Federal Republic of Germany, 2020, https://www.bmwi.de/Redaktion/EN/Publikationen/Energie/the-national-hydrogen-strategy.html

254 K. Zamorowska, *10 GW mocy z elektrolizy wodoru zielonego do 2040 r. w Strategii wodorowej Niemiec [10 GW of power from green hydrogen electrolysis by 2040 in the German Hydrogen Strategy], Teraz Środowisko*, https://www.teraz-srodowisko.pl/aktualnosci/strategia-wodorowa-Niemcy-zielony-wodor-8824.html, 2020; The German Hydrogen Strategy, Watson Farley & Williams, 2021, https://www.wfw.com/articles/the-german-hydrogen-strategy/

255 M. Kędzierski, *German hydrogen strategy...*

256 A. Fedorowska, *Strategie wodorowe w Niemczech, Rzeczpospolita Daily*, https://energia.rp.pl/nowa-energia/22411-strategie-wodorowe-w-niemczech, 2020

257 M. Kedzierski, *German hydrogen strategy...*

258 M. Foucault, *Security, territory, population*, PWN, Warsaw 2018.

259 This will enable the production of 14 TWh of green hydrogen per year.

260 S. Göss, *Germany's plans to be a Hydrogen leader: producer, consumer, solutions provider*, "Energypost.eu", 2021, https://energypost.eu/germanys-plans-to-be-a-hydrogen-leader-producer-consumer-solutions-provider/#comment-419583

261 *Germany has adopted an energy strategy. The key role of hydrogen*, "Gramwzielone.pl," 2020, https://www.gramwzielone.pl/trendy/103197/niemcy-przyjeli-strategie-energetyczna-kluczowa-rola-wodoru; K. Magdalinski, German Hydrogen Strategy, "Sovereign Thought" 2021, https://myslsuwerenna.pl/niemiecka-strategia-wodorowa/

8.3.2 United States

The US Department of Energy is the author of the US hydrogen strategy. The Americans plan to start producing hydrogen from electricity generated by renewable energy sources, nuclear power, and fossil fuels - subject to carbon storage. In August 2021, the Congress voted on a bill that would support hydrogen infrastructure with USD 9.2 billion in investments. Many hydrogen hubs are planned to be built. The bill also introduces a definition of clean hydrogen, indicating that only 2 kg of CO_2 can be emitted when producing 1 kg of hydrogen (producing 1 kg of so-called hydrogen from fossil fuels involves 9-12 kg of CO_2 emissions)[262].

Also important is the Department of Energy's plan, called the "hydrogen shot," to reduce the price of 1 kg of renewable hydrogen down to USD 1 by the end of 2030. The goal of an 80% reduction in the cost of producing renewable hydrogen is perceived as a key action to enable the development of widespread use of this carrier for, among other things, steel production, ammonia production, heavy-duty truck production. The Department of Energy estimates that lowering the cost of producing hydrogen would make it possible to compete globally[263].

The U.S. Hydrogen Strategy estimates the value of the global hydrogen technology market at USD 2.5 trillion by 2050. The hydrogen economy is projected to generate USD 750 billion in revenue and provide a total of 3.4 million new jobs in the United States by 2050. The industry is now beginning to invest in large-scale hydrogen projects, in many places these efforts involve both the production of storage and the end use of hydrogen for electricity generation, among other things. High-powered electricity generators capable of burning a mixture of hydrogen and high-methane gas have been produced. Many of these innovative technical solutions have been commercialized thanks to financial grants from the Department of Energy[264]. In the United States, municipalities have played an important role in the development of the hydrogen sector. For example, the Los Angeles municipality wants the city to become the first in the US to generate electricity with clean hydrogen. That is why they plan to abandon coal-fired and gas-fired power plants. The project of the city is to be implemented in two stages, which are to enable the replacement of a coal power plant in Utah with the capacity of 1.9 thousand MW. In the first phase, two 840-megawatt gas-fired plants will be built by 2025. They are then to be combined into a USD 1 billion energy storage facility adjacent to the hydrogen plant[265].

8.3.3 Japan

In Japan, a hydrogen strategy was approved already in 2017. It is planned that the development of the hydrogen sector will help to break the economic stagnation. All efforts are aimed at both lowering the price of available hydrogen on the market and developing technologies in which hydrogen can find application. They estimate that the price of renewable hydrogen will fall to EUR 2.7/kg by the end of this

262 M. Perzyński, *Amerykanie przeznaczą 9,2 mld USD na rozwój gospodarki wodorowej [Americans will allocate USD 9.2 billion for the development of hydrogen economy]*, "BiznsesAlert.pl", dated 05.08.2021, https://biznesalert.pl/usa-gospodarka-wodorowa-ustawa-zalozenia/

263 *Hydrogen Shot*, Overview, https://www.energy.gov/eere/fuelcells/hydrogen-shot

264 *Hydrogen Program Plan*, Department of Energy, November 2020, p. 3, https://www.hydrogen.energy.gov/roadmaps_vision.html

265 *Los Angeles wants to be the first US city powered by hydrogen*, "wnp.pl" of 16.03.2020, https://www.wnp.pl/energetyka/los-angeles-chce-byc-pierwszym-miastem-w-usa-zasilanym-wodorem,379140.html

decade and to EUR 1.7/kg in 2040 onwards. If this price reduction is achieved, then from 2030 there will be an economic case for the wider use of hydrogen in the economy. The production of hydrogen from renewable energy sources is assumed. It is envisaged to build a diversified hydrogen market, develop hydrogen technologies and build an international supply chain. This policy is based on the country's geographical location and lack of significant natural resources.

In Japan, as in other countries, so far state support for the development of the hydrogen sector has not been significant and has not exceeded an amount of several hundred million euros. The strategy plans the development of specific end-user sectors. Hydrogen will be used in electricity production; in 2020, the total installed capacity of hydrogen-fuelled generators reached 1000 MW. Important activities are planned in transport: at the end of 2025 the fleet of hydrogen cars is expected to reach 200,000 vehicles, five years later it will be four times as many. This will lead to an increase in the number of refuelling points: to 320 in five years, compared with 160 today. Heavy transport and coastal shipping are expected to grow over time.

Japan is planning to enter into energy partnerships just like Germany. The most important partner is to be Australia, and the cooperation is to concern both the supply of hydrogen and hydrogen cells. Japan already has experience in signing international partnerships - one of the suppliers of hydrogen to Japan is the Sultanate of Brunei[266].

266 Based on: *Basic Hydrogen Strategy,* Ministerial Council on Renewable Energy, Hydrogen and Related Issues, dated 26.12.2017, https://www.meti.go.jp/english/press/2017/1226_003.html and Germany and Japan. Hydrogen Future Strategies, Esperis Consulting, August 2021, https://esperis.pl/home-en-2-3/our-reports-2-4/

09

GREEN HYDROGEN AS A TOOL FOR DECARBONIZATION OF ECONOMY – SELECTED ISSUES

9.1 Blending of hydrogen with natural gas

The energy density of hydrogen is 1/3 that of natural gas, which makes the energy content per unit of mixture less than that of pure natural gas. It is indicated that a 3% mixture of hydrogen and natural gas will reduce the amount of energy transported through the pipeline by 2%[267]. This increases the load on the pipelines and their operating costs - more energy will be needed to pump the mixture with the energy equivalent of pure natural gas. For this reason, pipeline capacity will decrease. It is likely that in the next decade, the pipelines will be adapted to carry a mixture with increased hydrogen content.

Achieving certain levels of hydrogen/gas blending will depend on the ability to use the mixture in final equipment. Industry is already producing e.g. turbines generating electricity, adapted to run on 30% mixture of hydrogen with natural gas[268]. The upper limit of the mixture composition will depend on the technical possibilities of the equipment adaptation. International standardization is important, defining both common standards for the transport and storage of hydrogen-natural gas mixtures and the adaptation of terminal equipment to run on mixtures. Many gas-fired heating and cooking appliances used on the European continent are certified to run on a 23% hydrogen mixture, but no tests have been carried out on the lifetime of appliances running on this fuel[269].

There are currently 37 demonstration projects testing hydrogen mixing in the gas grid. The Ameland project in the Netherlands did not demonstrate that a 30% hydrogen blend poses difficulties for domestic appliances: boilers, gas hobs and cooking appliances[270]. In the UK, on the other hand, the H21 Leeds City Gate project is underway, adapting the city's natural gas distribution network to transport 100% hydrogen by 2028. Similar projects are being prepared by other British cities. Such transformations of networks and terminal equipment have already taken place in the past. In the 1960s and 1970s, over a ten-year period at a cost of USD 12 billion, all terminal equipment was adapted to high-methane gas in the UK, replacing city gas with 50% hydrogen. The same process was also carried out in Austria, Germany and the United States.

The greatest difficulty lies in industrial adaptation – a lot of terminal equipment has not been certified or tested for hydrogen fuelling. Most existing gas turbine designs can only run on a 3-5% hydrogen mixture. By the end of the decade, it is projected that turbines capable of operating on pure hydrogen will be produced[271]. It is possible that retrofitting of many industrial plants will enable them to be powered with much higher hydrogen content.

9.2 Transport and distribution of hydrogen mixtures

The main challenge of adapting hydrogen to distribution systems is the physical and chemical properties of gas: low volumetric energy density and high mass energy density. For these reasons, hydrogen appears to be the optimal energy carrier for use in flexible energy systems, and it can also be

267 *The Future of Hydrogen. Seizing. Today's Opportunities...*, p. 71.

268 *Hydrogen Program Plan*, Department of Energy, November 2020, p. 24, https://www.hydrogen.energy.gov/roadmaps_vision.html

269 *The Future of Hydrogen. Seizing Today's Opportunities...*, p. 71.

270 *Ibid*. p. 73.

271 *Ibid*, p. 156.

transported over very long distances.

Transport and storage costs are important to the formation of a renewable hydrogen market. If the carrier is used close to where it is produced, the costs will be negligible. If it is transported over long distances, transmission and distribution costs can be up to three times the cost of producing the hydrogen[272]. This is the diagnosis of the International Energy Agency. In the case of Poland, transport costs seem to be lower because of the shorter distances involved.

Blending hydrogen into gas networks is the cheapest and most efficient transport technology. It only requires technical adaptation of the existing gas pipelines to blend renewable hydrogen with high-methane natural gas. It is estimated that for distances up to 1500 km such transport will be the cheapest. Above 1500 km, which in the case of hydrogen production in Poland will not occur, the most cost-effective transport is that of hydrogen converted to ammonia and using the recently commercialized LOHC technology[273]. In many countries, liquid or compressed hydrogen is transported by truck and this mode of transport will dominate until the end of this decade. 15% of produced hydrogen is transported in this way, the remaining 85% is used in technological processes in the place where the carrier has been produced[274].

The tolerance for hydrogen in each link in the gas pipeline transmission chain varies. Transmission pipelines can be adjusted to a 10% blend of hydrogen and natural gas because hydrogen transmission requires higher pressures to be applied by compressors (due to the lower density of hydrogen than natural gas), which have the lowest tolerance for hydrogen. Currently used compressors in transmission networks allow pumping a 10% level of hydrogen admixture. It is highly probable that upgrading the least hydrogen-resistant components of these units will enable higher mixes. On the other hand, distribution networks, due to lower pressures, are characterized by higher tolerance - transmission of 50% hydrogen mixture is possible. Only some of the links in the natural gas distribution system show very high tolerance - polyethylene distribution pipelines can transport up to 100% hydrogen. In Poland, the challenge for transporting the hydrogen mixture with natural gas may turn out to be the outdated transmission and distribution system. Out of over 10.7 thousand km of transmission networks, half is over 36 years old, only 10% is less than 5 years old. Of the distribution networks with a length of approximately 195,000 km, over 25% are 30 years old and only 18% are less than 10 years old[275]. However, it may be assumed that the high level of exploitation of some of the transmission and distribution pipelines is not such a serious obstacle, since the energy policy announces that in 2030 the network will be capable of transporting 10% of the hydrogen-natural gas mixture.

In turn, scientific reports indicate that it is possible to use a mixture of hydrogen and natural gas in proportions: 20% – 80%. A higher proportion of hydrogen is possible if synthetic methane is used, which can also be produced from hydrogen. However, at current costs, such an operation would result in a sig-

272 *The Future of Hydrogen. Seizing today's opportunities...* , p. 67.

273 LOHC, or Liquid Organic Hydrogen Carriers, is a technology based on organic compounds that have the ability to absorb and then release hydrogen as a result of chemical reactions. This technology was applied on an industrial scale by Japan in 2020 in order to execute a hydrogen partnership with the Sultanate of Brunei. Hydrogen supplies to Japan use Kawasaki's toluene-based LOHC technology. LOHC technology is being developed in other countries in the Far East. Korean corporation Hyundai Motor is investing in the development of stationary and on-board LOHC systems. LOHC technologies make it possible to reduce transport costs, but generate significant costs in the processes of hydrogen conversion for transport and re-conversion to pre-economic use.

274 *The Future of Hydrogen. Seizing Today's Opportunities...*, pp. 67-68.

275 M. Maj, A. Szpor, Kierunki rozwoju gospodarki wodorowej [Directions of hydrogen economy development]..., p. 24.

nificant increase in the price of such a fuel compared to a hydrogen-natural gas mix per unit of energy[276].

9.3 Hydrogen transport sector and synthetic hydrocarbons

Hydrogen has potential as a fuel for transport, especially in those sectors where electrification is difficult. Most of the hydrogen strategies of EU countries that have been published in recent years indicate that hydrogen will mainly be used in transport. This will contribute to reducing the need for imported fossil fuels. Among the various modes of transport, high potential is indicated for the use of hydrogen in heavy transport, rail, maritime and aviation.

In heavy-duty and long-haul transport, fuel cells (FCEV) have on average four times the energy density of lithium-ion batteries (BEV) and therefore enable greater mileage ranges. Electric drives are not entirely suitable for heavy-duty transport, as the weight of the batteries adds to the weight of the vehicle. And the use of fossil fuels for these vehicles leads to very high carbon dioxide emissions. In addition, hydrogen as a fuel can also be refuelled more than ten times faster than lithium-ion batteries[277]. Therefore, it will also be suitable for local city buses. The key will be to expand the infrastructure of hydrogen refuelling stations. The existing refuelling infrastructure is adapted to conventional fuels. According to the European Automobile Manufacturers' Association, by 2025 nearly three hundred hydrogen filling stations should be built in Europe, and by 2030 there should be a thousand of them. The distance between each station should be 200 km[278]. Furthermore, hydrogen fuel can increase the mobility range of military vehicles and also increase their safety by reducing stoppages during various missions. It should be recalled that heavy transport is characteristic of the armed forces. Similar challenges are associated with the construction of hydrogen refuelling infrastructure for rail transport[279]. This particular branch of transport is also very promising for hydrogen solutions, which could be used in those parts of rail transport where electrification is not possible and diesel technology is used.

Furthermore, hydrogen can be an alternative fuel for maritime transport, including passenger ships and inland waterways and shipping. Deep-sea transport requires the use of synthetic fuels based on hydrogen, as does air transport, where synthetic liquid kerosene or other synthetic fuels are used. In aviation the use of liquid hydrogen as a fuel (used in space rockets) is also seen as reasonable.

9.4 Hydrogen storage

The development of RES energy production capacity, and in particular the construction of offshore wind capacity, will require the provision of large-scale energy storage. The expected further development of photovoltaics, which is correlated with summer peaks in electricity demand, and onshore wind farms, which produce electricity in similar time frames as offshore wind,[280] will only reinforce the need for system-wide energy storage. While short-term energy storage can be met with small, decentralized

276 *The Future of Hydrogen. Seizing Today's Opportunities...*, p. 147.

277 M. Dorociak, M. Tomecki, *Wodorowa Alternatywa, „300Gospodarka" [Hydrogen Alternative, "300Economy"]* 2019, https://static.300gospodarka.pl/media/2019/04/alternatywa_wodorowa_raport.pdf

278 T. Budzik, *Europe needs hydrogen filling stations. According to ACEA there should be 40 of them in Poland*, 2021, https://e.autokult.pl/41343,europa-potrzebuje-stacji-tankowania-wodoru-zdaniem-acea-w-polsce-powinno-byc-ich-40

279 *The National Hydrogen Strategy*, Federal Ministry of Economic Affairs and Energy of the Federal Republic of Germany, BMWI, 2020, https://www.bmwi.de/Redaktion/EN/Publikationen/Energie/the-national-hydrogen-strategy.html

280 *Energy Policy of Poland until 2040....*

storage systems, medium- and long-term storage will require the development of large-scale electricity storage technologies.

Value chain development of the renewable hydrogen sector will require storage facilities. A terminal shipping the produced carrier will need short-term storage to collect the hydrogen before shipment. In turn, short- and medium-term storage will be needed for the CHP and district heating sectors, while long-term storage based on large capacities will be needed for the wider use of hydrogen in the gas system, in line with the seasonal cycle of the sector (summer season stockpiling to meet winter demand). Underground storage is the most efficient and least expensive. Potentially, hydrogen can be stored in depleted oil or natural gas deposits, in aquifers, but the best results are obtained using salt caverns, created from leaching of salt deposits. While gas is injected slowly into the reservoir storage facilities and removed at a similar rate, cavern storage facilities, which enable the use of high pressure, make it possible to achieve both high filling and unloading rates. These technical parameters increase the usefulness of cavern storage for industrial and energy applications. The cost of storage is less than 0.6 USD/kgH_2, the efficiency is about 98%, and the risk of hydrogen contamination is estimated to be low. Currently, caverns in the United Kingdom are capable of storing 40 000 MWh H_2 and in Germany, a project is being implemented with a salt cavern storage capacity of 140 000 MWh H_2[281].

Depleted oil and gas reservoirs are typically larger than salt caverns, but their porous geological structure results in permeability, which facilitates contamination of the stored medium, which would need to be treated before industrial use. Such an operation would increase storage costs. Aquifers, on the other hand, have the least potential of the three storage options - scientific studies indicate many unresolved technical challenges. However, technical solutions seem to be necessary, as optimal salt deposits for hydrogen (suitable for cavern storage) are only found in a few places[282].

Poland has a favourable geological structure for subsequent cavernous deposits. Rock salt deposits and salt domes are found in several dozen places located in three main regions: the so-called Łeba Elevation, on the Pre-Sudetic Monocline, in the salt domes (Kujawy, the Łódzkie region), and in the Subcarpathian Foredeep[283]. At present, there are two storage facilities in salt caverns, with a capacity of 0.8 bcm of gas, and work is underway to increase their capacity to over 1 bcm. The analysis evaluating the possibilities of adapting the cavern storage facilities in Korsakowo to hydrogen storage indicates a capacity of 160,000 MWh, and in the case of Mogilno: even 260,000 MWh.

9.4.1 Synthetic hydrocarbons

The green hydrogen produced in the electrolyser can be further processed to produce synthetic fuel through power-to-X technologies. Hydrogen can be used directly as a liquid or gaseous fuel. This can be used as a gaseous fuel (power-to-gas), a liquid fuel (power-to-liquid) and other chemical fuels (power-to-ammonia)[284]. The main source driving the renewable process of producing low-emission electro-fuels should be clean electricity, which will be used to produce the so-called green hydrogen, and its

281 *Ibid*, p. 69.

282 *Ibid*, pp. 69-70.

283 The Łeba Elevation: Łeba, Mechelinka, Gulf of Puck reservoir. Pre-Sudetic Monocline: Gubin, Nowa Rola, Nowa Sol, Góra. Salt domes: Rogoźno, Wapno, Damasławek, Mogilno, Inowrocław, Góra, Izbica Kujawska, Kłodawa, Lubień, Łanięta, Dębina. Pre-Carpathian Foredeep. After: M. Maj, A. Szpor, *Kierunki rozwoju gospodarki wodorowej...*, p. 19.

284 J. Kupecki, M. Wierzbicki, *Hydrogen as a tool for sector integration in the new energy model*, "Nowa Energia" 2020, no. 5-6, pp. 37-38.

appropriate processing will enable the production of a wide range of synthetic fuels[285]. It is estimated that an important role in the process of energy transformation in the air transport sector will be played by e-kerosene. It is a fuel with parameters and properties similar to traditional aviation kerosene, and it is produced under the power-to-liquid technology using hydrogen and an appropriate carbon substrate. The fuel obtained in this way can be transported, distributed, stored and also used in aircraft. It should be emphasized that similar physico-chemical properties of synthetic kerosene in comparison to its conventional form, can contribute to improving the efficiency of transition from fossil fuels to renewable fuels, which at the same time will be compatible with the existing infrastructure. The dynamics of this process depend on the amount of renewable hydrogen that could be used to produce such a fuel. At the same time, at present, unit costs of airborne electrofuel (e-kerosene) are nearly four times higher than for traditional fuels[286].

285 S. Heyne, P. Bokinge, I. Nyström, Global production of bio-methane and synthetic fuels-overview, "Biomethane and Synthetic Fuels" 2019, p. 12.

286 This is close to 2 USD/litre compared to 0.5 USD/litre. See Hydrogen Council, *Path to hydrogen competitiveness: A cost perspective* 2020, p. 46; H. Blanco, W. Nijs, J. Ruf, A. Faaij, *Potential for hydrogen and Power-to-Liquid in a low-carbon EU energy system using cost optimization*, "Applied Energy" 2018, pp. 630-639; M. Cames, S. Chaudry, K. Göckeler, P. Kasten, S. Kurth, E-fuels versus DACCS, "Institute of Applied Ecology" 2021, pp. 23-24.

10

SUMMARY

The cost of producing 'green' hydrogen is currently at least twice as high as the cost of producing hydrogen by steam reforming hydrocarbons. However, this is set to change in the future due to falling costs of electrolysis plants and the rising price of CO_2 emission allowances. The cost of green hydrogen will come down significantly over the next decade, making it competitive with hydrogen obtained from reforming.

The pace of hydrogen market development will largely depend on the alignment of regulations and market standards. The main barrier to the development of renewable hydrogen is the high cost of each link in the hydrogen chain. Solving key technological and non-technological problems may prove to be an important axis for building competitive advantages[287]. Hydrogen demand and infrastructure spending can be stimulated by incentives including carbon price caps, pollution regulation and renewable energy content. Mass production of electrolysers and increasing their efficiency levels will contribute to cost reduction. Electricity produced at the lowest possible cost is essential if green hydrogen production is to be competitive, but the costs not only of installing green hydrogen production facilities, but also of storing and transporting the hydrogen need to be reduced significantly.

The analysis carried out in this report shows that ensuring the balancing of the power system through RES generation and hydrogen energy storage, as well as meeting the demand for hydrogen from other sectors of the economy requires significantly more installed capacity than predicted in the PEP2040 documents and the Polish Hydrogen Strategy (electrolysers). The following values were determined:

- for 2030: photovoltaics: 12 GW, onshore wind farms: 12 GW, offshore wind farms: 8 GW plus additional 2 GW from farms dedicated for exclusive hydrogen production; electrolysers using surplus energy: 2 GW, electrolysers dedicated to cooperation with offshore farms: 2 GW;
- for 2040: photovoltaics: 20 GW, onshore wind farms: 20 GW, offshore wind farms: 20 GW plus additional 10 GW from farms dedicated for exclusive hydrogen production; electrolysers using surplus energy: 10 GW, electrolysers dedicated to cooperation with offshore farms: 10 GW.

Pure hydrogen is currently treated by the EU as a fuel that will replace the hydrocarbons currently used in the economy. Its popularisation is inscribed in the process of energy transition and the transformation of other economic segments (e.g. transport, chemical industry). In the EU, the race to build a clean hydrogen economy has begun. The advantage will be gained by those countries which will manage the entire value chain in the hydrogen economy and will be able to create new technological solutions. By 2024 the power of electrolysers in the EU is to increase to 6 GW, and by 2030 to 40 GW. The Polish government estimates that by 2030 the power of domestic electrolysers will reach 2-4 GW. The biggest advantage of electrolysis is the possibility to use it with energy from renewable sources, such as offshore or onshore wind farms. Thanks to that, in contrast to other ways of raw material production, it does not generate unwanted by-products, mainly direct CO_2 emissions. The use of electrolysers gives great possibilities to control the production of hydrogen depending on current needs and the possibility of its storage. In addition, the hydrogen produced in this way is characterized by a very high "purity" (exceeding 99.9%), which allows for its use not only in industrial processes, but also in hydrogen vehicle propulsion systems.

Demand for green hydrogen will grow at a moderate rate until 2030. After that, an acceleration in demand growth is forecast. By 2050, annual demand for hydrogen in Poland may exceed 130 TWh,

287 *The Global Supply Chain and the Value of the Hydrogen Economy*, Report prepared for the Office of the Marshal of the Wielkopolska Region as part of funding from the Regional European Fund, p. 61, https://h2wielkopolska.pl/wp-content/uploads/2021/03/Swiatowy-lancuch-dostaw-i-wartosci-gospodaki-wodorwej-wersja-finalna-1.pdf

taking into account the complete elimination of hydrogen produced using high-carbon technologies from the industry.

EU policy documents indicate that pure hydrogen could meet up to 24% of global energy needs by 2050. The price of hydrogen production should reach 1 to 2 EUR/kg by 2050. The EU plans to create a hydrogen economy based on the full value chain. It is therefore not only about developing the area of hydrogen production and the infrastructure for transporting this raw material, but also about creating market demand, which is the driving force for increasing supply. This entails lowering the costs of production and distribution technologies. Hydrogen is expected to become more important after 2035, as falling technology costs combined with rising coal prices will allow hydrogen to increasingly compete with the hitherto dominant fuels.

Key to the development of renewable hydrogen production in Poland is the creation of good legal, institutional and organizational frameworks linking renewable hydrogen, on the one hand, to the technologies of its production and, on the other hand, to the key sectors of the economy with the greatest demand potential. It should be emphasized that offshore wind energy, due to its production characteristics (large volumes of electricity produced e.g. in the 24-hour period of low demand, an important role in the European strategy for greenhouse gas reduction) is an effective and optimal technology for renewable hydrogen production. The key action that creates the foundations for stable development of the renewable hydrogen market is the optimum design of the hydrogen transmission and storage sector. Gas transmission and distribution pipelines should be adapted to transport renewable hydrogen, and underground gas storage facilities should be adapted to store this energy carrier.

It appears that the gas, electricity and heat sectors may be the most promising market, with rising emission reduction targets and projected increases in the cost of emission allowances (EU ETS). On the other hand, the fastest growing market in the short term is the road, rail and sea transport. In the perspective of the next decade, urban public transport will develop dynamically. The development of heavy transport based on hydrogen is forecasted at the end of the medium term. An important source of demand for renewable hydrogen in the short term may be the refining industry and the chemical and fertilizer industries. In the short term, an optimum solution would be to substitute hydrogen produced using high-emission technologies with renewable hydrogen. The renewable hydrogen market, due to higher production costs and expensive end-use technologies, will need a long-term and multidimensional support system - based on subsidies, tariffs, consumption quotas in selected end-use sectors, production quotas - defining a minimum ceiling for hydrogen production from RES sources. It can be assumed with a high degree of probability that future EU regulations on support for hydrogen production will include specific solutions on the above mentioned issue which the member states will be obliged to implement. It is clear from reading the EU documents that the support instruments will be based on already known mechanisms from the natural gas market and the market for electric energy generated from renewable sources. It should be assumed that the entire renewable hydrogen sector will achieve market competitiveness in the medium to long term. This means a period of at least a dozen or so years of support instruments.


H2

11

RECOMMENDATIONS FOR REGULATORY CHANGES

1) **Act of 10 April 1997 - Energy Law ("EL"):**

a. Definition of hydrogen:

The current provisions of the Act do not define the concept of hydrogen. The definition of gaseous fuel contained in Article 3(3a) specifies that such fuel is high-methane or nitrogenised natural gas, including liquefied natural gas and propane-butane or other types of combustible gas supplied through the gas network, as well as agricultural biogas, regardless of its use. While it could be interpreted that hydrogen would fall within the definition of 'other combustible gas', in order to guarantee the unambiguous status of this fuel, it is proposed to introduce a definition of hydrogen in the EL. Such a definition could be introduced either by adding a separate editorial unit that contains a specific definition of hydrogen, making a distinction between conventional hydrogen and renewable and low-carbon hydrogen (from electrolysis using electricity from RES and other low-carbon hydrogen production processes). Extending the scope of the definition of gaseous fuel to include hydrogen is not recommended. The negative recommendation results from the fact that if hydrogen is considered a gaseous fuel, all the provisions concerning the regulation of the gaseous fuel market will apply to it. Over-regulation of the hydrogen market, which has not yet taken shape, would be an undesirable obstacle to its development. Existing regulations, which are applicable to a mature and commercialised gas market, should not be immediately implemented also for the emerging hydrogen market. In this context, the Polish legislator should, in particular, consider not applying to hydrogen transport pipelines the rules which are applied in the electricity and natural gas markets, such as the unbundling of transport activities from generation or trading activities and the TPA rules to hydrogen transport facilities. The application of such rules to the hydrogen sector, especially in its early stages, can be a significant barrier to its development.

b. No obligation to obtain a concession:

Consideration should be given to waiving the obligation to hold a licence for economic activities involving the production of hydrogen, the transmission of hydrogen through a gas network, and the storage of hydrogen.

c. Change the definition of direct line:

It is recommended that Art. 3 par. 11f) of the EL, which defines a direct line, be amended to mean either an electricity line connecting a separate electricity generation unit directly to the customer or an electricity line connecting the electricity generation unit of an energy company with installations belonging to that company or installations belonging to its subsidiaries. The amendment should include the possibility for electricity undertakings to supply through a direct line to a customer which has no capital ties with that electricity undertaking, and to connect the unbundled generation unit of a generator directly to a customer, regardless of whether it has a connection to the electricity system. Such a change would be in line with the Market Directive, which indicates that a Member State should take the appropriate measures to allow the connection by a direct line of an isolated generation site to an isolated customer or of a generator to an electricity supply undertaking for the direct supply of energy to its other own premises, subsidiaries and customers. A direct line should be treated as an alternative to the power system, whereas the Polish legislator limits the role of a direct line to a tool for solving the problem of insufficient development of the power grid. This approach of the Polish legislator is evidenced by the fact that when issuing a permit for the construction of a direct line, the President of ERO takes into account the system's capacity to provide services and the refusal of an entity applying for a permit for the construction of a direct line to provide electricity transmission or distribution services through the existing grid. This interpretation makes it impossible to connect a RES source to an industrial customer already connected to the grid via a direct line. It is therefore recommended that Art. 7(4) of the EL be amended to remove the requirement for the President of ERO to review the system's ability to provide services.

Support for the development of direct lines connecting RES installations with customers possessing electrolysers, enabling the storage of surplus produced electricity, regardless of their connection to the electricity grid, will promote the development of renewable hydrogen production.

2) **Act of 11 January 2018 on electromobility and alternative fuels[288]:**

At present, the provisions of the Act state that in case of local government units whose number of inhabitants exceeds 50,000, urban transport services should be provided by entities whose share of zero-emission buses in the fleet of vehicles used in the area of that local government unit is at least 30%. In turn, a zero-emission bus is defined as a bus using for propulsion electric energy generated from hydrogen in the fuel cells installed in it, or only the engine whose duty cycle does not lead to emissions of greenhouse gases or other substances covered by the greenhouse gas emission management system referred to in the Act of 17 July 2009 on the greenhouse gas and other substances emission management system (Journal of Laws of 2020, item 1077), and a trolleybus - a bus adapted to be supplied with electric energy from the traction network. Currently, the goal is to promote the use of zero-emission buses in the public transport fleet.

In order to promote the development of zero- and low-emission hydrogen technology, it would be appropriate to amend Article 36 of the Act, so that separate targets are set for the share of (i) hydrogen-powered buses, (ii) buses with engines without GHG emissions, and (iii) trolleybuses. The latter, pending significant decarbonisation in the transmission network and hence in the traction network, should have the smallest share in meeting the target for the share of zero-emission buses in the public transport fleet.

In accordance with the above, specific assumptions should also apply to the participation of vessels using only the engine for propulsion, the working cycle of which does not lead to the emission of greenhouse gases or other substances covered by the greenhouse gas emission management system referred to in the Act of 17 July 2009 on the greenhouse gas and other substances emission management system providing public transport services within the meaning of the Act of 16 December 2010 on public collective transport.

It is also proposed to bring forward the entry into force of Article 36. This provision, as currently drafted, is due to enter into force on 1 January 2028.

288 Journal of Laws of 2021, item 110, i.e.

3) Hydrogen-powered vehicles in the official vehicle fleets of chief and central state administration bodies and in the official vehicle fleets of local government units:
   a. The current provisions of Article 34 and 35 of the Act provide for specific targets for the percentage share of electric vehicles in the fleet of official vehicles of the chief and central bodies of state administration and in the fleet of official vehicles of local government units only. A similar solution should be implemented for hydrogen-powered vehicles, taking into account the mode of production, i.e. with the division of binding targets for the share of renewable and low-emission hydrogen-powered vehicles. These provisions are to enter into force on 1 January 2025. It is recommended to amend these provisions by extending their scope to include hydrogen-powered vehicles and setting binding targets for their share of the said fleets, and to speed up the entry into force of these provisions, in order to allow for the development of the hydrogen market.
   b. It is recommended to introduce provisions enabling the issuance of implementing acts that would define the technical conditions for hydrogen refuelling stations derived from the electrolysis process, as well as other processes for the production of low-carbon hydrogen, and to introduce a definition of hydrogen refuelling station and amend the related provisions.

4) Act of 20 February 2015 on renewable energy sources (RES):
   a. It is recommended that the RED II Directive regulations concerning guarantees of origin for hydrogen be implemented as soon as possible.
   b. The current law stipulates that guarantees of origin are issued only for electricity generated from RES installations and introduced into the distribution grid or the transmission grid. It means that no guarantee of origin will be issued for electricity generated in RES installations and supplied through a direct line. Amendments should be introduced to ensure that guarantees of origin are obtained for any amount of electricity generated in a RES installation, regardless of the manner of its delivery, be it through a power grid or a direct line.

5) Act of 20 May 2016 on investments in wind farms[289]:
   a. abolishing the requirement of a minimum distance of the wind farm from the residential building, which currently amounts to at least 10 times the height of the wind farm measured from the ground level to the highest point of the structure, including technical components, in particular the rotor with blades - the so-called 10H rule. This rule should be completely abolished or significantly reduced, in the sense that it should be permissible, under certain conditions, to locate wind farms at a distance of less than ten times their height from a residential building.

289 Journal of Laws of 2021, item 724. i.e.

6) Personal Income Tax Act of 26 July 1991[290] and Corporate Income Tax Act of 15 February 1992[291]:

a. It is proposed to amend to allow depreciation for hydrogen vehicles as currently applied to electric cars.

7) Regulatory sandboxes:

Development of innovative technologies and investments in the power industry needs a simplified regulatory regime. Too high barriers to market entry, including regulatory requirements, can hinder the rapid development of new solutions. Regulatory sandboxes" can be a solution to this problem. Regulatory sandboxes are legal constructs that provide a safe environment for the development of pilot projects and the deployment of new innovative technologies or system models, characterised by the removal or relaxation of the legal regulatory regime that would normally apply. "Regulatory sandboxes" in the energy sector can take the form of temporary derogations, e.g. from the requirement to obtain a license to conduct certain business activities or a waiver of tariff setting rules, providing greater freedom in their design. Regulatory sandboxes are most often supervised by the regulatory authority, which assesses the barriers to market entry for innovative technologies and the rules for their management, including by proposing new solutions that will best support the development of these technologies until they reach market maturity and full commercialization.

290 Journal of Laws of 2021, item 1128, as amended.

291 Journal of Laws of 2020, item 1406, as amended.


H2

12

EXAMPLES OF PROJECTS RELATED TO PRODUCTION AND STORAGE OF HYDROGEN FROM RES

12.1 Case study I - Ørsted:

Towards a world powered entirely by renewable energy sources

Hydrogen produced from renewable energy sources is key to reducing greenhouse gas emissions and, consequently, to halting climate catastrophe. Full decarbonization of the global economy, in particular, heavy industry, transport, deep-sea shipping or aviation is not possible without innovative technologies and solutions, including green hydrogen.

With the right stimulation of this technology, renewable hydrogen can become a cheap and widely available alternative to fossil fuels. That is why Ørsted is investing in research and development projects, building international consortia of partners from different industries to respond to global needs and scale up production of this fuel. Its commercial use will bring us closer to the vision of a world powered solely by renewable energy.

Our network of renewable hydrogen technology development and commercialization partnerships brings together organizations from different geographical regions and industries, representing the heavy transport, shipping and refining sectors, but also renowned research institutes. We conduct our innovative projects in cooperation with Siemens Gamesa, Maersk, Scandinavian Airlines or Copenhagen Airport, among others. These partnerships have, in less than three years, led to the development of projects in Denmark, Germany, the Netherlands and the UK, ranging from demonstration installations such as H2RES to industrial-scale facilities such as the 1300 MW "Green Fuels for Denmark" project. We have selected a few of these to present in more detail.

Four projects, so far, have been awarded public funding. These are:

1. H2RES - received DKK 34.6 million from the Danish Energy Agency
2. Westküste 100 - EUR 30.0 million (DKK 223.1 million) from the German Federal Ministry of Economic Affairs and Energy
3. Gigastack – GBP 7.5 million (DKK 65.0 million) from the Department of Business, Energy and Industrial Strategy (BEIS).
4. Oyster - EUR 5.0 million (DKK 37.17 million) from the Fuel Cells and Hydrogen Joint Undertaking (FCH2-JU)

12.1.1 H2RES: hydrogen as a fuel to connect the grid and transport

Ørsted's most advanced project to commercially produce green hydrogen is the H2RES demonstration plant located in Avedøre Holme near Copenhagen, Denmark. On the Ørsted-owned site, a 2 MW high-efficiency electrolyser will be built. The installation will produce hydrogen using energy from two offshore wind turbines with a total capacity of 3.6 MW. The resulting feedstock will be fed into the Danish grid in the autumn of 2021, just five months after construction of the plant began.

Once operational, the electrolyser is expected to produce 1,000 kg of hydrogen per day, which will be used to power road transport in the Copenhagen region and on Zealand.

The budget of the research project amounts to nearly 73 million Danish crowns, almost half of which was obtained from a grant of the Danish Energy Agency. The project is carried out by a consortium of seven companies (besides Ørsted Wind Power, there are also Everfuel Europe, NEL Hydrogen, Green Hydrogen Systems, DSV Panalpina, Hydrogen Denmark and Energinet Elsystemansvar), where each partner has a specific role in the development, design and construction of the electrolyser, the compression and storage system, as well as in studying the impact of the installation on the operation of the power grid.

The aim of the project is to demonstrate the operation of a highly efficient electrolyser that produces hydrogen from variable wind power in an integrated power system, and then uses the environmentally friendly fuel to power zero-emission transport. The hydrogen in the H2RES flagship project is set to become the link between the electricity system (grid) and the transport sector, which in turn will stimulate both the development of large-scale offshore wind farms and the commercialisation of zero-emission transport based on this fuel. The ambition of the project is also to launch the production of hydrogen from RES in conditions similar to commercial ones, as well as to develop recommendations on technologies, regulations and business models that will increase the competitiveness of green hydrogen in the near future.

Ørsted does not disclose the amount of capital expenditure for the electrolyser, nor the expected cost of obtaining 1 kg of green hydrogen.

Anders Nordstrøm, Vice President and Head of Ørsted›s hydrogen business:

> "Renewable hydrogen will be a milestone in achieving Denmark's ambitious decarbonisation goal. H2RES is an example of how public co-financing combined with a committed hydrogen industry and ambitious customers can drive the decarbonisation of the transport sector. H2RES is a small but important step towards large-scale hydrogen production from renewable sources and will allow us to demonstrate how offshore wind combined with onshore electrolysis can deliver decarbonisation beyond direct electrification."

12.1.2 Oyster: designing an electrolyser for use in harsh marine environments

Ørsted, alongside Siemens Gamesa Renewable Energy, Element Energy and ITM Power, is one of four members of a consortium that has secured EU funding to explore the possibility of producing green hydrogen directly at sea. The EUR 5 million grant will be used to build and test a complex system consisting of an offshore wind turbine and a 1 MW electrolyser designed to operate in a demanding marine environment.

The challenge is to build a compact plant that requires minimum maintenance. At the same time, the design must meet stringent cost and performance requirements so that the fuel is ultimately cheap.

The project will start already in 2021 and will last until the end of 2024. The demonstration test of the electrolyser launched in the port will start at the end of 2022 and will last 18 months.

The project is the first step needed to develop the commercial production of hydrogen from offshore wind farms directly at sea and then piped to land. The potential of this solution is expected to help in the deployment of commercial offshore wind farm hydrogen production systems at sea in Europe and beyond.

In the project process, ITM Power has assumed responsibility for electrolyser system development and testing. Ørsted, in turn, is conducting a deployment analysis and then a feasibility study of future physical realizations of such offshore installations. At the same time, it will support ITM Power in designing the electrolyser system and testing it in harsh marine conditions. SGRE and Element Energy will provide technical and design expertise.

12.1.3 SeaH2Land: world's largest hydrogen power plant for industry in the Netherlands and Belgium

Ørsted is working on a 1 GW renewable hydrogen plant to decarbonise ammonia, steel, ethylene and fuel production in the Dutch-Flemish North Sea port cluster.

The project involves building the plant by 2030 and then connecting it directly to a new 2 GW offshore wind farm in the Dutch North Sea.

This will enable the large-scale supply of renewable electricity required for the production of renewable hydrogen, which fits well with the Dutch authorities' ambition to accelerate the development of offshore wind in line with the growing demand for electricity.

A new offshore wind farm could be built in one of the zones in the southern part of the Dutch Exclusive Economic Zone that has already been earmarked for SHPP development. Such an electrolyser connected by pipeline to a cluster located in the Dutch-Flemish North Sea ports could produce enough green hydrogen to cover about 20% of the demand of the industry there.

Companies located in the region, including ArcelorMittal, Yara, Dow Benelux and Zeeland Refinery, currently rely on fossil hydrogen, generating Europe's largest demand of 580,000 tonnes per year. The industry is supporting the construction of the required trans-regional infrastructure to enable the future production of steel, ammonia, ethylene and fuels in a sustainable and zero-carbon way, helping the Netherlands and Belgium accelerate the decarbonisation of their industries by 2030 and in the decades to come. With decarbonisation efforts, industrial demand in the cluster could increase to about 1 million tonnes by 2050, equivalent to about 10 GW of electrolysis.

12.1.4 DFDS ferry: emission-free Copenhagen-Oslo

Ørsted together with DFDS and in cooperation with many other partners (ABB, Ballard Power Systems Europe, Hexagon Purus, Lloyd's Register, KNUD E. HANSEN, Danish Ship Finance) have set themselves the goal of connecting the Scandinavian capitals of Oslo and Copenhagen, using a ferry powered by hydrogen produced from renewable energy sources.

The ferry will be powered by electricity from a hydrogen fuel cell system that emits only water and can generate up to 23 MW to power the ferry. A major challenge for the partners is to build such a large installation. Today, the largest fuel systems produce only 1-5 MW. The key to success lies in partnering with companies that together can gain one of the world's best expertise in designing, approving, building, financing and operating innovative vessels.

The partnership has received funding from the EU's Innovation Fund. If the project develops as envisaged, the ferry could be fully operational on the route by 2027. The ferry, with the working name Europa Seaways, will be able to carry 1,800 passengers and will be able to accommodate 120 trucks or 380 cars.

The hydrogen to power it will be produced locally in the Copenhagen region based on offshore wind energy, and the project participants will investigate how to optimally integrate green hydrogen production into the local energy system.

12.1.5 Green fuels for Denmark

Ørsted has partnered with leading Danish companies to develop industrial-scale production of renewable hydrogen and sustainably produced fuels for use in road, sea and air transport. Behind the project is a partnership consisting of A.P. Moller - Maersk, DSV Panalpina, DFDS, SAS, Copenhagen Airports and Ørsted. Nel, Haldor Topsøe and Everfuel have partnered on the first phase of Green Fuels for Denmark and the development of the second phase. In addition, COWI is a content partner of the project. The project is supported by Molslinjen, the City of Copenhagen and the Capital Region of Denmark. The involvement of so many partners is intended to ensure both supply and demand for green hydrogen and enable the construction of a 10 MW electrolyser by 2023, a 250 MW electrolyser with the capacity to produce green fuels by 2027 and with a vision to increase the capacity to 1.3 GW. The energy needed for the electrolysis process is to be obtained from offshore wind farms off the coast of Bornholm in the Baltic Sea. Until the offshore wind farms around Bornholm are developed, the main part of the renewable hydrogen will be combined with sustainable coal harvesting to produce 250,000 tonnes of e-kerosene and e-methanol per year.

12.1.6 Westküste 100: towards more sustainable industry, aviation, construction and heating

The aim of the German project is to support the decarbonisation of industry, aviation, construction and heating using renewable hydrogen on a large scale. The project has received funding of EUR 30 million from the German Federal Ministry of Economic Affairs and Energy. With these funds, the Westküste 100 project has entered the implementation phase. It established the joint venture "H2 Westküste GmbH", consisting of EDF Germany, Ørsted and Heide refinery, which will build a 30-megawatt electrolyser. The plant will produce green hydrogen from offshore wind energy. The project will also collect and process information on the operation, maintenance, control and network services of the power plant. Transporting hydrogen through pipelines and using the fuel in existing and new infrastructure around Heide will also be tested. The consortium will also begin work on developing a vision for large-scale sector coupling, including a 700 MW electrolyser system.

Read more about our projects: **https://orsted.com/en/our-business/renewable-hydrogen**

12.1.7 Development pathway for renewable hydrogen in Europe

Climate challenges and the need to decarbonize the economy, if taken seriously and responsibly, become an opportunity for the development of innovative technologies. In response to these challenges, Ørsted started to develop new energy production technology as early as 1991, thus developing and commercializing the technology for clean energy production from offshore wind farms.

The ambition of deep decarbonisation of the economy is an important challenge for Ørsted. Each successive project with innovative partners brings us closer to the stage where we can successfully commercialize hydrogen production from renewable energy sources and respond to the needs of many sectors of the economy.

Renewable hydrogen technologies and the implementation of e-fuel production on a mass scale are key to keeping the Earth's temperature rise below 1.5°C.

The European Commission estimates, among other things, that achieving climate neutrality in Europe by 2050 will increase energy demand by up to 150% compared to today. Part of this growing demand will be driven by electrification or direct economic growth. However, it is estimated that renewable hydrogen and e-fuels will account for more than half of the European growth in power by 2050. The success of the green transition thus depends on the efforts of policy makers, investors, renewable energy producers and industrial consumers.

Participation in so many European projects is an expression of Ørsted's highest commitment to the global decarbonisation process, but also of many years of experience in commercialisation of SHPP technology, which teaches us that it may take up to 10 more years to reach the stage when green hydrogen will be used on a mass scale in all sectors of the economy.

The same happened to the costs of producing energy from solar farms and onshore and offshore wind farms.

12.2 Case study II - PGNiG, Gas Storage Poland:

Use of cavern storage facilities - importance for the energy system and scope of services possible to be provided

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12.2.1 Energy system transformation and large-scale energy storage

As described elsewhere in this Report, there are and will be more and more renewable sources of electricity generation in Poland's power system across a wide range of capacities: from the intensely growing photovoltaic sector, mainly due to an increasing number of prosumers, to the planned offshore wind farms. This will significantly change the model of the whole electricity system and its functioning. As the amount of energy produced from renewable energy sources (RES) increases, the market for energy storage is gaining importance and interest from prosumers interested in using the energy produced, as well as from grid operators and large RES sources (hybrid installations). The development of RES energy production capacities, in particular offshore wind capacity, will require the provision of a large-scale energy storage system. The expected further development of photovoltaics, whose operation is correlated with summer peaks in electricity demand, as well as onshore wind farms, which generate electricity in similar timeframes as offshore wind[292], will only strengthen the need for system-wide energy storage.

The integration of highly volatile and inflexible RES and the development and implementation of an efficient method for large-scale energy storage aims at coping with fluctuations in energy demand and integrating electricity generation from volatile renewable sources. If large amounts of energy could be

292 *Energy Policy of Poland until 2040...*

stored and fed back into the grid when needed, generation would no longer be dependent on fluctuating demand. Therefore, in the future, when energy production is based on RES, large-scale energy storage will be an indispensable key element of the energy system. The Gas Infrastructure Europe (GIE) report[293], based on the European Hydrogen Backbone (EHB) project, indicates that the demand for hydrogen storage capacity by 2050 will be almost twice as high as the demand for natural gas storage capacity, due to much lower energy density of hydrogen compared to natural gas. In Poland, at the current stage of planning in the perspective of 2040, it is assumed that 4-5 salt caverns for hydrogen storage will be built. Each salt cavern will have a geometric volume of 200,000-300,000 m^3 , which will allow storage of 320,000 to 450,000 MWh of energy in the form of hydrogen in a single cavern.

12.2.2 Energy storage in underground geological structures

While short-term energy storage will be met with small, decentralized storage systems, medium- and long-term storage will require the development of large-scale electricity storage technologies.

One of the most promising methods for large-scale electricity storage is in the form of compressed hydrogen in geological structures. Using hydrogen as an energy carrier could help solve the grid balancing problem in the future when large amounts of variable renewable energy are introduced into the energy mix. Storing energy in the form of hydrogen in geological structures is a very efficient solution to reduce investment costs and land area. One salt cavern with a geometric volume of 200,000 m^3 allows for storage of approx. 80,000 MWh of energy in the form of hydrogen. Together with the surface infrastructure, it occupies about 6 ha of land. To store a similar amount of energy in battery containers of 40 inches with a capacity of 0.8 MWh, it is necessary to install 100 000 containers, whose total length will be 1200 km, and the occupied surface area about 3.5 million m^2.

The underground storage of energy carriers in geological structures has been practiced on a large scale for decades. It is an economically and technically mature solution. Currently, numerous projects are being launched focusing on large-scale underground energy storage in geological structures in the form of hydrogen and compressed air. The underground space used for substance storage is natural pore space or artificially created cavities. Substances are stored in pore spaces of depleted natural gas or oil deposits, in water-bearing structures (the so-called aquifers) and in artificially created mining processes, post-mining excavations, rock caverns or salt caverns. Salt caverns have been gaining importance in recent years due to the possibility of large-scale storage of short-, medium- and long-term of all types of gaseous and liquid hydrocarbons, hydrogen and compressed air as well as excellent technical and operational parameters. Among all types of storage facilities in geological structures, only salt caverns are characterised by very high flexibility of operation, i.e. the possibility to switch from injection to withdrawal and vice versa within several hours. Moreover, the caverns have the possibility to perform many injection and withdrawal cycles during one year and large injection and withdrawal capacities, i.e. up to 200,000 m^3 of gas per hour, which is of key importance for energy storage function. Salt caverns also ensure very high technical and environmental safety due to physical and chemical properties of salt rocks. Rock salt has properties favourable for storing gases, including hydrogen. It is characterised by low permeability and porosity, contains no water and is chemically inert in relation to the stored substances. Its

293 *Picturing the value of underground gas storage to the European hydrogen system*, Guidehouse study, Gas Infrastructure Europe 2021.

specific rheological properties ensure the tightness of the rock mass for the stored substance. Rock salt is a medium essentially impermeable to stored media. Under certain conditions, however, when the pressure in the cavern approaches the lithostatic pressure prevailing in the rock mass, the rock salt behaves as a pore medium with very low permeability of 10-20 - 10-21 m^2. The suitability of salt deposits for the construction of underground gas storage facilities was demonstrated by the construction and operation of several hundred storage caverns worldwide, including 24 caverns in Poland for the storage of natural gas at Mogilno and Kosakowo caverns.

12.2.3 Salt caverns are the best solution for large-scale energy storage

According to the GIE Report[2], salt caverns are the only type of storage whose suitability for storing pure hydrogen or a mixture of hydrogen and natural gas has already been proven. Furthermore, the unified costs of storing hydrogen in salt caverns will be lower than storage in rock caverns, depleted gas and oil fields or aquifers.

There are currently six hydrogen-filled salt caverns in operation worldwide. The first large-scale hydrogen storage facilities were mainly used by the petrochemical industry. Currently, several salt caverns have been developed in the United Kingdom (e.g. in Teesside) and the United States to store hydrogen for petrochemical purposes, which is produced from natural gas. The technical details of these caverns are shown in Tab.12.1.

Table 12.1. Parameters of the existing salt caverns for storing pure hydrogen in the USA and the UK

Location/Parameters	Teeside, Sabic Petrochemical United Kingdom	Clemens Dome Conoco Phillips, USA	Spindletop, AirLiquide, USA	Moss Bluff Praxair, USA
Geology	Salt deck	Salt dome	Salt dome	Salt dome
Geometric volume [m^3]	3 x 70 000	580 000	906 000	566 000
Depth [m p.p.t.]	350–380	850–1150	1158–1524	> 820
Pressure range [MPa]	~4.5 MPa	7–13,5	6,8–20	5,5–15,2
Accumulated energy [GWh]	25	83.3 (approx. 2500 tonnes H_2)	n.a.	80

Source: Overview on all known underground storage technologies for hydrogen. HyUnder Project Report 2013.

Large-scale hydrogen storage in salt caverns in the US and UK clearly demonstrates that underground hydrogen storage is technically feasible. The GIE report confirms that hydrogen storage in depleted gas and oil fields and aquifers shows considerable potential, but requires further research to prove the suitability for storage of pure hydrogen or a mixture of natural gas and hydrogen.

12.2.4 Hydrogen storage in Poland

Poland has very favourable geological, mining and technical conditions for the construction of cavern storage facilities in salt domes. According to data from the Gas Infrastructure Europe GIE report[294],

294 *H_2 storage needs to exceed existing gas storage: GIE*, https://www.argusmedia.com/en/news/2225419-h2-storage-needs-to-exceed-existing-gas-storage-gie

Poland ranks high among European countries with respect to the possibility of storing hydrogen in salt caverns.

GIE studies predict that Poland will have needs for hydrogen storage at the level of 3.6 TWh in 2030 and about 36.5 TWh in 2050. Poland currently has the potential to store hydrogen in salt caverns at the level of 2.2 TWh, and in all types of storage facilities 9.3 TWh - Tab. 12.2.

Table 12.2. Potential hydrogen storage capacity

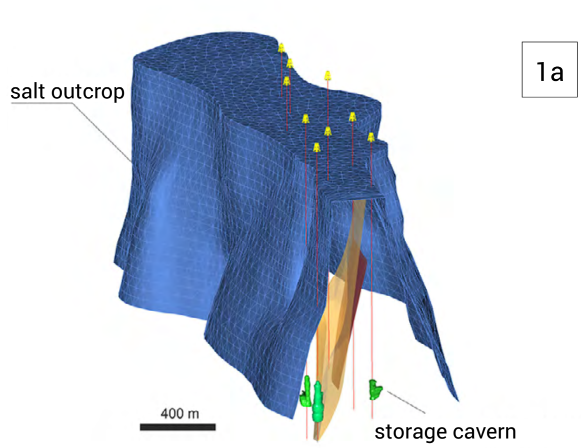
Country	Potential hydrogen storage capacity: salt caverns	Potential hydrogen storage capacity: all types of storage
Dishes	1.3 TWh	3.3 TWh
France	2.5 TWh	31.9 TWh
Germany	39.5TWh	61.4 TWh
Poland	**2.2 TWh**	**9.3 TWh**
United Kingdom	3.7 TWh	4.8 TWh

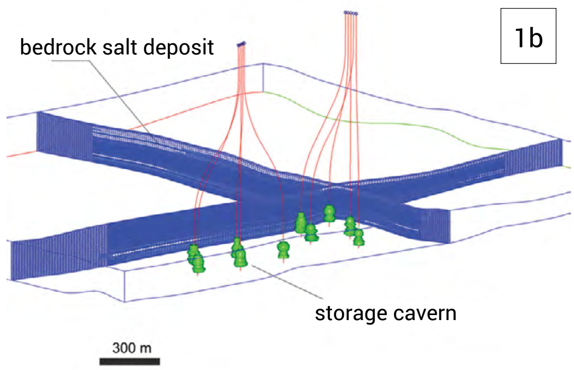
Source: H_2 storage needs to exceed existing gas storage: GIE (argusmedia.com).

Rock salt deposits in Poland are found in the form of both seam deposits (northern Poland and pre-Sudetic monocline) and outcrop deposits (north-western and central Poland), Fig. 12.1. The form of the deposit and its internal structure have a decisive influence on the storage capacity of an individual cavern and the entire storage facility. Outcrop deposits (Fig. 12.1a) are characterized by a limited horizontal extension of the deposit, practically unlimited thickness from the point of view of the structure of storage caverns and complicated internal structure, i.e. high-angle layer of evaporite rocks and presence of various lithological types of rock salts and potassium and magnesium salts, as well as overlaying of anhydrite, siltstone and claystone of highly diversified thickness.

Figure 12.1. Geological model for a) outcrop and b) bedrock salt deposit

Rock salt outcrop deposit	Bedrock salt deposit
a)	b)





Source: own study.

Outcrop deposits (Fig. 12.1b) are characterized by limited vertical extension of the deposit, practically unlimited horizontal extension and simple internal structure, i.e. horizontal or low-angle layer of evaporite rocks and presence of almost uniform lithological types of rock salts, lack of potassium and magnesium salts and interbedding of small thickness of anhydrites. The experience gained in the construction of salt caverns allows to conclude that due to the internal structure of the Polish outcrop deposits it will be possible to build caverns of the geometric volume of 300-400 thousand m^3 for hydrogen storage purposes. On the other hand, in Polish outcrop deposits it will be possible to construct caverns with geometrical volume of 150-250 thousand m^3 for hydrogen storage purposes. Such large geometric volumes will make it possible to store very large amounts of energy in the form of hydrogen. It is estimated that a single salt cavern with the geometrical volume of 200,000 m^3, located at the depth of 1000-1200 m below sea level and maximum bottom storage pressure of 17 MPa, will allow storage of approx. 2200-2400 Mg of hydrogen, i.e. approx. 82.5 GWh.

12.2.5 Hydrogen storage - business models

From the commercial point of view, the key issue related to storing hydrogen in salt caverns is to develop business models that will take into account not only the status of the storage facility operator (regulated role), but also the scope of services provided at the interface between the storage facility and the power system as well as the 'green hydrogen' tracking/certification system and the rules of its settlement. Below are presented four possible business models for storing hydrogen in salt caverns, taking into account the particular scope of services provided depending on market expectations.

In the first model, surplus electricity produced by e.g. offshore wind farms in the Baltic Sea is harvested. The energy, in the form of hydrogen (produced by an electrolyser working in conjunction with a cavern), is stored and then converted back into electricity and fed into the system, providing flexibility.

The model is thus one of receiving and then supplying electricity. The construction of the entire system is then on the side of the cavern manager, similar to what is currently done in pumped storage power plants.

The second possible model involves receiving the electricity, processing and storing the hydrogen, and returning the energy still in the form of hydrogen. In this solution, the energy storage service "ends" when the hydrogen is returned from storage. Further processing of the hydrogen or its application is already beyond the service of the cavern manager.

In the third model, it is not electricity but hydrogen that is collected (electrolysis is outside the cavity manager's service), which, after storage, is converted into electricity that is fed back into the system. In this model, the sources of electricity production 'behind the cavern' are also managed by the cavern manager.

The last model, the fourth one, includes only the hydrogen storage service, which is delivered and received to the cavern manager. In this case, there is neither electrolysis nor generation using hydrogen on the side of the storage manager, while the storage service itself is the simplest from a technical and business point of view.

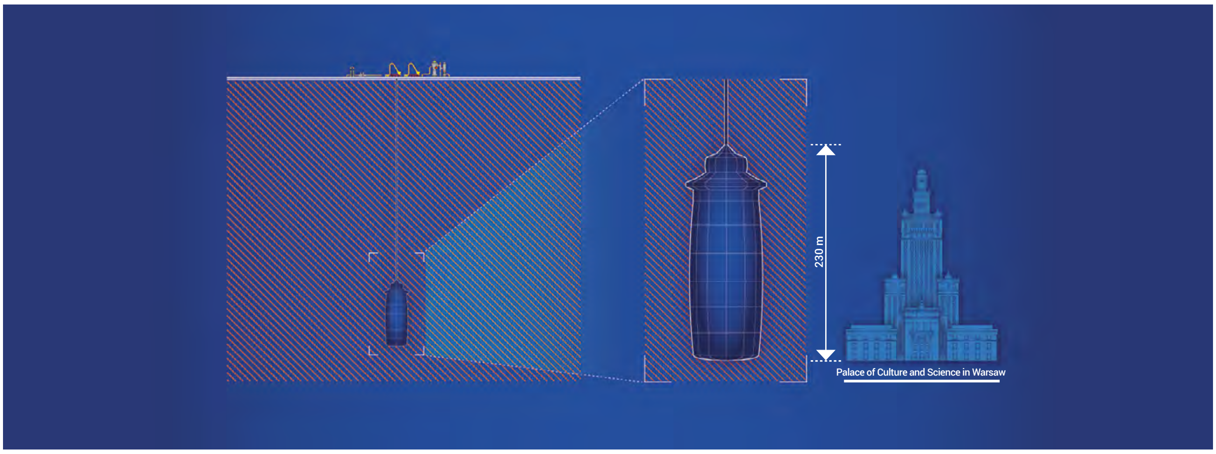
For the above business models to work, it is necessary to cooperate with various groups of energy market stakeholders - especially RES generators, the transmission system operator (TSO), the distribution system operator (DSO), energy users from various sectors of the economy, and the energy system regulator.

12.2.6 H2020 project - large scale hydrogen energy storage in salt caverns

In Poland, in 2020, Gas Storage Poland developed a "Concept for the construction of a large-scale green hydrogen storage facility in salt caverns" and launched a project called H2020, which includes the construction of a demonstration plant with a research cavern and a large-scale energy storage facility in salt caverns. The project involves the construction of salt caverns for the storage of green hydrogen cooperating with a RES source, a high power electrolyser for the production of green hydrogen and fuel cells and/or a hydrogen turbine for the production of green energy.

At present, Polish Oil and Gas Company in cooperation with Gas Storage Poland performs the project of large-scale commercial underground storage of energy in the form of hydrogen in salt caverns, which in the future will serve as energy storage for the needs of RES development, balancing the demand and supply of energy, while ensuring reliability, efficiency and security of electricity supply.

Figure 12.2. Cavern-type underground gas storage facility consisting of an aboveground facility which coordinates gas injection and withdrawal, and an underground chamber, i.e. a salt cavern



Source: own study.

12.2.7 Summary

The shift from conventional to renewable energy sources means that new methods of system-scale electricity storage are needed to balance supply and demand. Consequently, hydrogen will play an increasingly important role as a storage medium. At the same time, geological structures - salt caverns - are the only reservoirs with sufficient capacity and capability to store the large quantities of hydrogen (energy) needed by the system in the long term.

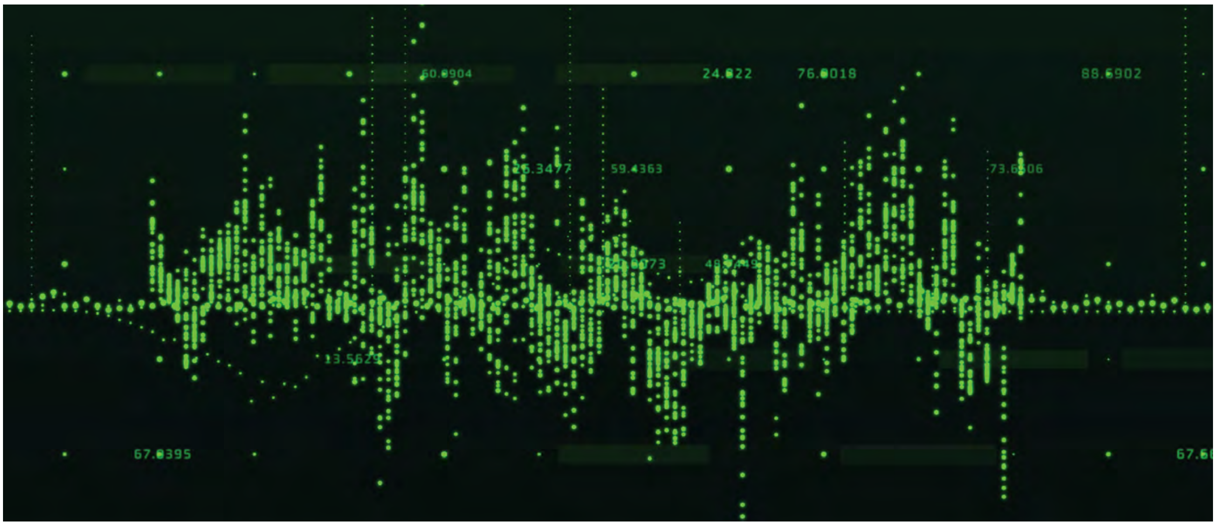
Poland has extremely favourable geological conditions and long experience in the construction of salt caverns for natural gas to be one of the few countries in Europe, which will have storage chambers for hydrogen. Storage of energy in the form of hydrogen in salt caverns will be an important element in the process of energy transition in Poland and Europe. At present, due to technical, technological and environmental reasons, no other methods of large-scale energy storage are considered for balancing energy production from RES.

Almost all currently implemented projects related to large-scale energy storage in the form of hydrogen assume its storage only in salt caverns, mainly for technical, economic, environmental and safety reasons. Due to the limited extent of occurrence of rock salt deposits or their lack in some countries, further research will be conducted on the possibilities of storing hydrogen in other geological structures, especially in depleted natural gas and oil reservoirs.

Large-scale energy storage projects with business models are currently being developed, while assets will be created in parallel with the emergence of the “green hydrogen” market over the next few to dozen years.

12.3 Case study III - Transition Technologies:

IT support for green hydrogen industry in Poland



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12.3.1 Use of modern IT technologies in the process of green hydrogen industry development as a necessary element of building competitive advantage

Competition in the field of materials and engineering technologies, necessary for the development of hydrogen economy, in particular, green hydrogen with the use of RES sources, with such industrial powers as Germany, USA, Japan or Korea, can be a real challenge and it is worth asking whether, as Poland, we are able to become a significant player in this sector and how to effectively build a competitive advantage in this area? In this chapter of the Report we put forward the thesis that we can achieve this only by incorporating widely understood digitalization and the use of IT tools at every stage of production, storage, transmission, distribution and use with the control of processes and their cost optimization. An area that deserves special attention is certainly the IT sector, where Poland has a long-established brand and recognition in Europe and even in the world. Focusing on the development of IT tools to support the green hydrogen market may give a new impulse to a completely independent sector of the economy and place Poland in the forefront of suppliers and consumers of this energy carrier.

A comprehensive approach to the topic of digitalization of the hydrogen industry requires an analysis of the interoperability of information systems providing support to process participants, both in the OT and IT layers. In the case of advanced IT tools, they can play an advisory role or, in a bidirectional connection with OT systems, be a source of control signals for automation systems eliminating the human factor in most routine processes. In principle, IT systems can be directed to support two areas of activity of entities involved in the hydrogen industry: technical and business.

Effective production and processing of a new gaseous energy carrier such as hydrogen is not possible without a modern and automated industrial process based on technologies described as Industry 4.0. Its main components usually include the following technologies: **Internet of Things, Big Data, Augmented Reality, Blockchain, SMART manufacturing** and **Connected Enterprise**. All these elements form the basis for the gradual digitalization of technological and commercial processes and thus obtaining additional benefits resulting from their optimization. It is very well described by Deloitte in its report titled *Industry 4.0 and manufacturing ecosystems. Exploring the world of connected enterprises*[295]. The approach consisting in using the advantages of Industry 4.0 technology in the ongoing transformation of the entire energy sector, in particular, in the course of its expansion by new segments, i.e. the hydrogen energy segment, undoubtedly increases innovation of the entire undertaking and enables development of completely new branches of economy. This is an opportunity that should not be missed by focusing solely on economic or process aspects. This phenomenon is indicated in many reports and studies of international organizations, including the UNIDO report[296] entitled *Accelerating clean energy through Industry 4.0 - manufacturing the next revolution.*

12.3.2 Support of technical processes

In terms of support for the technical area of the hydrogen industry, each of the individual stages of the supply chain: production, storage, transmission and distribution, and utilization, can benefit from the increase in efficiency and security of operations through the use of IT tools. The basic class of IT products, which through integration with automation systems enable further work with large volumes of data, are tools for data acquisition and archiving. These systems are the source of data for tools simulating and optimizing the operation of technological facilities. The main advantage of using simulation products for the facilities of the emerging hydrogen infrastructure is the possibility of assessing the effectiveness and profitability of new investments in installations and modelling their operational use. In addition, the use of such tools enables to determine the bottlenecks of the installation in order to create an effective plan for their expansion and retrofitting. The implementation of optimization tools is the next step to efficiently utilize existing plants within technical and business constraints. Optimization tools are usually the top layer of complex IT systems and, in combination with automation systems, lay the foundation for using artificial intelligence to manage processes in technological facilities.

The following subsections detail a number of areas in which information systems support will provide opportunities to enhance hydrogen industry development through increased efficiency and process safety.

12.3.3 Integration, acquisition and validation of process data

Reliable assessment of the technical condition of an industrial installation and the condition of technological processes is an absolute basis for making key operational and business decisions related

295 B. Sniderman, M. Mahto, M. Cotteleer, *Industry 4.0 and manufacturing ecosystems Exploring the world of connected enterprises*, https://www2.deloitte.com/us/en/insights/focus/industry-4-0/manufacturing-ecosystems-exploring-world-connected-enterprises.html

296 United Nations Industrial Development Organization, *Accelerating clean energy through Industry 4.0. Manufacturing the next revolution*, REPORT_Accelerating_clean_energy_through_Industry_4.0.Final_0.pdf (unido.org)

to the operation of the installation. The basic source of information, which allows to make this assessment are the automation systems that control the process carried out by the technical installation.

The provision of process data in an appropriately aggregated form to the personnel deciding on the business objectives for individual plants lies within the scope of the so-called process data warehouses already commonly used in industry. The main areas of operation of these systems include:

- process data acquisition from multiple automation systems to a single, central database using mechanisms supporting cyber security (e.g. data diodes ensuring fully unidirectional data transmission from the OT area to the IT network),
- manual and automatic process data validation (by means of digital models),
- visualization of the process "in real time" (e.g. by means of time trends of measurements or with the use of the so-called synoptic graphics), pre-processing and aggregation of process data to KPI indicators showing the quality of the technical process being performed, reporting of the current or archival status of the process,
- making process data available to other IT systems supporting analyses (BI (Business Intelligence) class systems), as well as operational and business decisions.

12.3.4 Technical asset management and maintenance support

Systems supporting technical asset management and maintenance processes (CMMS (Computerized Maintenance Management System) class systems and EAM (Enterprise Asset Management) class systems) have already entered the canon of IT solutions applied by industrial enterprises. Their primary objective is to ensure good technical condition of industrial installations through appropriate operating, maintenance and service procedures, optimally adjusted to the individual plant components.

The main tasks of CMMS/EAM class systems include:

- inventory and records of technical assets,
- planning, implementation and monitoring of maintenance strategies specific to the individual components of the technical installation,
- support for standard maintenance activities: preventive maintenance to prevent failures from occurring and corrective maintenance to recover from failures (reactive maintenance),
- handling of work orders comprehensively describing the scope of work, conditions for their execution, competences of the persons executing them, required parts, consumables, tools, etc.,
- classification of performed maintenance activities and defects, enabling the accumulation of knowledge necessary for the successive adjustment of the maintenance strategy,
- additional areas of EAM class system operation, such as management of investments, material resources, human resources, finance, risk.

The assumptions of Industry 4.0 with regard to supporting processes of technical asset maintenance are implemented by a range of modern IT solutions including:

- on-line diagnostic systems whose purpose is to detect "real time" operating anomalies of machines or of an entire industrial installation by comparing the measured values of the measurement signals with the estimated values of the signals determined from a digital model of the device/process (digital twin),
- systems supporting predictive maintenance, allowing to predict equipment failures in a certain

time horizon in the future - also using digital models, which can take into account information about the historical course of the process and equipment maintenance history,
- systems using Virtual Reality, Augmented Reality or Assisted Reality technologies, which provide staff with additional information, in a way that does not interfere with their work, using additional augmented reality glasses or so-called wearable computers, which is an alternative or complement to the mobile devices such as smartphones or tablets used so far.

The above-mentioned systems are usually integrated with CMMS/EAM class solutions in order to provide comprehensive support for technical asset management processes.

12.3.5 Prediction and detection of undesired infrastructure conditions

Another key aspect of hydrogen industry development is ensuring the integrity of the technological infrastructure. Phenomena such as corrosion of materials and ground deformation can damage the integrity of infrastructure facilities and cause leakage of the stored medium inside. Therefore, within this issue a comprehensive IT solution is proposed, the aim of which is both the prediction of undesirable phenomena and their immediate detection. The use of modern machine learning technologies, in conjunction with studies on the interaction of hydrogen with a number of materials, will result in the development of IT tools for effective modelling of the phenomenon of corrosion, which is an important advisory element in assessing the investment attractiveness of hydrogen infrastructure, as well as its further maintenance.

Another key issue is the detection of undesirable changes that may negatively affect the operation of the existing infrastructure. The most innovative and dynamically developing technology in this field is currently the technology of unmanned aerial vehicles (drones), equipped with appropriate sensors and software for data analysis. The great advantage of this method is the low cost and high mobility of the solution. Based on advanced methods of data analysis and machine learning, the high efficiency of over 90% enables the detection of even slight leaks of the medium or ground deformations which may lead to such deformations. The use of unmanned aircraft technology in conjunction with tools for the prediction of potential failures and optimization of raid routes, as well as the development of new sensors to detect the presence of hydrogen in the air, will certainly raise the level of efficiency and safety of the growing hydrogen industry.

12.3.6 Simulation and ongoing optimization of electrolyser and electrolyser units

The problem of cost-optimal management of the operation of electrolysis plants for the production of hydrogen is worth solving by means of a combination of online control of the electrolysis process and planning of load distribution between individual units based on their characteristics. The task of current control is to maintain their operating points in optimal areas, while controlling the current values of process parameters in such a way as to bring them to the level of set values. In combination with the aforementioned tools for current diagnostics, such solutions can ensure optimum, operationally and technologically safe management of individual electrolysers. The overarching tool that complements this process is an optimizer of load distribution between individual electrolysers, operating on the basis of a plan of aggregated demand for hydrogen production from the entire plant and electrolyser characteristics. This approach requires creation of models of individual hydrogen production units, the so-called digital twins.

12.3.7 Simulation and optimization of hydrogen storage process (also in combination with natural gas)

Currently, the most commonly considered method of storing large volumes of hydrogen is its storage in underground depots. On the basis of created models of storages, including both aboveground devices and underground infrastructure, and input data (including those obtained from data acquisition IT systems) it is possible to simulate or optimize the operation of these facilities. The use of simulation tools makes it possible to quickly verify the feasibility of injection or extrusion of the required medium volume and, as a result, to determine the bottlenecks in the installation.

The use of the optimization tool may serve to minimize the operating costs at this stage of the supply chain. For a given volume of injected or extruded medium and the boundary conditions, the optimizer will be able to propose the optimal medium flow path, a set of interconnected elements of the installation and their optimal operating points for performing the task. Additionally, the storage models can be used to solve another optimization task, i.e. maximizing the plant throughput. In this mode, the technical operator can estimate what is the maximum customer-usable storage throughput depending on the current fill level and the current and projected condition of the individual components of the technical installation.

The optimization tool can be used in an advisory mode, providing the operators with the information they need to optimize warehouse operations. The calculated optimal values of process parameters can also be transferred to the automation system in the form of control signals, thus ensuring full automation of the technical management of the warehouse.

12.3.8 Simulation and optimization of operation of gas transmission and distribution networks with distributed generation and hydrogen injection

Taking into account current development trends in the area of large-scale hydrogen transmission, an important aspect in the operation of gas networks in the near future will be to enable operational processes involving distributed hydrogen injection. Particularly important will be the task of maintaining acceptable hydrogen concentrations in natural gas, which may vary depending on the system segment, while maintaining continuous supply of the mixture with the required quality parameters. IT systems for the simulation of processes could provide important support in developing plans for the expansion of new network infrastructure dedicated to hydrogen to meet the growing demand for this energy carrier in places where the gas network could not already provide the necessary absorption capacity for additional volumes of the hydrogen medium.

The developed network model with its individual segments could be used within an optimization IT tool for efficient management of network operation at individual stages of development. This solution, operating in a multilayer structure, would ensure cost minimization in the superior layer through the use of optimal sets of devices on alternative lines designed to perform specific actions: compression of the transported medium in transmission networks or its pressure reduction in distribution networks along with hydrogen injection into the network from distributed sources. Based on these data, the slave layer would be able to distribute the load among the available devices in the sets, taking into account their efficiency characteristics and changing availability.

12.3.9 Technical and economic optimization of the use of produced hydrogen

According to the main development guidelines of the hydrogen industry, the use of this energy carrier is planned in three main areas: energy, transport and industry. IT support for multi-energy companies in this field can be provided by means of a multi-layered optimization tool, taking into account both commercial and technical aspects of the related processes.

The main objective of the optimizer could be to maximise revenue from hydrogen use based on information about available hydrogen volumes, current market conditions, data from existing economic support systems and the technical and cost characteristics of technological processes using hydrogen as an energy carrier. For each time step of the scenario, the optimizer would be able to provide the user with information on how the available hydrogen could be optimally used or resold to the end users. The tool will be able to support both teams that trade in gaseous fuels and operators of hydrogen facilities.

At the master layer, the optimizer would take into account currently available volumes and hydrogen demand, hydrogen and electricity prices, but also current electricity demand. The system would also take into account the hydrogen fuel demand profile and the criticality level of industrial plants.

The subordinate layer would realize the task of minimizing the operating costs of individual technical installations in the supply chain by planning the optimal load distribution between individual devices and the selection of operating points of the devices that guarantee the realization of the set process parameters.

12.3.10 Business process support

Currently, the hydrogen market is shallow, based on direct seller-buyer relationships, and there is no mass, institutionalized trading as there is in the natural gas market. Moreover, as mentioned in this report, there is a lack of regulations and guidelines related to trading, storage, transport and e.g. safety requirements. Without rapid development of these formal bases, Poland will not be able to become a significant participant in the hydrogen economy.

Nevertheless, observing political decisions and research directions, it can be foreseen with high probability that the hydrogen market will eventually be similar to the current natural gas market. As at present, such elements of the value chain as production, storage, transmission, distribution and use of hydrogen will be particularly important. At each of these stages, it will be necessary to create tools to support the functioning of individual participants and roles in this system.

12.3.11 Support for hydrogen trading processes

The creation of a mass and public hydrogen trading market will require the development of IT tools to support trading in this energy carrier. Currently, many companies from the energy sector use various CTRM class solutions to support trading processes. These tools enable trading and servicing of contracts for energy raw materials both in terms of strictly commercial aspects, as well as ensuring and servicing financing. At the same time, an important element of these systems is the management and mitigation of risks associated with occupied trading positions, agreements and credit contracts. These systems also support trading in property rights and emission certificates. Obviously, it is necessary to assume a certain specificity of trading in a new energy carrier, i.e. hydrogen, different from natural gas and the resulting necessity to modify these solutions, however, the similarities seem to prevail.

Contract portfolio optimization typically also includes opportunities to convert or transition between different energy types.

12.3.12 Business management of hydrogen transmission and storage services

Due to the lack of regulations and standards for hydrogen mentioned in this Report, it is only with a high degree of probability that hydrogen storage processes will be similar to the currently known natural gas storage processes. It will then be necessary to adapt the current tools and implement these changes in the existing natural gas market tools. They enable the processes of purchase and sale transactions by the operator of storage capacities and the accompanying injection or extrusion services. Tariff regulations impose a great diversity of those services and the resulting complexity of various packages. The use of auction platforms makes it possible to standardize sales processes and the circulation of transaction documents. Complicated mechanisms for validating these processes prevent mistakes and support the transparency of the market and individual transactions.

Special attention should also be paid to providing the necessary support for the management of hydrogen transmission services. Along with the development of the hydrogen industry and market, the possibility of reserving adequate network capacity for the provision of transmission services for the new medium will be added to the scope of services of transmission grid operators. Depending on the type and scope of services, it will be necessary to enable their effective and transparent reservation by customers, based on specific algorithms and market regulations.

The use of a platform supporting the processes of sale of transmission services will provide the possibility to standardize the processes along with ensuring a high level of transparency and circulation of the necessary transaction documentation.

12.3.13 Logistics and distribution of hydrogen

Due to the significant costs of developing a grid infrastructure dedicated to clean hydrogen, its scope will certainly initially be very limited. This makes it necessary to transport the produced hydrogen by other means to places where the availability of the gas grid is limited. One such option is wheeled transport. The form in which the hydrogen is transported, whether in compressed, liquid or even ammonia form in this ratio is of little significance. Of course, regulations concerning safety, environmental impact, etc. are important, but the supply chain itself, consisting of processes of certification and verification of authorizations, scheduling, loading, carriage and then unloading and settlement, remains similar to currently realized processes of cargo transport with similar specificity, e.g. LNG. Using the knowledge and experience of Polish IT companies in building tools to support these processes should be in the interest of the Polish state and serve to build Polish hydrogen economy based on the ideas of Industry 4.0.

Currently implemented IT tools of SCM (Supply Chain Management) class, supporting cooperation of various participants of transport market, provide support for the entire supply chain, starting from contracting and contract management, through vehicle and driver verification processes, scheduling and agreements of the seller, the supplier and the customer, ending with the acceptance and settlement processes. As the regulations related to e.g. hydrogen transport safety are implemented, it will be necessary to implement appropriate rules and algorithms optimizing the above mentioned processes and optimizing the routes of access, driver's working time or unloading and intermediate loading.

12.3.14 Management of energy clusters and distributed hydrogen generation

An increasingly frequent business model, observed in the market of entities owning or managing energy infrastructure or also trading in energy, is steering the production and sale of energy in various forms, based on a more and more liquid and dynamic market. Such an approach is based on technical possibilities of near real-time control of energy sources and the use of publicly available trading platforms. However, all these processes are possible only with the support of properly designed IT tools.

The result of current market changes are groups of entities referred to as energy clusters, based largely on distributed generation, opportunities for energy transformation and energy storage. Use of these technical capabilities allows to obtain additional economic and financial benefits. The systems allowing to associate many dispersed sources are Virtual Power Plant class systems. These tools support all the issues described above and additionally allow to aggregate production and represent it in the National Power System in the form of a unified collective source. This allows easier management of these dispersed, often small generations, achieving a definite effect of scale. Due to technological advancement, aggregation of various types of data, analysis based on diverse algorithms and objective functions, the development of this sector with hydrogen elements would not be possible without the use and support of the IT sector.

12.3.15 Summary

The various processes and aspects of the hydrogen economy outlined above are only possible with the active and efficient support of the IT sector. Current development and research projects only superficially support this segment of our economy. Of course, material, technological or constructional research is the basis for the development of the hydrogen economy, but in the present world the development of the IT sector cannot be neglected, as it enables coherent and cohesive cooperation of each element of this sector. Effective use of IT tools to support both business and technical processes taking place in the emerging hydrogen industry will create a competitive advantage for the Polish economy, and thus contribute to strengthening the Polish position in renewable energy and Industry 4.0.

12.4 Case study IV - LOTOS Group:

Hydrogen initiatives and projects in LOTOS Group

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Current global trends make it necessary to change the business models of traditional sectors. Meeting future market challenges will require fuel and energy companies to adapt to new conditions. Global oil companies are transforming and diversifying their activities in non-fuel directions, investing primarily in renewable energy sources and hydrogen technologies. Key macro trends affecting the operations of oil companies include: decarbonisation, decentralisation and digitalisation of processes. LOTOS Group possesses and is developing competences that fit in these areas. Readiness to implement innovations is one of the strategic objectives defined in the Strategy of LOTOS Group S.A. for 2017-2022. Investments in modern technologies over the last three decades have contributed to the fact that LOTOS Group is now one of the most modern and innovative refining facilities in Europe. The analysis of global trends, the identification of areas and the setting of strategic goals and tasks have been compiled in a document entitled Strategic Directions of Innovation Development in LOTOS Group in the perspective of 2030. Initiatives and projects related to the development of alternative fuels, in particular hydrogen, are one of the key areas of development for LOTOS Group. As part of the ongoing projects related to hydrogen technologies, the following can be distinguished: Green H2, Vetni, Pure H2, Hestor or WOW (hydrogen recovery node) and IT-Biogas.

12.4.1 Green H2

LOTOS Group has launched an investment programme to build a large-scale installation for the production of green hydrogen. According to the assumptions of the Green H2 project, hydrogen will be produced through electrolysis, i.e. decomposition of water using electricity. If energy from renewable sources is used to produce it, such hydrogen will be classified as so-called green hydrogen. The hydrogen produced will be used in refinery processes, which will make traditional petroleum-based fuels more environmentally friendly. As part of Green H2, a large-scale installation will be built comprising electrolysers, hydrogen storage facilities and fuel cells. The whole system is to produce zero-emission hydrogen for the needs of the refinery and, at the same time, support the Polish power system in the form of a pumped storage power plant. The first step under the programme is a pilot project which will enable the creation of a smaller scale electrolysis installation. The installation so designed will be the target configuration for the large scale project. The Green H2 programme will evolve. The aforementioned pilot is planned for 2020-2024 and will allow the first experiences to be gained and will form the basis for software development. Parallel to the pilot, the first phase is to be implemented, the aim of which is to create a large-scale electrolysis plant which will produce hydrogen for refinery needs, but will also be a participant in the electricity market. In the second phase, it is planned to further expand the capacity of the plant and increase its role in the electricity market. In the long-term, during the next phase, which will run until 2040, LOTOS intends to strengthen its position as the regional leader in hydrogen production and distribution.

12.4.2 VETNI

LOTOS S.A. Group, in a consortium with the Institute of Energy and the AGH University of Science and Technology in Kraków, is implementing VETNI project (isl. hydrogen) co-financed by the European Union under the Operational Programme Intelligent Development 2014-2020, Measure 1.1 “R&D projects of enterprises”, Sub-measure 1.1.1 “Industrial research and development works carried out by enterprises” (Fast Track, competition 1/1.1.1/2021). The goal of the project is to develop and construct a pilot plant for a system to produce hydrogen in solid oxide electrolysers (SOE), allowing the highly efficient production of high purity green hydrogen.

The project will involve R&D work focused on the development, construction and testing in real operating conditions of a system with an electrolyser integrated with the refinery process, which will provide process steam for hydrogen production. Parameters of the prototype electrolyser will allow for production of about 16 kg of hydrogen per day with purity of 99.999%, which will enable the refuelling of several hydrogen powered cars.

The VETNI project is unique in the world due to deep integration of SOE electrolysers into an existing process, which will be adapted to a new role. The use of the refinery facility as a source of steam in the hydrogen production unit allows to improve the efficiency of the process while developing industrial assets for new applications, including the production of hydrogen and derived fuels. In the long term, the VETNI project sets new directions for the modernization of industrial facilities, including their adaptation to new purposes, which will result from the successive development of the hydrogen economy. The project is characterized by a high degree of innovation and, importantly, is based on Polish technological and material solutions. Long-term stability of operation and high efficiency of the electrolyser will be ensured, inter alia, by using a new group of materials developed at AGH University of Science and Technology to construct the air electrode, in which the content of toxic and expensive cobalt will be minimized. Implementation of the project will undoubtedly be an important step in the energy transformation towards increased use of low-emission sources.

12.4.3 IT-BIOGAZ

The trend towards the dispersion of energy production (fuels) and the local correlation of generation with production is the future that not only countries but also consumers expect. The year 2030 with the prospect of a 55% reduction in CO_2 emissions and emission prices of at least 76 EUR/tonne is fast approaching. In this context, there is an exploitable opportunity for biomass for biomethane and biohydrogen. Therefore, there is a great opportunity for an organisation like Lotos Group to enter the biomethane, biohydrogen market by implementing a hybrid approach strategy for this market. The hybrid approach assumes Lotos Group's participation in the production of biomethane and bio-hydrogen, but also launching activities to build a community (ecosystem of cooperation) with investors who will be interested in a long-term process of biomethane and bio-hydrogen supply to Lotos Group. In order to achieve the aforementioned objective, a project has been launched which will provide a comprehensive innovative IT-BIOGAZ Platform that will enable the contracting of volumes of ecological fuels identified by LOTOS Group, ongoing supervision of the production processes of the contracted installations, fuel sales and promotional and informational communication with the community of potential technology suppliers, financing institutions or business partners. The internet auction platform will constitute an innovative business solution allowing LOTOS Group to effectively acquire significant volumes of alternative fuels. The designed system in the auction and trading layer will have functionalities similar to those used by the Power Users Platform.

For LOTOS Group the key investments are in the production of "green" hydrogen, however, in its portfolio it also has projects related to the use of "grey" hydrogen, produced in the refining processes. One of such projects is the "PURE H2" project. Hydrogen fuel produced in this way will also be offered to customers through the implemented IT-BIOGAZ Platform.

12.4.4 PURE H2

LOTOS Group intends to utilize its potential and experience in the field of hydrogen production and promote hydrogen as a zero-emission fuel of the future. The use of hydrogen as an alternative energy source will contribute to the reduction of air pollution caused by emissions from vehicles equipped with conventional engines, especially in urban areas. The subject of the PURE H2 project is to build and launch the infrastructure for production and sale of high purity hydrogen (99.999%) meeting the requirements of standards for hydrogen fuel intended to power fuel cells used in road transport. An installation for hydrogen purification to meet the relevant requirements will be constructed in Gdansk and located on the premises of the refinery. A pure hydrogen distribution station, i.e. an installation for filling so-called battery trucks (vehicles for compressed hydrogen transport) will be built from scratch on the existing storage yard located in the immediate vicinity of the refinery at Benzynowa Street. In addition, the PURE H2 project also assumes the construction of two installations for refuelling vehicles in the standard of 350 bar (e.g. buses) and 700 bar (passenger vehicles). These installations will be constructed within the existing fuel stations belonging to LOTOS Paliwa in Gdańsk and Warsaw.

Particular locations and elements of the project are integrated with each other and matched in terms of capacity and logistics. The hydrogen purification installation in Gdańsk has the capacity to produce about 160 kg/h of hydrogen, and the hydrogen produced in this way will go entirely to the hydrogen compression node. Then, using the distribution and refuelling node, it will be possible to sell hydrogen in

Gdańsk. Adequate amounts of hydrogen will be transported to Warsaw by two battery trucks (trailers) acquired as part of the project, which will also be used for deliveries to other large consumers. The project is carried out by a consortium of LOTOS Group and LOTOS Paliwa. The PURE H2 project has received funding under the CEF instrument (2017 CEF Transport Blending MAP Call II competition), under the Connecting Europe Facility (CEF).

12.4.5 HESTOR

Under the HESTOR project, carried out jointly with AGH University of Science and Technology in Kraków, Silesian and Warsaw Universities of Technology, CHEMKOP and GAZ-SYSTEM companies, LOTOS Group worked on energy storage technology in the form of hydrogen obtained in the process of electrolysis from surplus energy from wind and solar power plants. The project was co-financed by the National Centre for Research and Development (NCRD) under the Gekon Generator of Ecological Concepts programme. According to the project assumptions, the possibility of obtaining and storing hydrogen in salt caverns, which can then be used for refinery processes e.g. in case of failure of the hydrogen production plant or as a supplement to the hydrogen network, was analyzed. In addition, the project considered technical and economic aspects of the use of hydrogen as a fuel in transport and analyzed issues related to the development of the hydrogen market, modern energy storage services in the form of hydrogen, the possibility of producing and trading electricity, and the use of hydrogen in technological processes. An important aspect was to determine the economic conditions of project profitability. The hydrogen produced and stored in the salt cavern will be used, thus improving energy efficiency, for:

- energy purposes,
- technological processes in the refinery, reducing the need for its production from natural gas and allowing for rationalization and optimization of hydrogen management;
- transport purposes: use of hydrogen in transport.

The issues related to energy storage were one of the key issues of the project and the results of analyses of possible technical solutions with consideration of the economic criterion will allow to generate basic socio-economic benefits and determine implementation conditions.

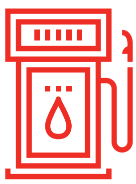
As an example of hydrogen projects, related to reducing CO_2 emissions to the atmosphere, LOTOS Group has implemented a project to install a Hydrogen Recovery Node.

12.4.6 WOW (Hydrogen Recovery Node)

The Hydrogen Recovery Unit set up at the LOTOS Group refinery will produce 70,000 tonnes of LPG, 43,000 tonnes of crude petrol, 39,000 tonnes of light petrol and almost 9,000 tonnes of hydrogen per year.

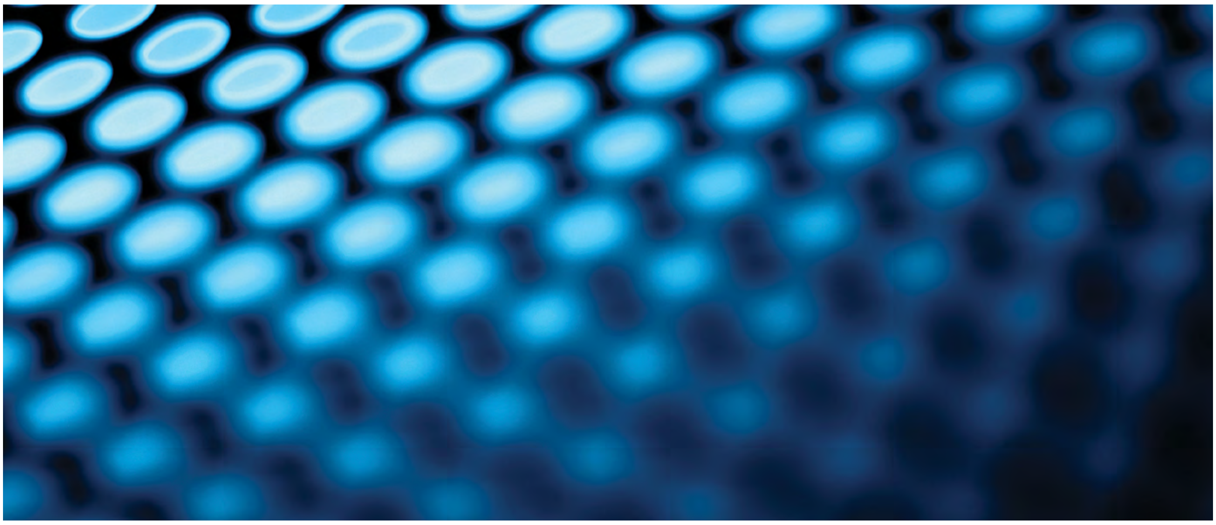
The refinery fuel gas network flows fuel which is a mixture of natural gas from the external network (approx. 50%) and gases generated in the refinery processes. The Hydrogen Recovery Node (WOW) is to isolate LPG, light and crude petrol and hydrogen from this mixture. Additional hydrogen will be directed to refinery processes (which will ultimately lower its production cost), and LPG and gasoline will be sent to the market. The resulting deficit in the refinery's energy balance will be made up by purchasing additional natural gas from an external network. Increasing its share in the refinery's fuel gas network will have an impact on lowering the emissions of the fuel burned in the plant, both in terms of CO_2 and energy pollutants. The heart of WOW working in the cryogenic technology is the so-called coldbox, in which the mixture of residual gases at -180°C and 45 bar pressure is separated into liquid hydrocarbons and gaseous hydrogen. Under these conditions, we obtain hydrogen of 98.6% purity. When this temperature is lowered to -187 degrees, we achieve 99.5% purity of hydrogen. The most important device of the installation is the batch compressor, which is powered by the largest engine in the refinery, with a power of over 4 MW. The compressor compresses 24.7 thousand m^3 of feedstock gas: from 4.5 to 64 atmospheres.

These are just a few examples of projects that have been initiated at LOTOS Group to develop hydrogen technologies. Thanks to the geographical advantage, i.e. the strategic location near the Baltic Sea, LOTOS Group opens up the possibility of a broader development of hydrogen technologies intended, for example, for shipping. This is made possible by the wharf at the Dead Vistula (Martwa Wisła), which, according to research, can be accessed by vessels of up to 9,000 tonnes deadweight. Additionally, LOTOS Group is an active market participant that both monitors and participates in the creation of legislation in the area of hydrogen.



12.5 Case study V - PKN ORLEN:

Low and zero emission hydrogen as a key to decarbonisation of Central and Eastern Europe



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Zero- and low-carbon hydrogen is recognized as one of the key elements in the value chain leading to green transformation - it can be used as a feedstock, fuel or energy carrier and storage. Due to its energy potential combined with its minimal carbon footprint, it is the subject of continued interest in Europe and worldwide. As a result of the global acceleration of climate ambition, hydrogen has acquired the status of a key pillar of the transition. With its wide range of applications in the industrial, transport and energy sectors, which are the main CO_2 emitting sectors in the EU, hydrogen plays an important role in achieving the ambitious goal of at least 55% reduction in CO_2 emissions by 2030 and climate neutrality by 2050.

In its hydrogen strategy, the European Commission sets as the main objective the development of this type of technology based on renewable energy sources. At the same time, it leaves room for low-carbon alternatives in the short and medium term.

ORLEN Group, in line with its Strategy 2030 and its commitment to achieve total carbon neutrality in 2050, will implement projects across the low- and zero-emission hydrogen value chain to decarbonise its assets, as well as to develop an industry related to transport using hydrogen as a new fuel.

In the development of this emerging market, cooperation not only between companies, but also between the public and private sectors will be crucial. To this end, ORLEN Group supports and promotes large, domestic and international ecosystems across the hydrogen value chain, where technological development, investments and public-private sector activities strongly interlace. These translate directly into projects implemented by the Group. Two of them: Clean Cities - Hydrogen mobility in Poland (phase I) and Hydrogen Eagle will enable the creation of hydrogen corridors on key routes within the TEN-T network and in major cities. Due to the strategic location of Poland, the Czech Republic and Slovakia, on major transport corridors, our network of hydrogen filling stations will become part of a larger pan-European network, including primarily north-south and east-west corridors. It will thus contribute to the development of the hydrogen fuelled mobility sector throughout Europe. ORLEN Group is committed both to road transport and to building an ecosystem for rail hydrogenisation in Poland.

The “Clean Cities - Hydrogen mobility in Poland (phase I)” project includes the production of high purity hydrogen from electrolysis in the HUB in Włocławek, ultimately powered by RES, the construction of two public hydrogen refuelling stations in Poznań and Katowice and a mobile (container) refuelling station located in Włocławek. This is currently the largest national project, in terms of volume of hydrogen production, which was supported by a non-refundable grant of about 9 million PLN from the CEF Transport Blending Facility, which supported the development of alternative fuels, including hydrogen, the construction of infrastructure and purchase of mobile assets. The infrastructure assumed in the project, enabling the use of hydrogen as a fuel, will allow the refuelling of a total of over 40 buses fuelled by fuel cells and additionally other high-purity hydrogen vehicles. Implemented zero- and low-emission technologies will directly contribute to improving air quality in cities, because owing to the use of hydrogen in a wide range of transport, fossil fuel fumes will be eliminated and only water will be emitted instead. Noise levels will be significantly reduced, as hydrogen-powered buses do not have internal combustion engines, but electric motors that are powered by electricity from high-purity hydrogen fuel cells.

ORLEN Group is also behind a flagship hydrogen project in Central and Eastern Europe. Hydrogen Eagle is a comprehensive infrastructure project aimed at creating and expanding hydrogen infrastructure in Poland, the Czech Republic and Slovakia. Its implementation will enable joining the international hydrogen refuelling network by building more than a hundred stations for both road and rail transport, and reaching the zero-emission hydrogen production capacity of about 50,000 tonnes per year by 2030. The project involves the construction of eight new hydrogen hubs, including five in Poland, two in the Czech Republic and one in Slovakia, focused on the production of zero- and low-emission hydrogen based on renewable energy sources and “Waste to Hydrogen” technologies. In total, the target capacity of RES-powered electrolysis installations will be around 250 MW. The programme also includes three innovative installations for municipal waste processing into low-emission hydrogen, located in Płock, Ostrołęka and the Czech Republic. Hydrogen Eagle has successfully passed the stage of pre-notification of support to the European Commission in the competition for projects in the area of hydrogen technologies and systems under the IPCEI mechanism.

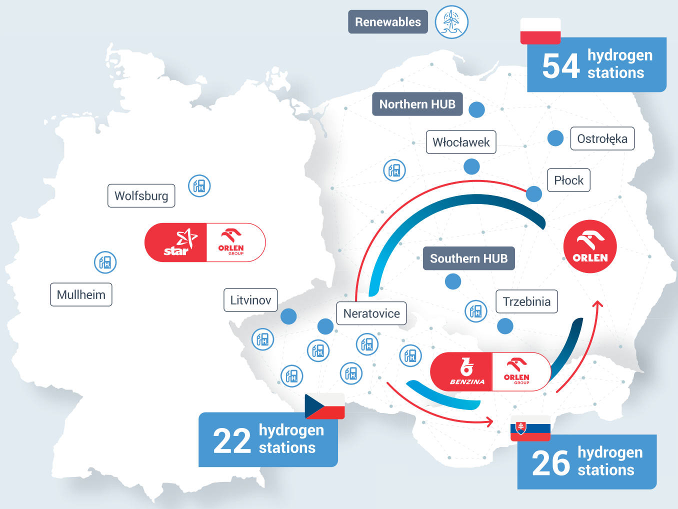
ORLEN Group also implements technologies of production of low-emission hydrogen coming from sources other than electrolysers powered by electricity from RES. An alternative to electrolytic technologies is, among others, production of hydrogen using municipal waste of appropriate calorific value as a raw material. The list of installations for thermal waste processing to generate electricity and heat is relatively long and, especially in some Western European countries, it has become the basic way to solve waste management problems. Waste incineration is a simple but inefficient way to recover the energy accumulated in waste. There are also chemical methods of converting non-recyclable waste to useful petrochemical products and semi-finished products, which are currently being developed and implemented in ORLEN Group. The decisive factor determining the low-emission character of hydrogen produced in

HYDROGEN EAGLE

The flagship hydrogen project in CEE region is one of ORLEN Group's initiatives to achieve a net zero carbon footprint by 2050.

The ORLEN Group

- The largest corporation in Central and Eastern Europe
- Operates in: Poland, the Czech Republic, Germany, Lithuania, Slovakia and Canada
- Annual processing capacity of over 35 million tonnes of various types of crude oil
- Owns the largest network of over 2,800 modern service stations



Poland
- **54** HRS,
- **110 MW** electrolysis capacity,
- **15 kt H_2** from municipal waste,

Czech Republic
- **22** HRS,
- **80 MW** electrolysis capacity,

Slovakia
- **26** HRS,
- **60 MW** electrolysis capacity,

The most important project parametres:
- **102** HRS
- **250 MW** electrolysis capacity
- **15 kt H_2** / year from municipal waste
- over **1 mln tonnes CO_2** emission reduction annualy

Hydrogen Production Units (existing and under development)

Hydrogen Refuelling Station (existing and under development)

- Hydrogen Eagle is a staged, comprehensive infrastructure project run by ORLEN in Poland, Czech Republic and Slovakia which aims to establish generation, transport and distribution capacities for zero/low-carbon hydrogen and to utilise it in the mobility sector and, potentially, for energy and industry applications, contributing to the development of a solid supply chain at the European market level.
- Hydrogen Eagle has also the potential to become an important part of the European Hydrogen Backbone vision. This would offer an opportunity to join this pan-European initiative creating systemic interconnections with the neighbouring countries.
- Cross-border coordination in infrastructure development is a prerequisite for the establishment of a European HRS network in the transport sector. Due to Poland, Czech and Slovakia strategic location at the crossways of main European transportation corridors our HRS network will form a part of a bigger pan-European HRS network, it would contribute to the development of a mobility segment relying on hydrogen as a new fuel, and therefore will allow smooth transport along the North-South, as well as East- West European corridors.

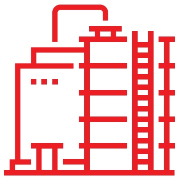
Purpose

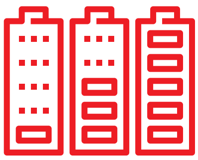
- CO_2 emission reduction from urban, heavy duty and railway transport
- Shift from conventional fuels to low and zeroemission hydrogen
- Low- and zero-emission hydrogen production on a large scale in CEE region using offshore RES, onshore RES and municipal waste
- Set up a necessary infrastructure in CEE region
- Enhancing Europe's competitiveness and advancing its climate neutrality goals based on environmentally sustainable solutions
- Potential to become an important part of the European Hydrogen Backbone

Benefits

- Diversified hydrogen generation – Energy security of supply improvement in CEE region
- Hydrogen Eagle will create over **5 000** new jobs
- Solving the municipal waste management problem – Circular Economy solution
- After 2030 logarithmic scalability of hydrogen generation in EU

this way is not so much the raw material itself as the method of managing the CO_2 produced. It is our ambition that produced hydrogen will be truly low-emission, that is why investments in generation assets implemented by the company include the element of capturing carbon dioxide produced. Currently, the only technology used on a large scale which allows us to manage CO_2 is its injection underground (Carbone Capture and Storage), however, its applications deep inside the continent are very limited. Methods of CO_2 chemical bonding, or CCU (Carbon Capture and Utilization), are not currently ready for commercial application on an industrial scale. Development of such technology and its implementation in Poland is one of ambitions of ORLEN Group, which we want to pursue together with Polish scientific centres. Completion of this and other R&D projects, as well as further implementation of their results, will allow us to develop technologies of zero- and low-emission hydrogen production, which will be applicable not only in regions with high RES energy potential. The goal of achieving carbon neutrality is undoubtedly very ambitious and involves taking up a number of technological and business challenges, but it is above all an opportunity for our region to improve living conditions and economic development.





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The Lower Silesian Institute for Energy Studies (DISE), based in Wrocław, is one of the most important Polish Think Tanks dealing with the issues of energy transition, gas market liberalization, financial management of energy companies and the issues of efficiency of infrastructure projects in the energy sector. DISE is a Foundation bringing together a group of experienced experts: economic practitioners, managers from the energy and mining industries, as well as representatives of the world of science. The DISE team prepares analyses, opinions as well as economic, legal, geopolitical and technical expertise in the field of energy and fuel policy for the needs of the government administration, local government, non-governmental organizations and companies from the energy and mining industry. It also provides substantive support for Polish and EU parliamentarians. The Lower Silesian Institute for Energy Studies also conducts scientific, research and educational activities, organizing study visits to the most important facilities in the energy and mining industry in the world.

The Polish Wind Energy Association (PWEA) is a non-governmental organization that has been working for the development of wind energy in Poland since 1999. The association brings together leading companies operating on the wind energy market in Poland: investors, developers, producers of turbines and power plant components. PWEA associates both large entities with foreign capital and Polish entrepreneurs within the entire supply chain for the wind industry. PWEA supports and promotes the development of wind energy, and its aim is to create favorable conditions for investing in wind energy in Poland and to systematically increase the use of wind energy as a clean source of electricity generation. The overriding goal of the Association is to work to improve the existing and create new legal provisions as well as to increase political and social awareness in the field of wind energy. PWEA activity includes active participation in consultations of legal acts (laws, regulations), strategies, policies and sector programs, as well as close cooperation with decision-makers, education and disseminating knowledge about wind energy.

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