3W World. Today and tomorrow

Uncertain and volatile – these two adjectives have been used to describe the world around us for some time now. A world of many crises, namely the climate, energy, geopolitical, food and raw materials crises, whose negative effects are cumulative and increasingly visible in our daily lives. Therefore, the need for a comprehensive understanding of the present becomes a priority, because how we deal with today's challenges will determine the shape of the world in which our children and grandchildren will live.

Water – without which Earth would be devoid of life – and safe access to water is becoming a global challenge that requires a responsible and integrated approach from the international community. In the wake of the energy transition challenge, the importance of the hydrogen economy and the potential of **hydrogen** as part of the energy ecosystem is growing. Concurrently, **carbon**, which is becoming more and more used in advanced technologies, such as advanced materials technologies, still faces the challenge of limited production and high costs.

These areas require not only continuous innovation, but also systemic support to achieve a breakthrough. We strongly believe in the mission of continuing education of the public that will allow them to understand the challenges ahead and recognize the opportunities presented by 3W resources.

We invite you to read the latest edition of the 3W Idea report entitled **"3W world. Today and tomorrow"**, prepared jointly by organizations from the 3W world involved in creating technologies from the areas of water, hydrogen and carbon. This report is a source of valuable information useful for better understanding of the opportunities and threats for the global community. We analyze key areas that are not only essential for the understanding of the challenges at hand, but also to determine the future of generations to come.

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WATER

INTRODUCTION

The historic picture taken in 1968 by members of the Apollo 8 mission orbiting the Moon shows Earth as a white and blue sphere suspended in black space[I]. This photo symbolically highlights the beauty of our planet and its uniqueness, which resulted in the existence of life on Earth.

Unlike its reddish neighbors (Venus due to its surface temperature and Mars, whose colour is owed to the dominance of iron oxides in the ground), the colour of our planet is given by water, but not because it reflects the blue of the sky, but because of its interesting features. The wavelengths of light corresponding to red, orange and yellow (long wavelength) are absorbed by water to a greater extent than the wavelengths of light corresponding to blue (short wavelength). Sunlight reaching the water mainly reflects blue light, absorbing the others.

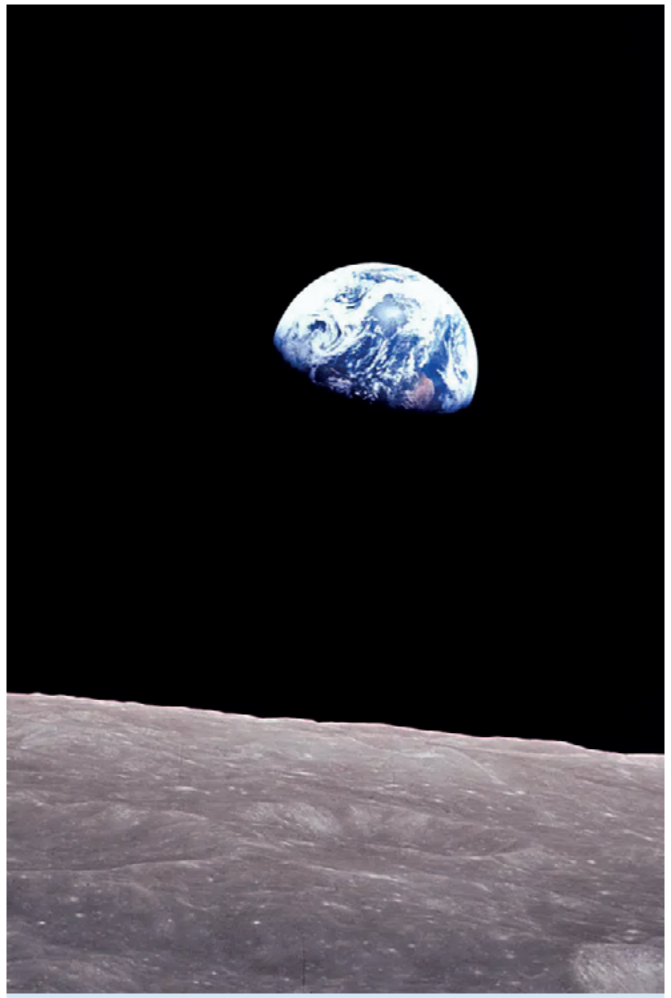
Water facilitated the creation and spread of life on Earth. Water is not only the building material of living organisms, an essential element of life processes, but also the habitat of countless species of flora and fauna. It is the world in which they are born, live and transfer their energy to the environment in an endless cycle of life and death.

Water is all around us. We use it at home, at work, while on holidays in the mountains, at the lake or by the sea. We live with a thought that this resource is and will always be available. But is that really true?

Doubt comes when an unexpected event occurs in our environment: flood, a situation of threat to life, property or infrastructure. When something truly dangerous happens, for instance an environmental disaster, we sound the alarm, because we begin to understand that a comfortable life with easy access to water is not necessarily given to us forever.

In 2022, the mass poisoning of organisms living in the Oder River caused by toxic algae bloom made us all aware that water is a fragile living environment and how much we need to do to use its limited resources safely and responsibly. Our activities cannot focus solely on long-term economic and social goals. Our access to water must be reasonable, we must use responsible and efficient solutions to minimize water consumption, we must take care to maintain or restore its quality.

Science supports us in these efforts, and while sometimes the costs of the technologies used are high, we shall keep in mind that the water resources we can use are not infinite and that our successors also have the right to use water.



Source: NASA, https://www.nasa.gov/image-article/this-week-nasa-history-apollo-8-captures-earthrise-dec-24-1968/

Over the past few years, climate change has amplified extreme events that could not be predicted by any models based on past data. This phenomenon has been observed particularly in Europe. The 2022 drought was the most extreme of its kind in 500 years. The countries that were hit the hardest were Spain, France, Italy, Portugal and the UK. Farmers were losing crops, life in rivers was dying off, the industry was struggling with limited access to water. The effects are still being felt today, including in our wallets.

Food production is a water-intensive industry. As a result of the drought, food prices have soared.

Water is important to each branch of the industry. Without access to this resource in sufficient quantity

I. NASA: https://www.nasa.gov/image-article/this-week-nasa-history-apollo-8-captures-earthrise-dec-24-1968/

and quality, we encounter barriers and constraints to socioeconomic development. That is why it is so important to support technological advancement and take any initiatives that will support the integrated development of the water sector in Poland, Europe and across the world.

As the problem with water became a global issue – some 2 billion people around the world do not have access to good quality drinking water – this year for the first time in more than half a century a UN conference was held that was fully dedicated to addressing this situation. During the talks held in New York it was made clear that the growing global water crisis must be urgently addressed in order to achieve the 2030 Agenda for Sustainable Development and accelerate progress in facilitating access to water and improving sanitation (Goal 6).

The climate forecasts for the coming years are not optimistic. The problems related to water will get worse. We need to start taking care of water resources immediately.

At the same time, we need to implement extensive information and education activities to ensure that our societies are aware of the scale of the risks and, just as importantly, the impact that the approach and actions of individual enterprises and households can have on our future and that of our children.

SUMMARY

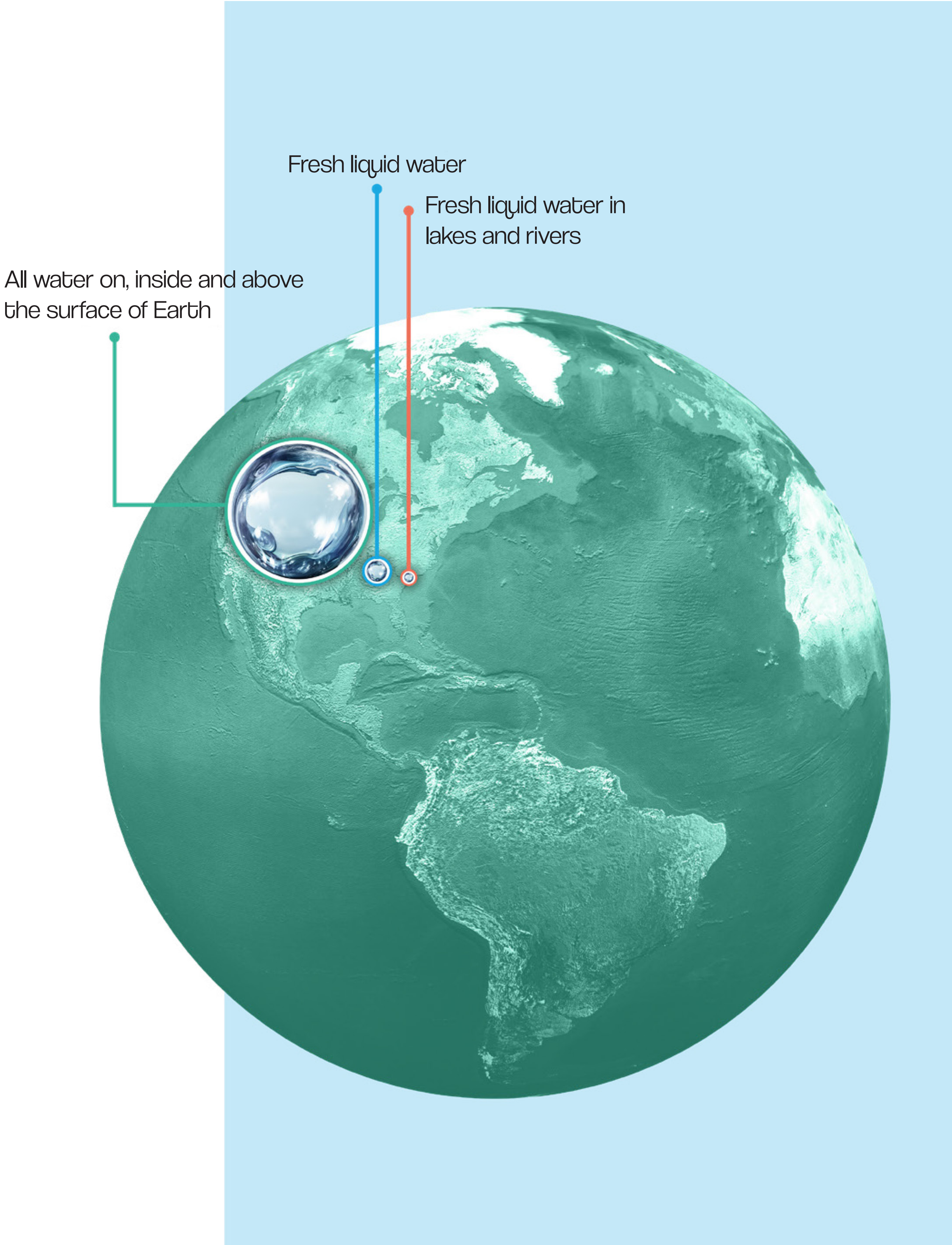
Without water, life as we know it would not have had a chance to be created on Earth and would not have been able to develop and thrive. Water is a key element that guarantees the proper functioning of basic processes in our bodies and in our environment.

1. The Earth's water resources are estimated at about 1.386 billion km^3, which, compared to the globe's volume[I] of approximately 1,083.207 billion km^3, represents only 0.128% of the total.
2. The vast majority of water is found in the oceans – salt water (including brine) accounts for as much as 97.5% of Earth's water supply. Fresh water makes up only 2.5% of Earth's water resources, and is mostly trapped in glaciers (68.7%) or stored in groundwater (30.1%). Realistically, we can use a smaller portion of the Earth's fresh water resources. Surface waters (rivers, lakes) account for only about 1.2% of fresh water resources.
3. The largest renewable water resources per capita per year are found in Iceland. The amount of water per citizen is as much as 463.9 thousand m^3. In the case of Poland, the rate varies (depending on the amount of annual precipitation) from 1.1 thousand m^3 to 1.8 thousand m^3, with an average of some 1.6 thousand m^3 per year, and is close to the threshold of water stress. The average for Europe is above 4–5 thousand m^3.
4. The value of the global water market has been growing consistently. In 2020, the market was valued at more than USD 800 billion and according to estimates in the Global Water Market 2023 report its value will grow to about USD 1,470 billion by 2028[II].
5. The availability of water resources does not automatically mean that residents have universal access to drinking water. According to the SDG Report[III], the proportion of the global population using safely managed drinking water services was 74.3% globally in 2021 and has grown from 63.4% in 2005. **More than 2 billion people have limited or no access to drinking water.**
6. **Climate change amplifies the occurrence and intensity of extreme events.** Models based on historical data are not able to predict and accurately describe them sufficiently in advance. Anomalies are increasingly noticeable and pronounced. NASA announced that this past meteorological summer (June–August 2023) was the hottest summer since global records began in 1880[IV].
7. About 74% of the natural disasters between 2001 and 2018 were water-related. They included both droughts and floods. The frequency and intensity of such events is likely to increase as climate change worsens[V].
8. Ocean water temperatures are rising and have accounted for approximately 93% of the planet's warming since the 1950s[VI].
9. Global warming is causing the ice caps to melt. According to a recent report by the European Space Agency (ESA)[VII], the rate of ice loss in Antarctica and Greenland has accelerated. Based on satellite data, it was estimated that since the 1990s it increased as much as fivefold. Glaciers cover almost 10% of the land surface. The melting of the glaciers of Greenland would raise the water level by 7 meters, and the melting of the entire Antarctic ice cap – by about 60 meters[VIII].
10. Over the past several years, Polish agricultural yields have been significantly reduced by the impact of droughts. The average annual loss in the three crop categories (tubers, cereals, oil seed crop) estimated using the climate-related water scarcity index is about PLN 3.9 billion, while losses estimated using the normalized difference vegetation index (NDVI) could be as high as PLN 6.5 billion[IX].

I. NASA: Facts & Figures, http://solarsystem.nasa.gov/planets/profile cfm?Object=Earth&Display=Facts&System=Metric [accessed on 14 October 2023]
II. Research and Markets: https://www.researchandmarkets.eom/report/water#cat-pos-1 [accessed on 14 October 2023]
III. The Sustainable Development Goals Report 2022, https://unstats.un.org/sdgs/report/2022/
IV. NASA: https://climate.nasa.gov/news/3282/nasa-announces-summer-2023-hottest-on-record/
V. UNICEF: https://unicef.pl/co-robimy/aktualnosci/news/woda-i-globalny-kryzys-klimatyczny-10-rzeczy-o-ktorych-musisz-wiedziec [accessed on 14 October 2023]
VI. Climate change, impacts and vulnerability in Europe 2016
VII. Simonsen, SB, Slater, T., Spada, G., Sutterley, TC, Vishwakarma, BD, van Wessem, JM, Wiese, D., van der Wal, W. and Wouters, B.: Mass balance of the Greenland and Antarctic ice sheets from 1992 to 2020, Earth System Science Data, 15, 1597-1616, https://doi.org/10.5194/essd-15-1597-2023, 2023.
VIII. https://www.usgs.gov/faqs/how-would-sea-level-change-if-all-glaciers-melted
IX. PIE: Report 3/2022, "Gospodarcze skutki suszy dla polskiego rolnictwa" (Economic effects of drought for the Polish agriculture)

11. According to a report[I] prepared by Christian Aid, the world's ten most expensive climate disasters resulted in losses estimated at USD 168.4 billion. For the first time, the list also included Poland (due to a cyclone named Eunice, February 2022).
12. The North Pacific is considered the most polluted ocean in the world. **Between Hawaii and California there is a huge accumulation of plastic waste called the Great Pacific Garbage Patch or Pacific Trash Vortex.** It is estimated to contain more than 1.8 trillion pieces of plastic with a total weight of more than 80,000 tons[II] and an area of about 1.6 million km^2 (more than twice the size of France)[III].
13. According to the National Oceanic and Atmospheric Administration (NOAA), billions of harmful trash[IV], sewage and oil spills get to the oceans each year. The oceans currently hold approximately 50–75 trillion pieces of plastic and microplastic[V]. According to Główny Inspektorat Ochrony Środowiska (the Chief Inspectorate for Environmental Protection), about 60% of Polish rivers have moderate ecological status, 30% have bad or poor, and only 10% have good or very good[VI].

I. https://www.christianaid.org.uk/sites/default/files/2022-12/counting-the-cost-2022.pdf
II. https://theoceancleanup.com/great-pacific-garbage-patch/
III. Plastic Collective: Blog, https://www.plasticcollective.co/what-is-the-great-pacific-garbage-patch/ [accessed on 14 October 2023]
IV. https://www.noaa.gov/education/resource-collections/ocean-coasts/ocean-pollution
V. https://oceanliteracy.unesco.org/plastic-pollution-ocean/
VI. https://www.gov.pl/web/klimat/stop-zanieczyszczaniu-rzek



Source: Howard Perlman, USGS, Jack Cook, Woods Hole Oceanographic Institution, Adam Nieman

Source: Igor Shiklomanoc, http://ga.water.usgs.gov/edu/earthhowmuch.html

WATER RESOURCES

The term blue planet is unequivocally associated with the Earth and is related to the fact that water covers a significant part of the Earth's surface (approximately its 71%). It would seem, therefore, that water is widely available and in an unlimited amount, but the reality is far from this perception. The Earth's water resources are estimated at about 1.386 billion km^3, which, compared to the globe's volume[I] of approximately 1,083.207 billion km^3, represents only 0.128% of the total.

All Earth's water constitutes the Hydrosphere, which consists of all water resources found on the surface, underground, in the atmosphere and in the biosphere, which also includes all living organisms.

A vast majority of water is accumulated in oceans[II]: the Pacific Ocean (660 million km^3), the Atlantic Ocean (310.4 million km^3), the Indian Ocean (264 million km^3), the Southern Ocean (71.8 million km^3) and the Arctic Ocean (18.7 million km^3). Salt water (including brine) accounts for as much as 97.5% of global resources, and fresh water only for 2.5%.

Fresh water is mostly trapped in glaciers (68.7%) or stored in groundwater (30.1%). Realistically, we can use a smaller portion of the Earth's fresh water resources. Surface waters (rivers, lakes) account for only about 1.2% of fresh water resources[III].

We mostly use the water that takes an active part in the water cycle (i.e. the so-called renewable resources), which represents only 0.3% of the world's fresh water resources[IV]. It should be remembered that a crucial condition, from the point of view of being useful to people and the economy, is the availability of clean water, which represents a fraction of the renewable resources.

The distribution of renewable resources of water is uneven in different continents. Their volume depends on climate features (in particular, the amount of precipitation and air temperature), geological structure, characteristics of terrain and land cover. Deficit areas are concentrated primarily in the tropical and subtropical climate zones and in the interior of the continents.

The world's total renewable water resources[V] are about 42,808 km^3, with the largest found in Latin America (32.4%) and East Asia (23.6%).

Interestingly, when analyzing the world's renewable resources of water, Australia has only 1%, while 6 countries (India, China, Russia, USA, Brazil and Canada) have as much as 40%[VI].

For statistical purposes, renewable water resources can be calculated per capita per year (Table 1.1). Due to low population density, some of the world's dry countries have higher renewable resources per capita per year than Poland – with Australia serving as an example.

I. NASA: Facts & Figures, http://solarsystem.nasa.gov/planets/profile.cfm?Object=Earth&Display=Facts&System=Metric [accessed on 14 October 2023]
II. Eakins B.W., Sharman G.F.: Volumes of the World's Oceans from ETOPO1. Boulder, CO: NOAA National Geophysical Data Center, 2010
III. U.S. Geological Survey, Water Science School, https://www.usgs.gov/special-topics/water-science-school/science/where-earths-water
IV. https://zpe.gov.pl/a/obszary-nadmiaru-i-niedoboru-wody-na-swiecie/DMcmqVzvD
V. https://databank.worldbank.org/reports.aspx?source=2&series=ER.H2O.INTR.K3&country=#
VI. Śliwiński J., Ciesla M.: "Zasoby wodne na świecie a produkcja żywności" (World's water resources and food production), Warsaw University of Life Sciences

Table 1.1 Size of renewable water resources by world region

World region	Size of renewable water resources [billion m³]	Share of the world's renewable resources [%]	Size of renewable water resources per capita [m³]
North America	5,668.0	13.3	15,338.87
Latin America and the Caribbean	13,867.7	32.4	21,336.6
Sub-Saharan Africa	3,883.8	9.1	3,373.6
North Africa and Middle East	230.5	0.5	480.2
Europe and Central Asia	7,070.9	16.5	7,684.2
East Asia and the Pacific	10,105.5	23.6	4,335.8
- of which: Australia	492.0	Australia: 1%	Australia: 19,177.3
South Asia	1,982.2	4.6	1,052.9
World	42,808.6	100	5,499.5

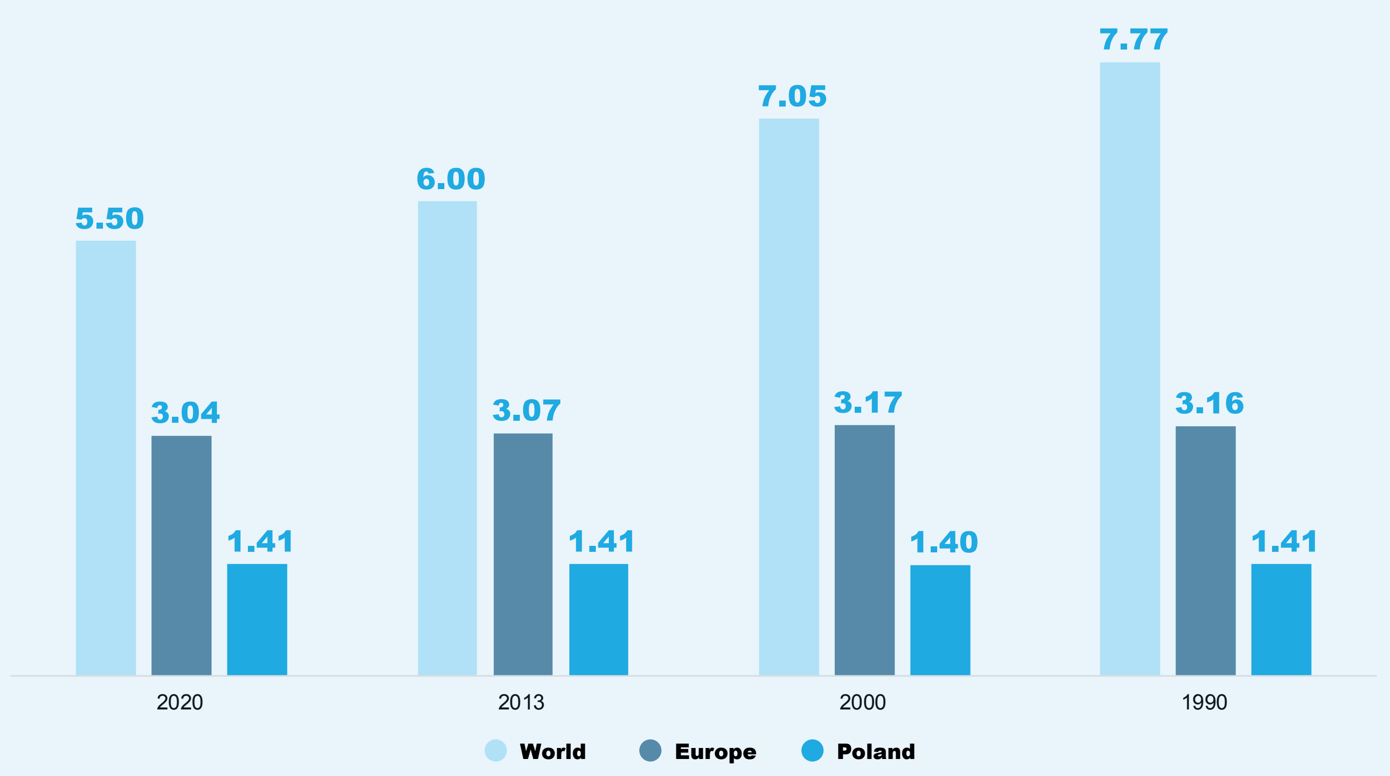
source: https://databank. worldbank.org/

According to the World Bank data[I] for 2020, for Poland the rate of renewable water resources per capita per year was 1.414 thousand m³, which was well below the average for Europe and the world. The index is also lower than in the case of countries such as: Senegal (1.569 thousand m³), Mali (2.827 thousand m³) or in comparison with Sub-Saharan Africa (3.373 thousand m³).

It is worth noting that in 2020 even lower rates were recorded for countries such as: Czechia (1.229 thousand m³) and Belgium (1.04 thousand m³).

The largest renewable resources per capita per year are found in Iceland, for which the rate is 463.9 thousand m³.

Fig. 1.1 Renewable fresh water resources per capita per year (thousand m³)



I. World Development Indicators, https://databank.worldbank.org/reports.aspx?source=2&series=ER.H2O.INTR.PC&country=#

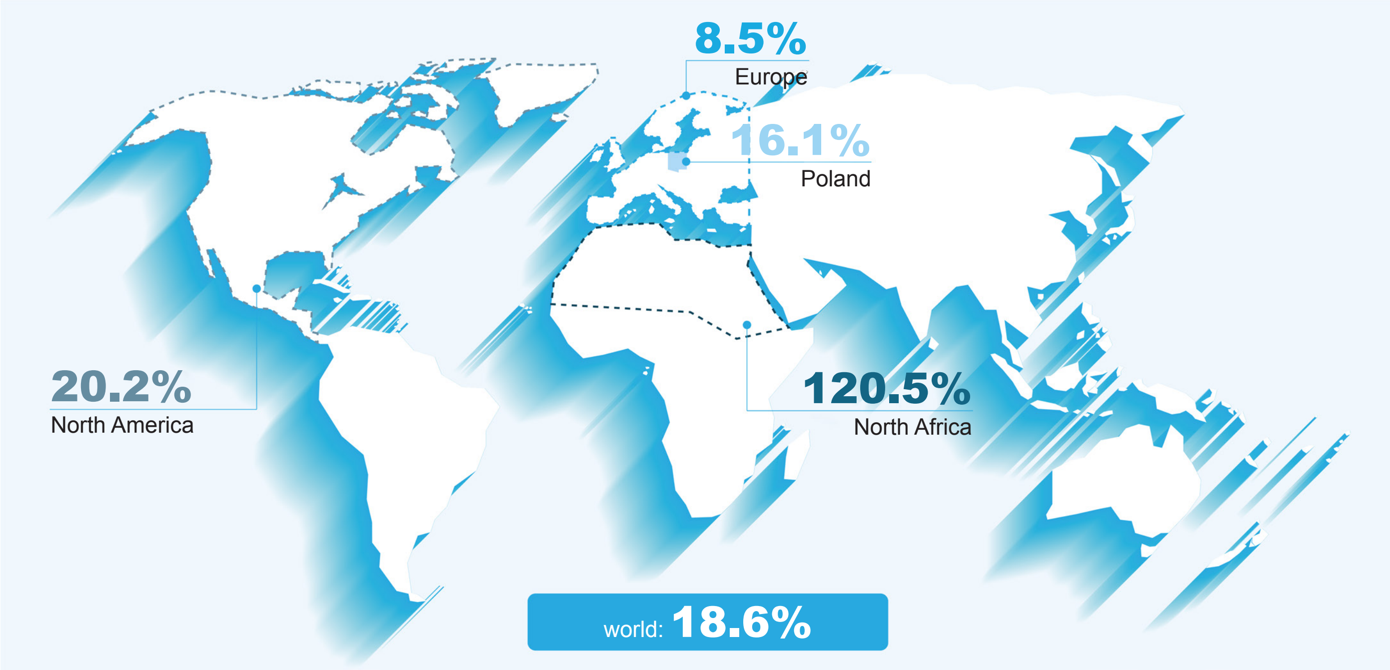
Fig. 1.2 Renewable fresh water resources per capita per year (m³)

Analyzing the level of indicators over the past decades, there is a downward trend in the amount of renewable water resources per capita per year. This has to do with population growth and is beginning to be relevant to water availability.

The water deficit is the outcome of a number of factors, such as climate change (increased insolation and evaporation), higher water consumption for domestic and industrial purposes, river regulation and drainage of peatlands, among other things.

The above factors will increase water stress (water scarcity or inaccessibility of good quality water), which is one of the challenges for many societies in the 21st century. The situation is dramatic in North Africa, where annual water withdrawal exceeds the volume of renewable water resources.

Fig. 1.3 Water stress
(Share of water withdrawal in total volume of renewable resources, 2019)



WATER DEMAND

Water demand is defined as the volume of water requested by users to satisfy their needs. In a simplified way it is often considered equal to water intake, although conceptually the two terms do not have the same meaning[I]. Consumption of water, in accordance with the definition used by Statistics Poland (GUS), is the amount of water used for needs of the national economy and population which is drawn from own intakes, water supply network or purchased from other units.

The demand for water is increasing across the world. The latest World Water Development Report[II] (coordinated by UNESCO) indicates that water consumption has been increasing by roughly 1% per year over the last 40 years. The bulk of this increase is concentrated in middle- and lower-income countries, particularly in emerging economies. This trend has been driven mainly by: population growth (resulting in increased demand for water for households, farming and food production needs), socio-economic development (access to water) and changing consumption patterns.

Regions with the highest water consumption per capita in the world include North America (e.g. the United States – 1,342 m^3/year), South America (e.g. Guyana – 1,837 m^3/year) and Central Asia (e.g. Turkmenistan – 4,352 m^3/year). In Poland, the value reached 243 m^3 in 2020[III] and 256 m^3 in 2021. These rates are below the European average of 440 m^3/year and below the average for the 30 OECD countries of 735 m^3/year[IV].

Total water consumption in Poland in 2021 was 8,845 hm^3. The largest volumes were used for industrial purposes (including power generation) (72%), operation of the water supply system (18.5%) and filling and refilling of fish ponds (9.5%). It should be noted that water consumption in agriculture is not (except for filling fish ponds) included in Statistics Poland's data. Compared to other countries, what is noticeable is very high water consumption for industrial purposes, with coal-based power generation accounting for the largest share. This results from both the coal production and processing technology as well as cooling processes in coal-fired power plants.

Almost 80% of water in the water supply system in Poland is consumed by households (the remainder is used for manufacturing and other purposes, such as provision of services). In Poland, in 2021 each household member used an average of 34 m^3 of water (93 l/person/day), an increase from 2010, when the value was 31 m^3. The distribution of water consumption per capita is different in individual provinces, with a general upward trend.

Compared to other European countries, household water consumption per capita in Poland is low. The highest is in Switzerland – 300 l/person/day, in Italy – 220 l/person/day and in Portugal – 204 l/person/day. The lowest water consumption in households is recorded in Slovakia (79 l/person/day) and Malta (77 l/person/day)[V].

When analyzing water consumption in Poland, it is important to keep in mind the use of groundwater for the purposes of both municipal services and farming. According to Statistics Poland, groundwater consumption in 2021 was approximately 19%. Estimates by the Polish Geological Institute (Państwowy Instytut Geologiczny) indicate that groundwater consumption for normal use (not registered) is between 0.3 and 1.6 km^3/year[VI].

I. https://www.eea.europa.eu/help/glossary/eea-glossary/water-demand
II. Partnerships and cooperation for water, The United Nations World Water Development Report 2023, https://unesdoc.unesco.Org/ark:/48223/pf0000384655
III. Aquastat, https://data.apps.fao.org/aquastat/?lang=en
IV. OECD (2023), Water withdrawals (indicator). doi: 10.1787/17729979-en (accessed on 23 June 2023)
V. https://smartwatermagazine.com/news/locken/water-ranking-europe-2020; https://www.eureau.org/resources/publications/eureau-publications/5219-the-governance-of-water-services-in-europe-2020-edition/file
VI. https://www.pgi.gov.pl/dokumenty-przegladarka/psh/artykuly-psh/4637-ocena-poboru-rzeczywistego/file.html

POLLUTION

Water pollution occurs when various factors cause adverse changes in its biological, chemical and physical properties. There are many classifications of types of water pollution, e.g. organic or inorganic; natural (e.g. soil and rock degradation substances) and anthropogenic; undegradable, persistent (remaining in water for a long time) or degradable. Regardless of how it is classified, the main source of pollution are human-related factors. The most common sources of pollution include:

- municipal pollution (globally, more than 80% of wastewater[I] flows back into the ecosystem without being properly treated);
- industrial pollution;
- agricultural pollution.

According to the National Oceanic and Atmospheric Administration (NOAA), billions of harmful trash[II], sewage and oil spills enter the oceans each year. The oceans currently hold approximately 50–75 trillion pieces of plastic and microplastic[III]. The North Pacific is considered the most polluted ocean in the world. Between Hawaii and California there is a huge accumulation of plastic waste called the Great Pacific Garbage Patch or Pacific Trash Vortex. It is estimated to contain more than 1.8 trillion pieces of plastic with a total weight of more than 80,000 tons[IV] and an area of about 1.6 million km^2 (more than twice the size of France)[V].

I. https://www.unwater.org/sites/default/files/app/uploads/2018/10/WaterFacts_water_and_watewater_sep2018.pdf
II. https://www.noaa.gov/education/resource-collections/ocean-coasts/ocean-pollution
III. https://oceanliteracy.unesco.org/plastic-pollution-ocean/
IV. https://theoceancleanup.com/great-pacific-garbage-patch/
V. Plastic Collective: Blog, https://www.plasticcollective.co/what-is-the-great-pacific-garbage-patch/ [accessed on 14 October 2023]

The North Pacific is being polluted not only by plastic waste, but also by oil. About 40 million liters of oil leaked from the Exxon Valdez tanker in 1989, contaminating the ocean and more than 2,000 km of Alaska's coastline (the size of the spill was equivalent to about 12 Olympic-size swimming pools filled with oil).

European marine waters are also polluted. The EEA (European Environment Agency) report revealed widespread pollution in all four regional seas. In the case of the Baltic Sea, the problem affects 96% of its area, the Black Sea – 91%, the Mediterranean Sea – 87% and the North-East Atlantic Ocean – 75%[I]. The main sources of pollution are synthetic chemicals and heavy metals.

The EEA report diagnoses the overall status of Europe's waters, indicating that only 44% of surface waters are in good or very good ecological status[II]. The status of groundwater is slightly better, with about 75% showing good chemical condition.

According to Główny Inspektorat Ochrony Środowiska (the Chief Inspectorate for Environmental Protection), about 60% of Polish rivers have moderate ecological status, 30% have bad or poor, and only 10% have good or very good[III]. The heavy pollution of Polish rivers is caused by a variety of factors, including inflows of industrial and municipal wastewater and surface runoff water from rural areas.

I. https://www.eea.europa.eu/publications/contaminants-in-europes-seas/
II. https://www.eea.europa.eu/pl/sygna142y/sygnaly-2020/articles/zapewnienie-czystych-wod-ludziom-i-przyrodzie
III. https://www.gov.pl/web/klimat/stop-zanieczyszczaniu-rzek

WATER TREATMENT TECHNOLOGIES

Water can contain numerous physical, chemical and microbiological contaminants that make it unfit for direct consumption. To ensure that people have access to water of an adequate quality, various methods of water treatment are used. The choice of technology depends on the level and type of contaminants present in the water as well as the cost and intended use of the treated water.

There are three types of fresh water treatment technologies: physical (application of ultrasound, UV radiation), chemical (involving the introduction of strong oxidizers into the water, in most countries, including Poland, chlorine gas is used most often) and biological (using the activity of living organisms). Below are some examples of such technologies:

Filtration is one of the key processes of physical water treatment, capturing particles and solid contaminants. It can be implemented in a single or multiple stages. Filtration is used as one of the stages of water treatment in water utility companies (e.g. sand filtration).

Flocculation: typically used before filtration for pre-treatment of wastewater, it works well in water filtration for slurries and turbidities, and in sludge thickening and dewatering processes in municipal and industrial wastewater.

Disinfection involves killing or removing microorganisms such as bacteria and viruses from water. Adding chlorine is the most commonly used method.

UV-C: ultraviolet radiation is used to kill microorganisms in the water eliminating the need to use chemicals.

Ozonation: it is used to oxidize and disinfect water and it helps in eliminating organic contaminants and microorganisms.

Distillation: heating water to the boiling point, when the produced steam is collected and condensed as free of most contaminants.

Reverse osmosis: the process of passing water through osmotic membranes that trap organic compounds (such as pesticides, drugs, detergents and others), mineral salts (such as fluoride, chlorine, sodium and others), and bacteria and viruses.

The increasing area facing water stress results in limited or even no of access to good quality drinking water. In the poorest countries, projects are being implemented to treat biologically contaminated fresh water using e.g. solar energy[I].

In many places, improvement of the supply of fresh water can be achieved through desalination of sea

I. https://cordis.europa.eu/article/id/415839-using-the-sun-for-water-disinfection-in-africa/pl

water, for instance in the United Arab Emirates, Israel and Singapore.

Desalination of sea water (or salt water) is increasingly being carried out using technologies based on reverse osmosis. Although the process is cost and energy-intensive, it is also highly efficient. As a byproduct, it produces brine that can be harmful to the environment.

Europe's largest desalination plant in Barcelona can serve as an example of the application of this technology. The plant was virtually unused when it was launched in 2009 and is now operating at a maximum capacity[I]. Scientists continue to seek for even more efficient, but sustainable desalination methods[II].

Particularly noteworthy are biological water treatment technologies based on the activity of animated nature – water treatment through natural processes (in the natural environment of the soil, in ponds, lakes, in trickling filters, sewage digesters or activated sludge chambers). Hydrophytic systems are used to treat gray wastewater, rainwater, recover phosphorus from wastewater or nutrients from sewage sludge to be reused, for instance in agriculture. Hydrophytic technology is also a coherent and important part of the idea of blue-green infrastructure systems[III] and has a very high potential in the context of circular economy.

I. https://wodnesprawy.pl/barcelona-stawia-na-odsalanie-wody-by-zlagodzic-sku/
II. "Przełomowa technologia oczyszczania wody w sposób inspirowany naturą" (Break-through technology of water treatment inspired by nature), https://webcache.googleusercontent.com/search?q=cache:h_6qfzek8mcj:https://cordis.europa.eu/article/id/428488-bringing-nature-s-own-technology-to-the-fore-of-the-clean-water-revolution/pl&cd=21&hl=pl&ct=clnk&gl=pl
III. Kłodowska I.: "Systemy hydrofitowe przyjazne środowisku" (Environmentally-friendly hydrophytic systems), Warmińsko-Mazurski ODR, Olsztyn 2021.

WATER DISTRIBUTION

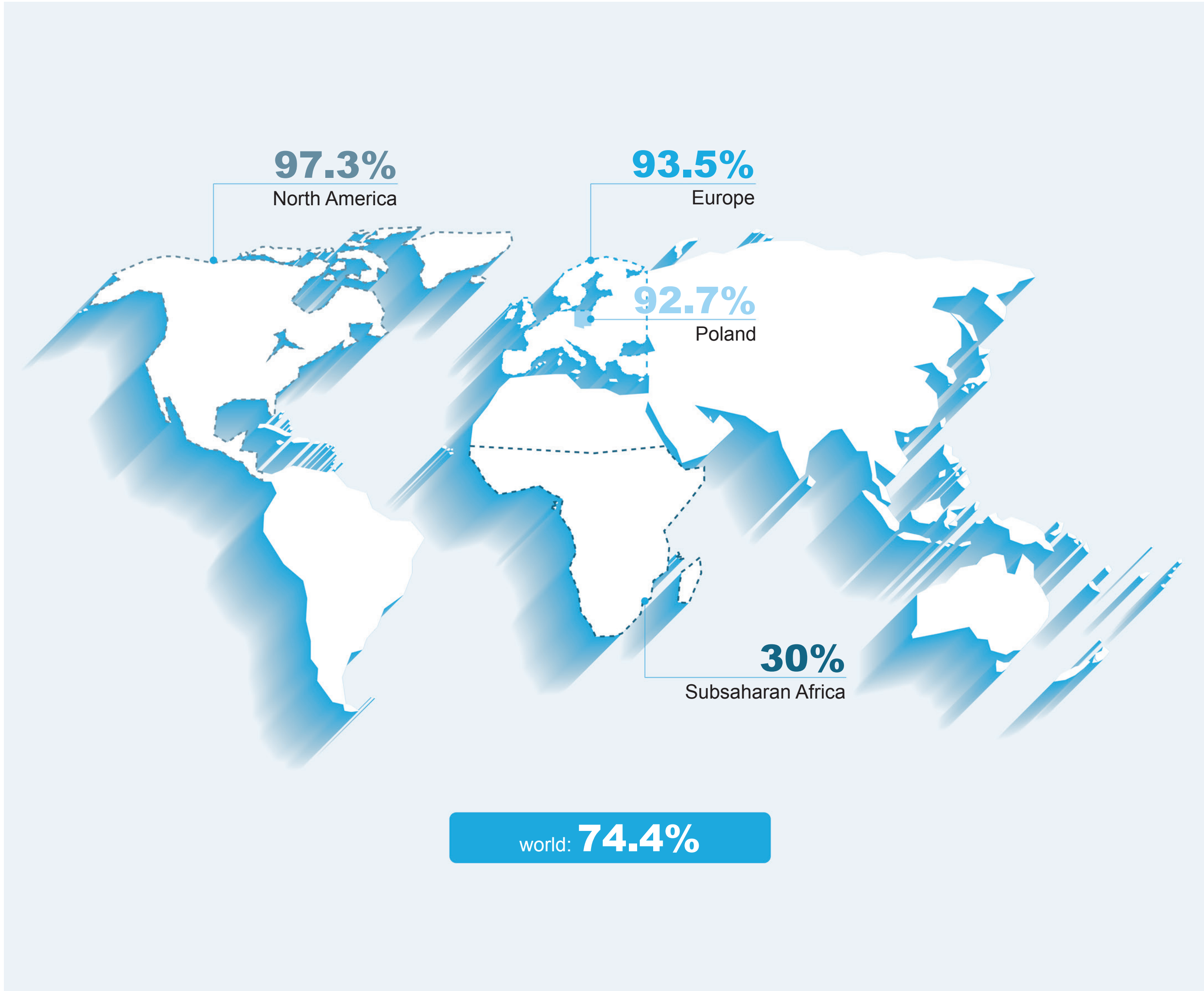
Water distribution is the supply of water to the public, which involves intake, treatment and supply of water by a water and sewerage company[I].

The availability of water resources does not automatically mean that residents have common access to drinking water. According to the SDG Report[II], the proportion of the global population using safely managed drinking water services was 74.3% globally in 2021 and has grown from 63.4% in 2005. Still more than 2 billion people have limited or no access to drinking water.

Residents of cities are in a better situation (85% have access to a water supply network), while in rural areas only 53%[III] use a safely managed drinking water distribution system.

In North America and Europe, the availability is secured at 97.3% and 93.5%, respectively. Sub-Saharan Africans are in the most difficult situation, because the percentage of the population with guaranteed access to drinking water was the lowest in 2021, at 30%.

Fig. 1.4 Ratio of population using a water supply system to total population, 2020.



I. The Act on Collective Supply of Water and Collective Discharge of Wastewater (consolidated text, Journal of Laws of 2023, item 537)
II. The Sustainable Development Goals Report 2022, https://unstats.un.org/sdgs/report/2022/
III. https://raportsdg.stat.gov.pl/2020/cel6.html

RETENTION

Retention means keeping water in the place where it fell as precipitation. This can be achieved by natural means: by collecting water in river valleys unaltered by human activity, forests, wet meadows, and marshes, and artificially: by building dams on rivers and reservoirs, among other things. Both methods have their own specific features, they can be beneficial, but they also have their limitations. Therefore, they cannot be used interchangeably because not all serve the same purposes.

Natural retention – includes activities that increase the potential of water storage in the ground, landscape or aquifers. This is nothing more than bringing ecosystems back to their natural state through restoration of rivers and floodplains, regeneration of lakes, revival and maintenance of meadows and pastures, creation of buffer strips, and application of good agricultural practice. In urban areas, these activities include: eliminating dams, using permeable pavement, building rain gardens and many more.

When enumerating the methods used for natural retention, it is worth noting the benefits of such measures. Maintaining a biological flow in rivers and mitigating the effects of climate change, improving microclimates and water quality, and protecting biodiversity are just some of them. The social aspect – tourism, the economic aspect – the availability of naturally treated water, or finally the cultural aspect – protecting the environment for the benefit of future generations – are all equally important. Natural retention can also have a negative effect, e.g. limited economic use of water resources resulting from the lack of regulated water navigation routes, etc. It also does not provide direct access to a water intake.

Artificial retention – it mainly involves hydro-engineering and drainage measures. Artificial retention can also be broken down into so-called small-scale retention and large-scale retention. The former mainly consists in the creation of small bodies of water (e.g. field and forest ponds) and has a small negative environmental impact. However, they have many positive effects:

- reduced effects of drought (e.g. they can be used for watering in agriculture and forestry),
- meeting the needs of the population (providing drinking water intakes),
- flood protection (polders, dry reservoirs),
- electricity production (small hydropower plants),
- recreation (e.g. bathing sites, fishing ponds), supporting biodiversity (e.g. in protected areas that have lost their natural ecosystem properties),
- improving the water balance (the least frequently applied technique, designed to reduce erosion, ensure retention of surface runoff or serve as a water supply for underground aquifers).

The so-called large-scale artificial retention, i.e. large water reservoirs, is often provided as a comprehensive solution serving multiple purposes. These may include: flood control, generating energy, water source for municipal purposes, prevention of the effects of drought, regulation of runoff or irrigation. After a dam is built on a river, the role of the valley changes. A new, artificially created ecosystem is built and the introduced changes are irreversible[I].

The world's largest structures of this type include: Jinping-I in China (dam – 305 m high, reservoir capacity: 7,760 million m^3), Nurek in Tajikistan (dam – 300 m, capacity: 10,500 million m^3). In Europe, the largest dam is the Grande Dixence dam in France (dam – 285 m high, capacity: 400 million m^3). The largest Polish structure is the Solina dam (dam – 81.8 m high, capacity: 472 million m^3).

For the past several years, there has been a global trend to abandon or demolish these huge hydroelectric structures due to environmental, social and financial costs (construction and maintenance costs). In 2014, the Chilean government canceled a plan to build five dams on rivers in the territory of Patagonia. In turn, in 2018 the Brazilian government announced the discontinuation of its policy to build large dams in the Amazon. The world's largest completed removal project involved two dams (the Glines Canyon Dam with the height of 64 meters and the Elwha Dam with the height of 32 meters) on the Elwha River in the USA, which were dismantled between 2011 and 2013.

I. ps://wodnesprawy.pl/bajka-o-retencji-retencja-to-temat-ktorym-zajmuje-s/

Retention – interesting global trends:

Sponge cities are modern urban areas designed to effectively manage rainwater and mitigate the effects of extreme weather events, such as droughts and floods. Cities are designed so as to resemble natural ecosystems as much as possible. They are supposed to absorb and retain water during rains, and then release it slowly during droughts. They are based on so-called blue-green infrastructure, using solutions such as rain gardens, green roofs, green walls, and permeable pavements. This urban concept is applied across the world: in Shanghai, Singapore, Rotterdam, and in Poland, where Bydgoszcz is a good example.

Photo: Bydgoszcz

Tunnels and sewers with large diameters are specially designed underground structures used to manage the flow of rainwater. They can capture large quantities of water, which is particularly useful in areas with high flow rates, such as urban sewer systems or areas prone to urban flooding. An interesting example of such an application is the Stormwater Management And Road Tunnel (SMART) in Malaysia's capital Kuala Lumpur. This is an innovative project of a two-level, nearly 10 kilometers long tunnel with 13 meters in diameter, serving as both a road and a drainage canal. During heavy rainfalls, water is directed to the tunnel, protecting the highway from being flooded. If the risk of flooding increases, the road tunnel is also closed, allowing more water to flow through.

Nature parks, e.g. the Billancourt Park near Paris, covering nearly 5 hectares, is a key component of the rainwater management system in a regenerated district. Thanks to the permeability of the ground and its ability to store water, the park filters rainwater, some of which is reused for irrigation. The park was designed to include areas with different degrees of moisture. The main reservoir for collecting rainwater consists of wetlands, peat bogs and sandy valleys, the higher parts of the park are covered with flower meadows. In the case of a risk of flood, a system of water gates allows turning the park into a reservoir.

Permeable pavements – In the United States, the first drainage pavements began to be built in the 1970s. They are specially designed to effectively drain water from the surface. Thanks to the porous structure and special materials, such as permeable concrete or asphalt, rainwater quickly percolates through the pavement and infiltrates into to lower layers or special drainage systems. In Copenhagen, testing of new permeable sidewalk slabs was completed in 2020. Rainwater flows through them and collects underneath them in the aquifer. From there, excess water can be diverted to a nearby garden, field or be stored.

BLUE GOLD

Access to water is a guarantee of a healthy society and economic development. The water industry, along with its related branches, today forms an ever-growing Blue Market sector, where water is a major area of focus, research and development and investment activities. Also, more and more entities from other industries recognize the opportunity to get involved in projects related to water trading. Financial markets are no exception. The sector has developed a range of instruments in the form of water indices, ETFs and futures contracts. Thanks to them, investors have the opportunity to hedge against the risk of shortages, but also to participate in the long-term growth in the value of companies related to water management[I].

The value of the global water market has been growing consistently. In 2020, the market was valued at more than USD 800 billion and according to estimates in the Global Water Market 2023 report its value will grow to about USD 1,470 billion by 2028[II]. Key drivers of growth include water shortages, deteriorating water quality, growing population, fast-growing emerging economies and rising standard of living.

These factors encourage investment in the water industry. The world's largest companies are striving to outperform one another in developing innovations and unique technologies related to water acquisition, optimizing water transport, treatment, wastewater treatment, consumption optimization, etc.

Interesting examples illustrating trends and rapid development:

Artificial intelligence at the service of the water supply industry – water losses due to leaking water mains reach up to 40%. A UK company FIDO Tech has developed a new standard in detecting water leaks through the use of artificial intelligence (AI), which automatically identifies leaks, their size and exact location based on analysis of files generated by acoustic recorders and hydrophones.

Water from the atmosphere – Atmospheric Water Generation Technology – AWG[III] is a technology that enables the production of drinking water from the air. AWG generators are available for domestic purposes, producing from 1 to 20 liters of water per day, or for commercial use, with a capacity of 1,000 to more than 10,000 liters per day. Water produced by AWG generators is usually subjected to treatment and disinfection processes to meet safety and quality standards for drinking water. The AWG system consumes large volumes of electricity and its operation is expensive.

I. https://wodnesprawy.pl/blue-market-niedoceniane-na-swiatowych-rynkach-nieb/
II. Research and Markets: https://www.researchandmarkets.eom/report/water#cat-pos-1 [accessed on 14 October 2023]
III. https://www.epa.gov/

Aquaponics – it is a landless form of farming, a system of food production that combines conventional aquaculture (raising of water animals in reservoirs) with hydroponics (growing plants in water). Fauna and flora form a so-called symbiotic environment. Plants use the waste produced by animals, as a result of which fish or crawfish can live in a cleaned, healthy environment. The functioning of this system is modeled on the processes taking place in natural bodies of water and its main advantages include:

- production of clean, nutrient-rich food;
- cultivation that continues throughout the entire year, regardless of weather conditions;
- water savings compared to crops grown in traditional agriculture (up to 90%);
- smaller area required to grow plants than in traditional agriculture;
- reduced waste discharged into the environment, most components are used in a closed loop;
- retention and management of rainwater from green roofs.

The first such project, a farm called Urban AquaFarm, was implemented in Wrocław in March 2023[I] and it also provides education on climate change.

Passive systems – wastewater treatment in rural areas with dispersed settlements presents many challenges. According to the report “Stan techniki stacji zlewnych w Polsce” (The state of the art of cast stations in Poland) released in April 2023 by Ścieki Polskie in partnership with 3W Idea and BGK, more than 10.5 million Poles are not connected to a collective sewage system. One possible solution is provided by passive systems, which include hydrophytic treatment plants that replicate the processes naturally occurring in wetland ecosystems. Microorganisms degrade and assimilate carbon compounds, retain phosphorus compounds and heavy metals, and are also responsible for the assimilation and volatilization of nitrogen compounds. Such a facility has been in operation for more than two decades in Velka Jasenice in Czechia. An example of such a solution in Poland is the passive wastewater treatment system in Udrzynek (in Brańszczyk municipality). The treatment plant was designed and built by RDLS, a spin off of the University of Warsaw[II].

I. https://aqfarm.eu
II. https://wodnesprawy.pl/oczyszczanie-sciekow-poza-aglomeracjami-systemy-pas/

BLACK SWANS

Climate change is causing a growing risk extreme events in our environment, whose potential occurrence and intensity are usually unpredictable and sudden. The social and economic impact is typically enormous. According to UNICEF, as much as 74% of the natural disasters which occurred across the world between 2001 and 2018 were related to water. They included both droughts and floods[I]. Other unforeseen phenomena and events, such as the Covid-19 pandemic or Russia’s aggression against Ukraine, have completely changed the key elements of our lives, and their impact on the developments in regions or countries is immense.

Increased occurrence of extreme events – climate change exacerbates the occurrence and intensity of such events, which cannot be predicted and described by models based on historical data . Anomalies are increasingly noticeable and pronounced. NASA announced that this past meteorological summer (June–August 2023) was the hottest summer since global records began in 1880. The temperature was also 1.2°C higher than the average between 1951 and 1980[II].

Europe’s experience was particularly severe last year. Water shortages and drought affected a large part of the continent. In August, the water level dropped to below 40 cm in some parts of the waterway on the Rhine River in northern Germany, which was the lowest level on record in those places. In Italy, the water level on the Po river was 7 meters below the multi-year average. France was struggling with the worst drought in the country’s history, with more than 100 municipalities suffering from a lack of drinking water.

According to the Climate Reanalyzer University of Maine[III], a record high average air temperature at ground level for the entire Earth was set in early July 2023. Intergovernmental Panel on Climate Change (IPCC)[IV] announced that global temperatures have not been this high in 125,000 years.

Drought is not the only problem in Europe. The floods that hit Germany in 2021 and Italy in 2023 were the largest in more than 100 years. The worst situation was in the Ahr Valley. At the time, more than 170 people died and 17,000 were deprived of their homes.

Extreme events also occur in other regions of the world. In 2022, a flood in Pakistan resulted in the death of nearly 2,000 people and displaced 7 million Pakistanis. The consequences of last year’s flood in the KwaZulu-Natal province on South Africa’s east coast was also proved dramatic. 459 people were killed and losses were estimated at EUR 3 billion. In July 2023, India and Pakistan grappled with the aftermath of heavy rainfall that caused flooding and mudslides. Although the monsoon season commonly occurs in the Indian subcontinent, this time rain was particularly intense – Delhi saw the highest rainfall in more than 40 years. According to a report[V] prepared by Christian Aid, the world’s ten most expensive climate disasters resulted in losses estimated at USD 168.4 billion. For the first time, the list also included Poland (due to a cyclone named Eunice, February 2022).

In Poland, extreme events mainly include flash floods and droughts. Floods caused by rainfall, known as flash floods, are most often a consequence of storm events and heavy rains in urban areas. The most vulnerable areas are those with a dense urban fabric (sealed catchment areas). According to Statistics Poland, in 2021 nearly 30,000 interventions of the fire service were recorded in connection with excessive rainfall and flooding.

In recent years, drought in Poland has been particularly severe. In 2023, it threatened crops in more than 65% of communes and municipalities. Significant shortages of water were also recorded in the Pomorskie, Mazurskie and Wielkopolskie lake districts. Almost 170 communes and municipalities requested their residents to save water due to its shortage. In the report published last year by the Polish Economic Institute (PIE) entitled “Gospodarcze koszty suszy dla polskiego rolnictwa” (Economic cost of drought for Polish farming), it was estimated that each year we lose crops worth even PLN 6.5 billion[VI]. In the same report, PIE predicts that a 2°C increase in average temperature will cause crop yields to fall by at least 14%.

The **Covid-19 pandemic** caused tremendous social, economic, political and environmental challenges for the world. Interestingly, for the environment, it was a moment of relief resulting from a general lockdown, a reduction in the number of flights (a drop in business

I. UNICEF: https://unicef.pl/co-robimy/aktualnosci/news/woda-i-globalny-kryzys-klimatyczny-10-rzeczy-o-ktorych-musisz-wiedziec [accessed on 14 October 2023]
II. NASA: https://climate.nasa.gov/news/3282/nasa-announces-summer-2023-hottest-on-record/
III. https://climatereanalyzer.org/
IV. https://www.ipcc.ch/
V. https://www.christianaid.org.uk/sites/default/files/2022-12/counting-the-cost-2022.pdf
VI. PIE: Report 3/2022, “Gospodarcze skutki suszy dla polskiego rolnictwa” (Economic effects of drought for the Polish agriculture)

and tourist traffic) and limited activity of societies. Both air and water quality improved. In the Ganges, which is one of the world's most polluted rivers, after an eight-week lockdown for industry, the water from the river on the section between the cities of Rishikesh and Haridwar was suitable for drinking[I].

Biodiversity in natural ecosystems has always helped to prevent contagious pathogens from causing a pandemic, due to natural systems of control and maintaining a balance[II]. The loss of protected areas and natural habitats, resulting mainly from pollution and rapid urbanization, are serious threats that undermine nature's inherent preventive capacities, which we also enjoy as humanity on a global scale.

An important discovery made during the Covid-19 pandemic was the analysis of wastewater to diagnose the level and direction of the spread of the epidemic. It was not only possible to confirm the presence of the virus, but also to study its type and concentration, which enabled modeling of infection growth rates. Based on lessons learned, water monitoring to check the potential presence of the virus is becoming a standard procedure. In Poland, such studies are carried out by water supply and sewage companies, for example in the Warsaw agglomeration[III].

Russia's aggression against Ukraine is a humanitarian disaster that has been unimaginable in the realities of the 21st century. Warfare causes death, suffering and destruction. In the areas of direct fighting and at the sites of missile attacks carried out by Russia, people are losing their homes and their life's possessions. To survive they have to flee, the scale of migration is unprecedented, more than 6 million Ukrainians have left their country due to the war. More than 93% of them ended up in Europe, of which more than 25% applied for asylum or temporary protection in Poland[IV].

The consequences of this war are also tragic for the environment, including as a result of fires caused by shelling or the use of munitions containing high concentrations of toxic metals, such as lead, mercury and arsenic. The movement of the military destroys peat bogs and wetlands, eroding their functions as an ecosystem.

The destruction of the Kakhovka Dam released an enormous amount of water from the reservoir, which covered an area of 2,155 km^2 and held 18.2 million m^3 of water. As a result, some 120,000 hectares of land was inundated. People, animals and the entire ecosystem of the Dnieper River basin have suffered. Ukraine has definitely lost a part of its protected areas.

The ongoing war has accelerated Europe's energy transition. Poland also has accelerated efforts to build infrastructure for the production of electricity using nuclear power. It turns out that this will have a major impact on water resources. Nuclear power plants require constant access to a stable source of water, which is the coolant of the reactor core, the medium of heat transfer from the reactor to the turbine, and is also used for other processes.

In conventional power plants, such as coal-fired facilities, water is used to generate steam that drives a turbine, and after it is cooled down it is returned to the source (e.g. a river). In a nuclear power plant, water is used to transfer heat. After cooling, it is returned to the power plant for reuse. For cooling purposes, nuclear power plants can use fresh or salt water.

I. https://www.india.com/viral/ganga-in-rishikesh-becomes-fit-for-drinking-and-shines-like-diamond-in-haridwar-netizens-share-stunning-pictures-3999338/
II. Everard et al. The role of ecosystems in mitigation and management of Covid-19 and other zoonoses, 2020
III. ???
IV. The Office of the United Nations High Commissioner for Refugees: Operational Data Portal, https://data2.unhcr.org/en/situations/ukraine [accessed on 14 October 2023]

HAS THE PROBLEM WITH WATER BEEN CREATED BY SCIENTISTS?

Despite noticeable improvements, about 2 billion people still have no access to safely managed drinking water distribution, of which as many as 771 million lack basic access to drinking water[I]. According to estimates by The World Resources Institute, demand for fresh water will exceed its availability in 2030 by as much as 56%[II]. In turn, the global demand for water is estimated to increase 30% by 2050[III].

Societies are more and more aware of the fact that the world around us is undergoing changes, largely caused by the effects of human activity. Growth of population and "consumerism", the pursuit of ever higher production or the effects of climate change are generating new water-related phenomena that are already noticeable today and which will become more severe in the future.

Awareness of the scale of the problems, e.g. insufficient availability of water resources and unfavorable trends in this area, has been growing, but is still insufficient. Forecast shows that by 2025 half of the population

I. World Bank: https://blogs.worldbank.org/opendata/world-water-day-two-billion-people-still-lack-access-safely-managed-water [accessed on 14 October 2023]
II. World Resources Institute: https://www.wri.org/research/setting-enterprise-targets-modeling-downstream-water-use-consumption [accessed on 14 October 2023]
III. World Resources Institute: https://www.wri.org/water [accessed on 14 October 2023]

will live in regions suffering from water shortages[I]. Without strong global measures, conflicts caused by competition for water will escalate[II].

The Water Conference was held at the UN headquarters in New York on 22-24 March 2023. Its main goal was to adopt the Water Action Agenda. More than 700 voluntary commitments made by multilateral partnerships were presented at the event. They are the first response to the world's water and climate challenges. Below are selected examples of such initiatives[III]:

- The United States of America will allocate USD 49 billion to investments to support infrastructure and water and sanitation services resilient to climate change;
- Japan plans to contribute to solving the water-related social problems affecting the Asia-Pacific region by developing high-quality infrastructure and providing financial assistance (USD 3.65 billion) over the next five years;
- Vietnam will develop a policy to manage major river basins by 2025 and to ensure that all households have access to clean, running water by 2030;
- more than 50 leading global companies (including DANONE, Starbucks, Ecolab, Gap Inc. Xylem) will work together towards the achievement of SDG 6 (Sustainable Development Goal 6 focusing on providing clean water and sanitation for all).

The issues of ensuring good quality water for people and protecting the existing water resources are widely addressed in the European Union law. Over the past 30 years, EU Member States have made significant progress toward improving water quality by adopting, among other things, the Water Framework Directive (WFD)[IV], the Urban Waste Water Directive[V], the Drinking Water Directive[VI] and the Regulation of the European Parliament and of the Council on the establishment of a framework to facilitate sustainable investment (the so-called Taxonomy)[VII].

In February and March of this year, Poland adopted updated water management plans for areas located in individual river basins. They will be effective in the next planning cycle[VIII].

The European Economic and Social Committee (EESC) is working on the Blue Deal, a strategy that outlines directions for change and investment in water management. It will address issues related to water management, improving water availability, as well as protection of resources in view of the deficits occurring throughout Europe. On 26 September 2023, the Consultative Commission on Industrial Change (CCMI) adopted the so-called Umbrella Opinion on the Blue Deal. The next step will be for the EESC to present its recommendations on the Blue Deal to the European Commission.

I. https://www.afro.who.int/health-topics/water
II. https://wodnesprawy.pl/zmiany-klimatyczne-a-rosnace-ryzyko-wystepowania-ko/
III. https://sdgs.un.org/conferences/water2023
IV. https://environment.ec.europa.eu/topics/water/water-framework-directive_en
V. https://environment.ec.europa.eu/topics/water/urban-wastewater_en
VI. https://environment.ec.europa.eu/topics/water/drinking-water_en
VII. https://ec.europa.eu/sustainable-finance-taxonomy/
VIII. https://wodnesprawy.pl/komplet-rozporzadzen-w-sprawie-planow-gospodarowani/

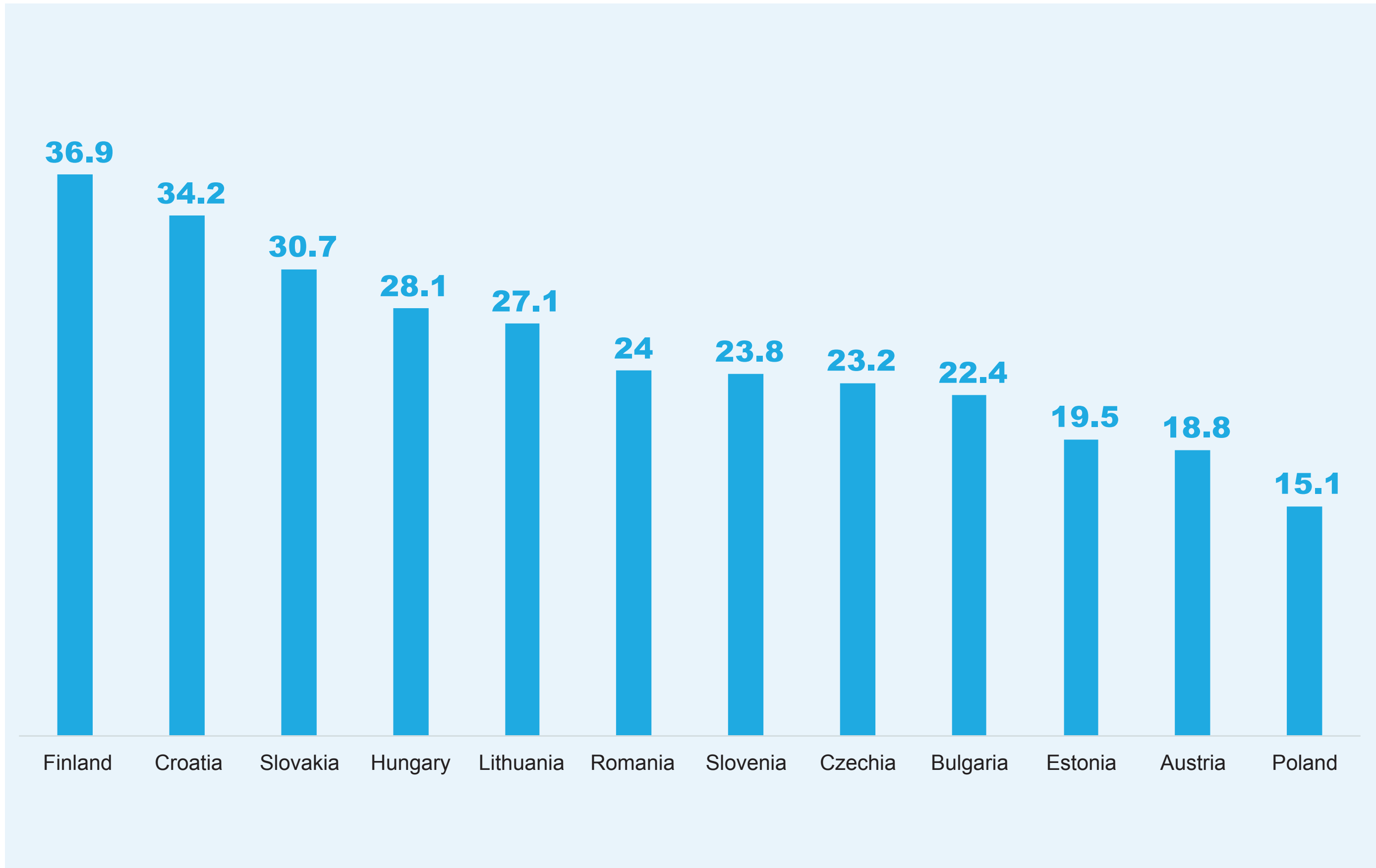
WATER IN THE THREE SEAS REGION (3 SEAS INITIATIVE – "3SI")

The Three Seas Initiative was established in 2015. Until recently, its members included 12 countries: Austria, Bulgaria, Croatia, Czechia, Estonia, Lithuania, Latvia, Poland, Romania, Slovakia, Slovenia and Hungary. In September 2023, Greece's accession was officially announced at the Summit held in Bucharest (6-7 September).

The Three Seas Initiative focuses on issues related to the following sectors: transport, energy and digital communications. To respond to the challenges related to development and climate change, the activities of the 3SI could also cover other sectors. **They could, but do they?**

The different economic and political potentials of the 3SI member countries may affect the degree of economic, political and financial commitment to this format of cooperation. The latest data in this area indicates that in 2021 the share of reciprocal trade between the 3SI countries in total trade was respectively[I],[II]:

Fig. 1.5 Share of the 3SI area in the trade of a given country, 2021

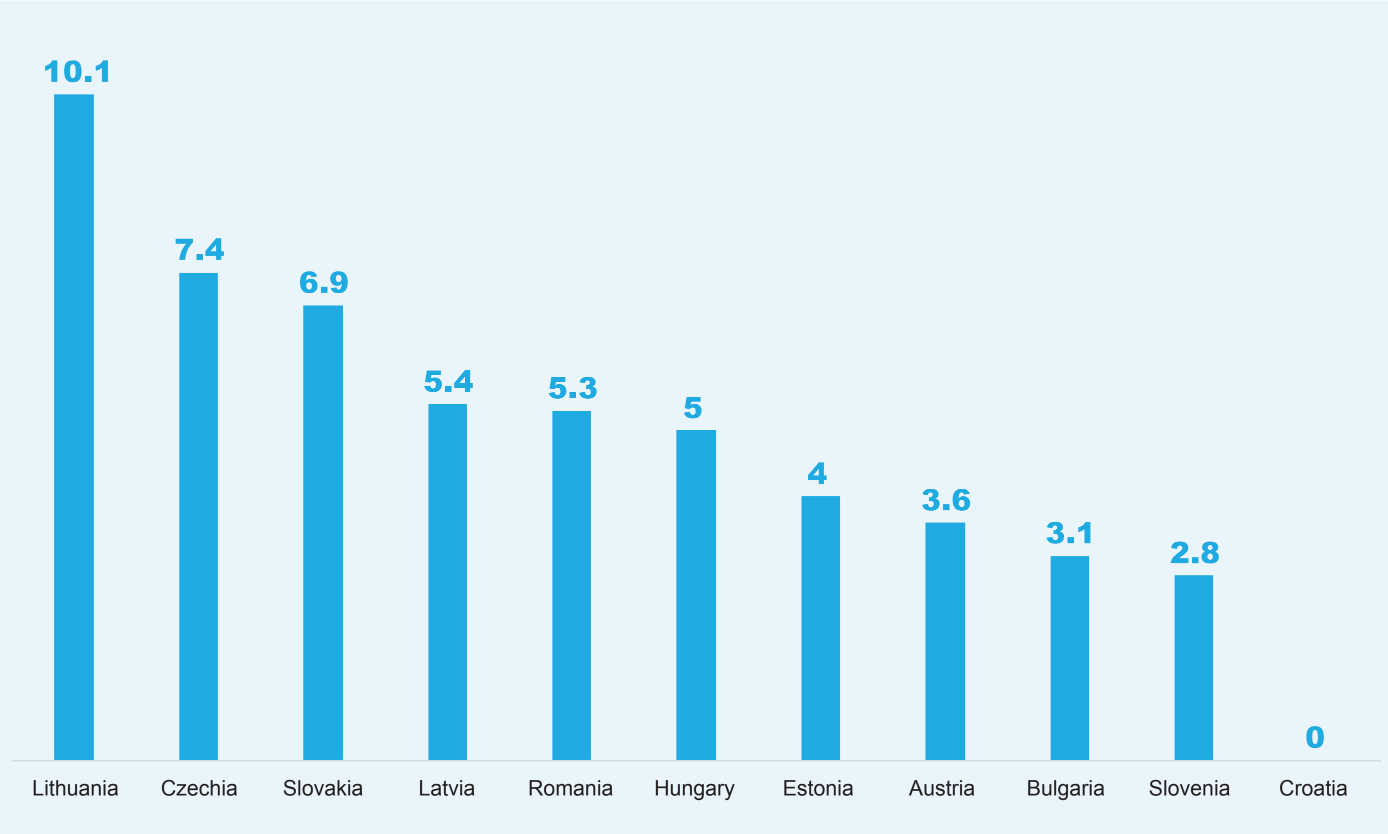


I. https://ies.lublin.pl/komentarze/nowe-szanse-rozwoju-dla-europy-srodkowej-wspolpraca-gospodarcza-w-ramach-inicjatywy-trojmorza/#_ftn1
II. www.trademap.org

From an economic point of view, trade with the 3SI member countries is very important for Croatia and Latvia, as it accounts for more than 1/3 of their total trade. At the other extreme is Poland, for which trade with the 3SI countries represents just over 1/7 of total trade.

Poland's most important trade partners among the 3SI countries are its direct neighbors, namely Lithuania, Czechia and Slovakia.

Fig. 1.6 Share of trade with a given 3SI country with Poland, 2021



Despite the fact that trade with the 3SI countries accounts for a smaller portion of Poland's international trade, Poland assumes the role of the initiator of many activities, in particular projects designed to accelerate economic growth, such as the construction of North-South infrastructure: the Via Carpathia and Via Baltica road links, the Rail Baltica connection and the Danube-Oder-Elbe water corridor. A similar situation in terms of the economic benefits of membership in the Initiative is observed in the case of the Baltic States as well as Romania and Bulgaria.

On the other end is Austria, which does not participate in any strategic project. Also Czechia, Slovakia and Hungary show lower commitment; Czechia engaged in only one priority project – the Danube-Oder-Elbe water corridor[I].

The Danube-Oder-Elbe waterway was designed to connect Poland, Czechia and Slovakia with a 450-kilometer-long canal, which would create a network of water transport routes and establish a water connection between seaports throughout the region. The project was intended to be financed with funds from the 3SI Investment Fund set up in 2019 with the aim of improving inter-regional connectivity and accelerating investment in regional infrastructure projects.

The project to build the waterway was also included in the Polish investment priorities declared on the Three Seas Initiative Summit held on 16-19 September 2018, alongside the Via Carpathia and Via Baltica projects. Unfortunately, in 2023 the Czech government enacted the cancellation of the territorial reserve for the Danube-Oder-Elbe connection, whereby Czechia withdrew from the project.

Interestingly, no official speeches or cross-sectional documents on the Three Seas Initiative mention any water management projects in the industry. Neither in terms of its use, nor in terms of its saving, i.e. adapting the economy to closed-loop technologies.

There is much greater emphasis on issues and projects related to infrastructure, energy and energy security, which results from the original assumptions for the establishment of the 3SI. Today, the issues related to water and challenges in this area are gaining importance and unarguably an initiative that stretches geographically between the three seas should address these challenges and expand the catalogue of priorities to include water projects.

I. https://3seas.eu/about/progressreport

OUTLOOK ON THE FUTURE

Access to water determines people's ability to function on Earth – any disruption to the water cycle can be dangerous and even catastrophic to our continued existence. The past decade was the warmest since measurements began in the 19th century and included 9 of the 10 warmest years on record. Ocean water temperatures are rising, which has accounted for approximately 93% of the planet's warming since the 1950s[I].

The warming is caused by greenhouse gas emissions (GHGs). More and more solar energy is "trapped" in the atmosphere and transferred to the environment.

The pH of waters is falling and ocean acidification occurs causing irreversible changes to fauna and flora. Warm water has lower capacity to store CO_2.

Further rise in temperature will cause the oceans to start getting rid of this gas. In view of shifting climate zones, forest clearing and water shortages, vegetation will have limited ability to absorb carbon dioxide.

Higher temperatures and higher air humidity resulting from evaporation will accelerate the processes of decay and release of carbon and methane, further contributing the greenhouse effect. Melting permafrost will release another portion of greenhouse gases into the atmosphere, whose volume will amount to 10-100% of emissions from fossil fuels. If this scenario materializes, land will become a source of emissions rather than the medium for their storage already in this century[II].

Melting permafrost could also have other catastrophic consequences in the form of the release of dormant viruses previously unknown to humans. Research results are alarming. Scientists have proven, sampling viruses from 30,000 years ago, that their activity may be restored[III].

Global warming is causing the ice caps to melt. According to a recent report by the European Space Agency (ESA)[IV], the rate of ice loss in Antarctica and Greenland has accelerated. Based on satellite data, it was estimated that since the 1990s it increased as much as fivefold. It should be remembered that glaciers cover almost 10% of the land surface (mostly Greenland and Antarctica). The melting of the glaciers of Greenland would raise the water level by 7 meters, and the melting of the entire Antarctic ice cap – by about 60 meters[V].

A similar process is observed in the case of mountain glaciers. The complete disappearance of a glacier in the mountains cuts off river sources, which contributes to more droughts. An example of this process is seen in Europe's most numerous glaciers in Switzerland, which melted at a record high rate in 2022. As reported by the Swiss Academy of Sciences, the glaciers lost as much as 6% of their total volume[VI].

A key element of climate change is the impact on the hydrological cycle, namely on all processes owed to which a repeated pattern of the closed water cycle exists, keeping the global resource at an even level. The latest climate models clearly indicate that precipitation will become more variable and the risk of drought or flooding will be higher[VII].

The AR6 Synthesis Report – the final, concluding part of the report of the Intergovernmental Panel on Climate Change – was completed in March 2023. It was compiled from more than a hundred thousand peer-reviewed scientific articles. UN Secretary-General Antonio Guterres called the document "a survival guide for humanity."

The report attributes the responsibility for climate change to human activity and states that climate change is progressing and is increasingly problematic. According to the report, continued global warming means more frequent occurrence of extreme and increasingly dangerous weather events, including floods and droughts. Temperature rise by more than 1.5°C will make life impossible in some regions of the world.

I. Climate change, impacts and vulnerability in Europe 2016
II. https://naukaoklimacie.pl/aktualnosci/czy-i-dlaczego-klimat-ziemi-sie-zmienia-4/
III. https://przystaneknauka.us.edu.pl/artykul/zarazliwe-wirusy-z-wiecznej-zmarzliny
IV. Simonsen, SB, Slater, T., Spada, G., Sutterley, TC, Vishwakarma, BD, van Wessem, JM, Wiese, D., van der Wal, W. and Wouters, B.: Mass balance of the Greenland and Antarctic ice sheets from 1992 to 2020, Earth System Science Data, 15, 1597-1616, https://doi.org/10.5194/essd-15-1597-2023, 2023.
V. https://www.usgs.gov/faqs/how-would-sea-level-change-if-all-glaciers-melted
VI. https://scnat.ch/en/uuid/i/2e076759-0234-567e-9bfb-2cdfebd6ff34-Worse_than_2003_Swiss_glaciers_are_melting_more_than_ever_before
VII. https://earthobservatory.nasa.gov/features/Water/page3.php

IPCC's sixth report in numbers[I]:

from 3.3 to 3.6 billion people

are exposed to the negative consequences of climate change;

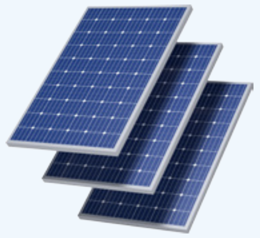
54% of CO_2 emissions from the last 10 years,

resulting from human activity has been absorbed by nature:

31% – terrestrial ecosystems; **23%** – seas and oceans;

approx. 1/3 of emissions

of greenhouse gases is generated by the food industry;



the cost of harvesting solar energy dropped **by 85%**,

the cost of harvesting wind energy dropped **by 55%** in 2010-2019.

Energy from these RES is cheaper and more accessible than ever.

I. https://www.wwf.pl/raport-ipcc-zbyt-wolna-reakcja-na-kryzys-klimatyczny-doprowadzi-do-katastrofy

TRENDS AND CHALLENGES

Water demand has been growing consistently, by 1% for the past 40 years, as confirmed by the AR6 Synthesis Report. Water shortages result from overconsumption, the effects of climate change, and water pollution, whose self-purification powers have dropped.

The development of industry, agriculture and population growth means that the situation does not improve. Approximately 2 million tons of wastewater, agricultural and industrial waste are discharged into waterways each day. It is estimated that as much as 80% are not properly treated.

According to scientists, the amount of wastewater generated will increase by 50% by 2050 and the world's water quality will rapidly deteriorate after that date. The problem of untreated wastewater also involves lack of access to sanitary facilities – this applies to as many as 6 in 10 people worldwide. This results in the spread of many diseases caused by bacteria and parasites.

Smart water management systems will be one of the solutions ensuring reduction of water consumption. By using sensors and relevant algorithms, we can expect that the efficiency of water use in agriculture will improve. Adjustment of water consumption depending on soil moisture, temperature, sunshine, stage of crop growth and many other factors, which will be calculated by AI.

Implementation of circular economy solutions, which will allow the recovery of used water and the use of water with lower parameters for applications for which the water quality is appropriate.

Reduction of water losses in water supply and sewage networks, through modernization of systems and monitoring based on AI. Increased investment in wastewater treatment plants not only in developed countries, but especially in developing countries.

Proper management of rainwater runoff, use of blue and green infrastructure in cities to retain water. Development of modern forms of retention based on modeling results, with particular emphasis on small-scale retention.

Abandonment of the construction of large hydroengineering facilities – water reservoirs, including the necessary facility demolition.

Protection of biodiversity on a much larger scale than it is now, restoration of watercourses, leaving valleys to their natural processes.

Phasing out subsidies to fertilizers in individual countries. Subsidies cause excessive use of substitutes and uneven fertilizer application. They amplify nutrient runoff to waters.

WHAT CAN WE DO FOR WATER?

It is expected that there will be increased precipitation in the winter season in the coming years, but that does not mean an end to the problem of drought in the summer.

If we do not retain the water, it will quickly drain through rivers into the sea. Let us remember that precipitation water is free, while water drawn from the water supply system is not. As users, we can join in water retention and saving. What can we do?

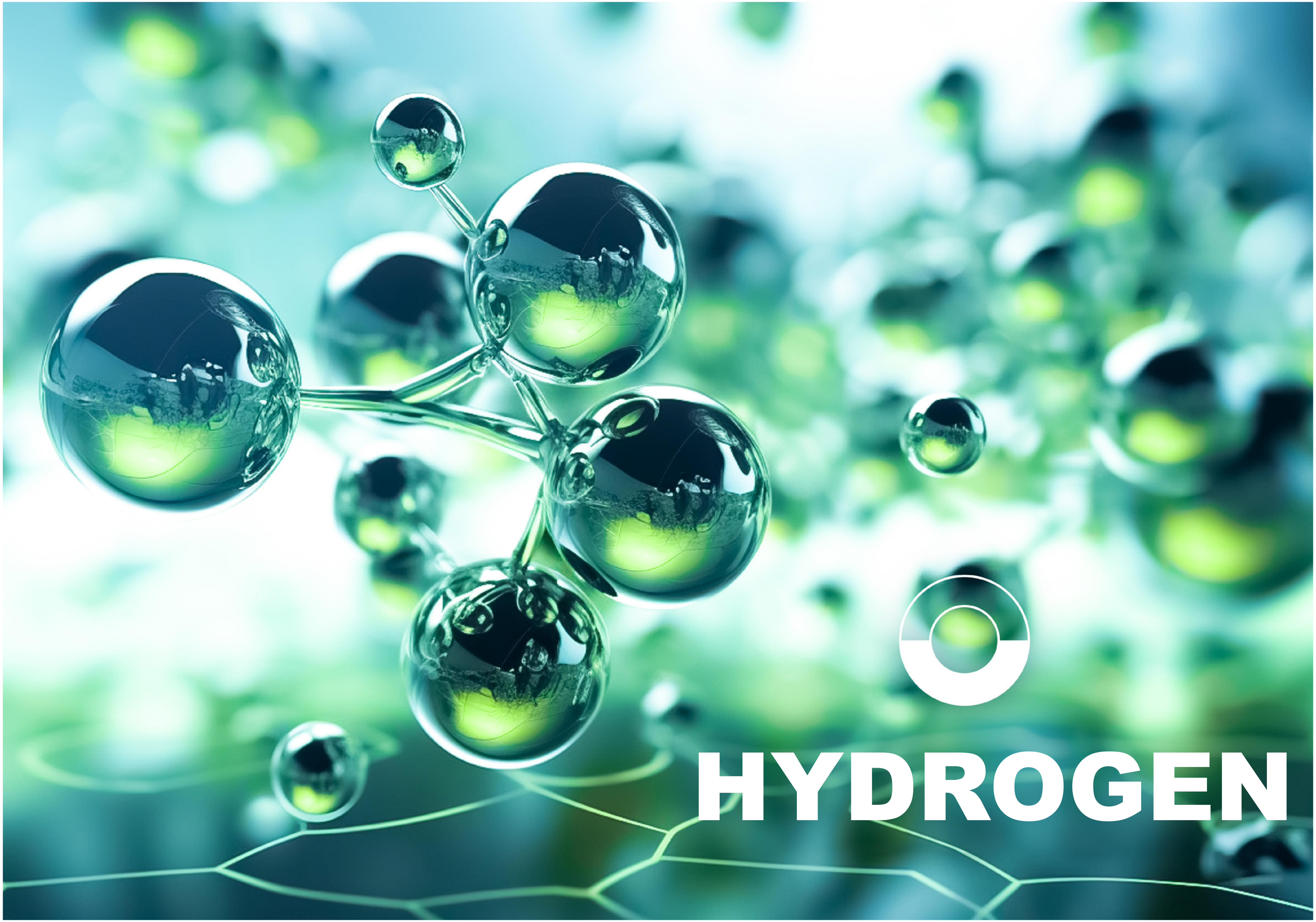
Rainwater harvesting – make a rainwater tank, pond, ensure that not all rainwater from the roof flows into the sewage system;

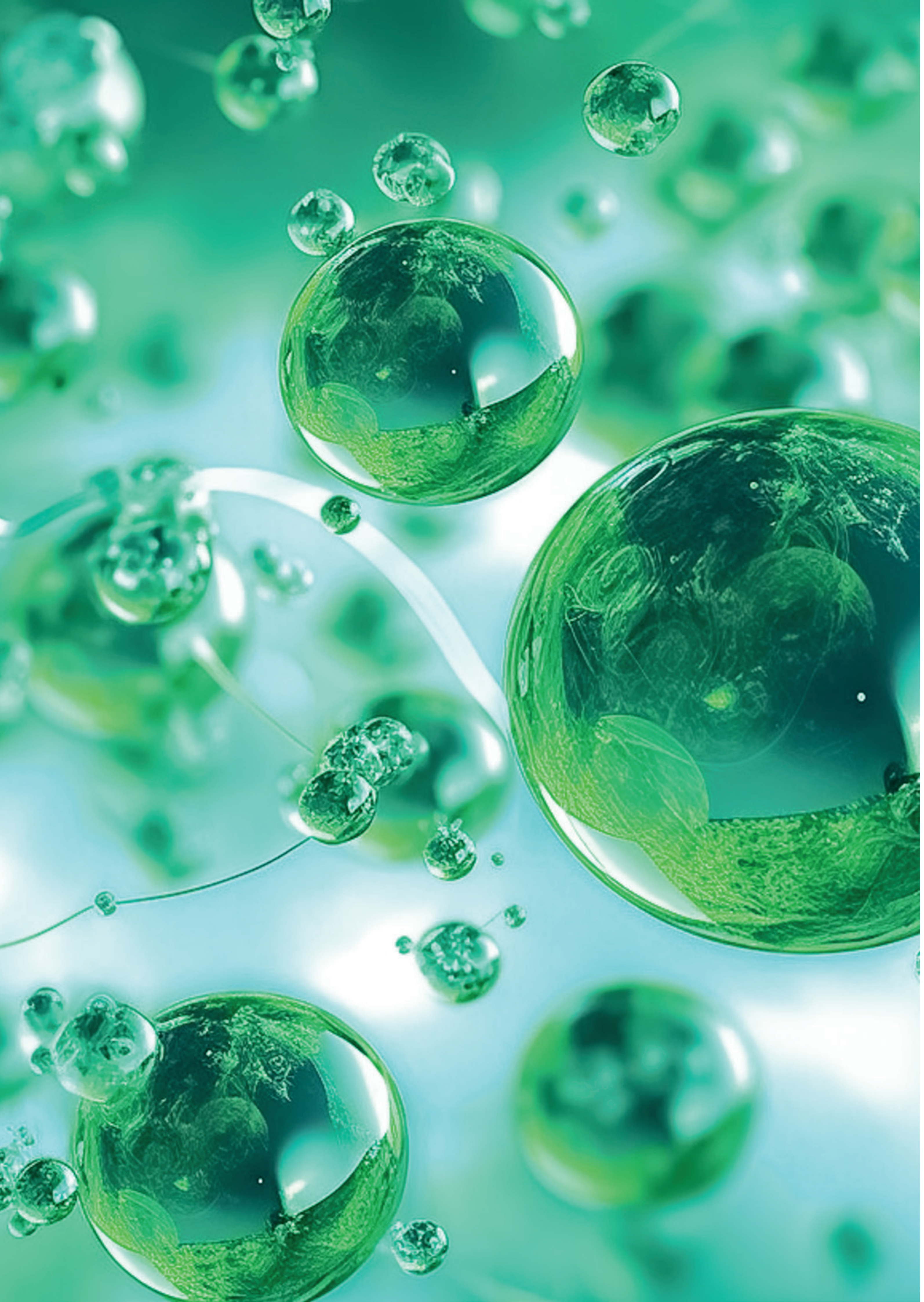
Ensure permeable surfaces – do not lay concrete or pave (e.g. with cobble stone) areas where it is not absolutely essential, let rainwater soak into the soil, where it can stay longer and be available to the surrounding ecosystem;

Meadows in place of lawns – in many cases, replacing lawns (which require more frequent watering and evaporate water faster) with meadows is justified. Not only do meadows retain moisture longer and provide a natural habitat for many insects and animals, but also when improperly maintained for example they can facilitate the spread of ticks;

Reduce the water footprint – including by buying local products that do not require long supply chains, switching from bottled water to tap water, not wasting food, using reusable bags.

Our personal initiative and involvement is important, but we should not forget the need to take action on a larger scale; in residential areas, districts, city or country. Climate change adaptation measures must become a priority and one of the most important of them is retention, which effectively mitigates the effects of climate change. We must also not forget about education and the need to build social capital in this area as well.


HYDROGEN



INTRODUCTION

Hydrogen is the most common element in space and it is no accident that it is becoming an ever more common object of interest of scientists who seek solutions that would support the energy transition. It easily reacts with oxygen to generate energy and water vapor. It seems to be the right answer to the challenges related to the climate and energy security. In the era of unstable supply chains, it may finally allow a break from dependence on fossil fuels and geopolitical considerations.

In the industry there is a growing level of optimism about the development of hydrogen economy. The interest in hydrogen technologies is growing around the world, new investments are made, and the efficiency of constantly improving technologies is increasing. We can produce hydrogen in an environmentally friendly way, and we know and understand the constraints of hydrogen distribution, storage and the characteristics of its consumption.

Undoubtedly, decarbonization of the global economy is necessary, and hydrogen has every chance of being the answer to this challenge. In 2022, the U.S. Department of Energy announced the *National Clean Hydrogen Strategy and Roadmap*[I], which indicates that clean hydrogen production in the United States of America will reach 10 million tons per year by 2030. China's carbon dioxide emissions are set to peak at the same time. More than 30 countries accounting for more than 70% of the global GDP have created national hydrogen strategies.

Is the world ready for higher production and wider use of an environmentally friendly resource? Can we as a country organize and build an economy based on low-carbon hydrogen? In the Three Seas region, do we have a chance to become not only a transit country, but also an exporter of advanced hydrogen technologies?

This part of the report provides a summary of the state of the art in the development of the hydrogen ecosystem with reference to the situation at a global and national level and as part of the Three Seas Initiative. Looking for answers to these questions, we invite you to read the next part of this report.

I. https://www.hydrogen.energy.gov/library/roadmaps-vision/clean-hydrogen-strategy-roadmap

SUMMARY

1. Interest in hydrogen, in particular in low- and zero-carbon hydrogen, has been getting stronger especially since the second decade of the 21st century.

2. In terms of the characteristics of the largest players in the hydrogen market, two main sectors of industrial hydrogen applications can be distinguished: chemical (including mainly fertilizers) as well as refining and petrochemical industry.

3. It is expected that hydrogen use will increase in transport (railway, buses, passenger cars and trucks), steel industry (replacement of process streams based on fossil fuels with hydrogen in the production process), non-ferrous metals industry (mainly the production of copper and silver), energy storage (hydrogen as an energy carrier) and heating.

4. In Europe, hydrogen is viewed as a tool that will enable reduction of carbon dioxide emissions. Due to strong demand, Europe will also have to import hydrogen.

5. In 2022, global hydrogen consumption was about 95 million tons.

6. The amounts of capital invested in the development of innovative technologies based on hydrogen have been growing consistently. Europe and the United States are at the forefront in that respect. Globally, in 2021 capital expenditure increased year on year by 35%, whereas Europe's outlays doubled. Looking at the broader context of decarbonization, hydrogen-based technologies account for 5% of total spending on "clean innovation".

7. The hydrogen market is attracting large investments in production, sales, research, development and education. In 2022, the value of the global hydrogen market was estimated by PIE at approximately PLN 600 billion. Its value could triple by 2050 as a result of decarbonization of the global economy.

8. Under the RePowerEU program, two important hydrogen transmission corridors will lead through the 3SI countries.

9. Hydrogen valleys play a special role in terms of security, innovation development and cooperation. The 3SI countries are taking regional initiatives together with other European countries, an example being the Baltic Hydrogen Valley. The project members include stakeholders representing technology and energy industries from Finland, Estonia (project leader), Poland, Denmark, Sweden, Germany, Norway, Lithuania and Latvia.

10. It may be difficult for the 3SI countries to work out a common strategy for the development of hydrogen technology and economy, nonetheless these countries should establish certain essential elements, such as: priorities for a common regional policy in the area of hydrogen technology development, strengthening mechanisms for the development of innovation in the area of energy security, measures supporting the integration of the hydrogen market.

11. Poland has particular potential to contribute to the development of the global hydrogen economy. 1.3 million tons of hydrogen are produced in the country per year. It is the third largest hydrogen producer in the European Union (after Germany and the Netherlands, which produce respectively 2.5 and 1.5 million tons per year). Globally, Poland is the fifth largest producer of hydrogen.

12. The largest volumes of hydrogen in Poland are produced by Grupa Azoty S.A. (190,000 tons per annum in Puławy, 77,000 tons in Kędzierzyn Koźle and 88,000 tons in Police).

13. The power sector can be divided into two main branches – electricity and heat generation. In Poland, hydrogen can be used in both areas, provided that there is adequate RES or nuclear power generation capacity, supporting departure from fossil fuels and reducing greenhouse gas emissions. It is worth noting that both areas provide synergistic benefits – energy production can generate both electricity and heat (cogeneration).

14. To cut carbon emissions in the steel sector, coal and coke should be replaced with low-carbon hydrogen. Strong potential for decarbonizing the steel industry using hydrogen is recognized in blast furnace technologies.

15. In 2022, Poland consumed about 31 TWh of hydrogen[I]. The forecast demand for 2030 is 46 TWh, and for 2040 – 89 TWh[II]. The anticipated growing demand for hydrogen requires stimulation of its supply in the area of domestic production and imports.

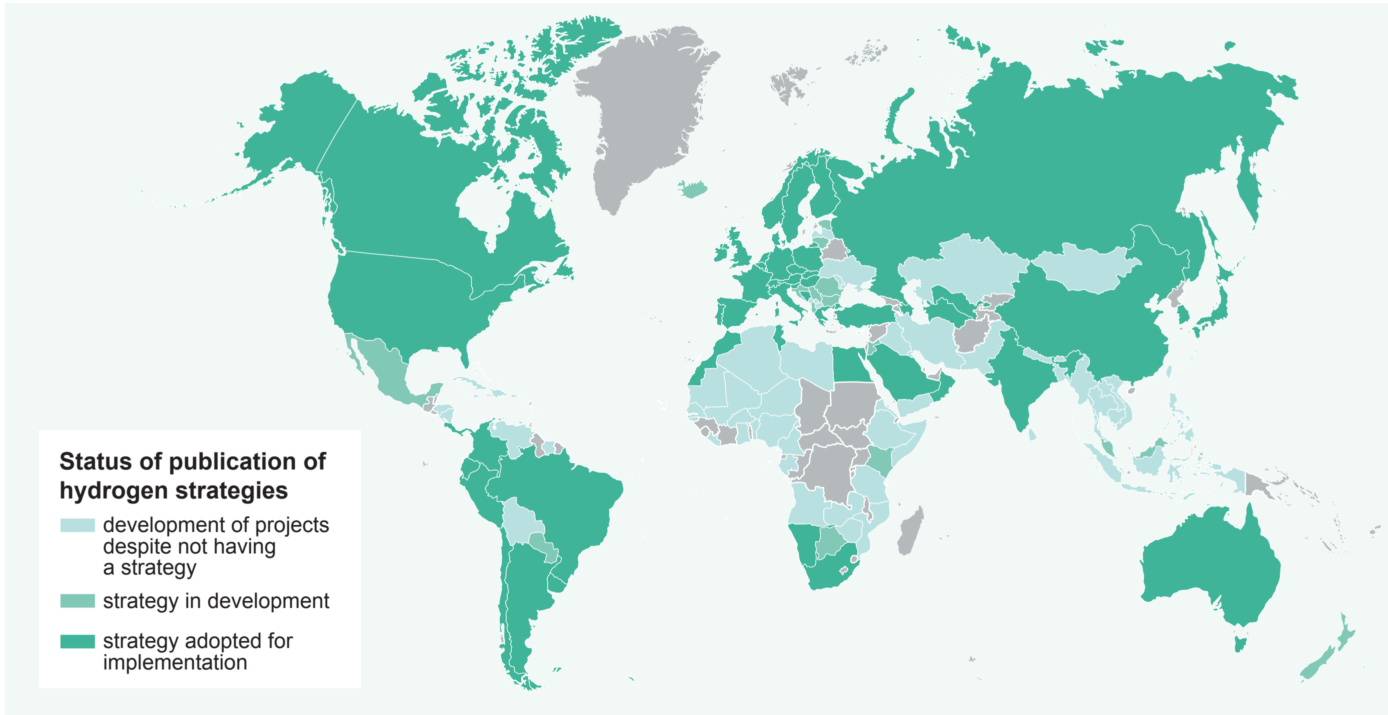
I. Calculated based on: Fuel Cells and Hydrogen Observatory, Chapter 2. 2022 Hydrogen Supply Capacity and Demand [31 July 2023],
II. The Lower Silesian Institute for Energy Studies, http://psew.pl/raport-zielony-wodor/, 2023 [accessed on 31 July 2023],

HYDROGEN IN THE WORLD

Interest in hydrogen, in particular in low- and zero-carbon hydrogen, has been getting stronger especially since the second decade of the 21st century. The leading players in the hydrogen technology market are the United States of America and Canada. In Latin America, Chile is the leader, while Brazil, Colombia and Uruguay announced their work on strategy development. Australia and New Zealand have also published their strategies. In Asia, Japan and South Korea lead the way, followed by China and Singapore.

Official discussions about hydrogen are also held in Africa – in 2021, Egypt and Morocco declared that they would work on a national hydrogen strategy. In the Middle East, Oman and Saudi Arabia committed to work on hydrogen technology[I]. It is worth noting that developed hydrogen production is not always associated with the advancement of hydrogen technologies, especially those based on low-carbon hydrogen – hydrogen production can be related to strictly industrial applications, instead of e.g. decarbonization.

Fig. 2.1 Global map of national hydrogen strategies (as at 17 July 2023)



Source: In-house analysis.

The priorities of individual countries may vary. In Europe, hydrogen is viewed as a tool that will enable reduction of carbon dioxide emissions, thus decarbonizing industry and transport. Australia intents to rely on zero-carbon hydrogen, while Canada's plans are limited to low-carbon hydrogen. France wants to produce hydrogen for export, while the Netherlands plans to become a distribution center in Europe, converting its famous port of Rotterdam into the largest hydrogen hub.

Due to limited access to natural resources, Japan and South Korea intend to use hydrogen imported from Australia to resign from energy supplies from Russia. They also see great potential in hydrogen fuel cell vehicles. As a major player in the energy market, Australia also sees hydrogen production primarily as an opportunity to expand into foreign markets. The EU and Canada have different approach to the hydrogen economy – they plan to generate demand within their own territories first, and

I. World Energy Council, Working Paper | National Hydrogen Strategies. Hydrogen on the horizon: ready, almost set, go?, 2021 [31 July 2023], when that is achieved they will move planning exports. However, it may be assumed that due to strong demand Europe will also have to import hydrogen[I].

Poland is one of the most developed hydrogen economies in Europe. However, competition is getting stronger, because when the EU announced its hydrogen strategy, almost the entire continent engaged in developing a hydrogen economy. In the coming years and decades, we may witness tremendous growth and development of hydrogen technologies[II].

Global hydrogen market

In 2020, the value of global hydrogen exports exceeded PLN 450 million (based on incomplete data on foreign trade from 37 countries). In the previous year, it was about PLN 670 million (based on trade data from 65 countries). The largest exporters are Canada, the Netherlands, Belgium, the United States, Germany, Slovakia and Poland. Key importers include the United States, the Netherlands, Germany, Canada, Mexico and Czechia. Poland is ranked 14th in that respect[III].

However, if this data is analyzed together with the links between countries and the hydrogen transport and transmission infrastructure, it turns out that this ranking is not a coincidence. According to experts responsible for the Polish Hydrogen Strategy, hydrogen is produced mainly for domestic consumption and is relatively rarely exported; "while global hydrogen production is 100-120 million tons per year, about 100-150 thousand tons"[IV], or only some 0.1% of total production, are in trading.

With this in mind, it is easier to understand why China – the largest producer of hydrogen – is not among the top exporters and importers. The United States – the largest importer – buys hydrogen from neighboring Canada – the largest exporter. It also shows that European countries, due to their location close to one another, can more easily transport hydrogen across borders.

The amounts of capital invested in the development of innovative hydrogen technologies have been growing consistently. Europe and the United States are at the forefront in that respect. Globally, in 2021 capital expenditure increased year on year by 35%, whereas Europe's outlays doubled. Looking at the broader context of decarbonization, hydrogen technologies account for 5% of total spending on "clean innovation"[V].

What do individual countries strive to achieve?

The most popular goals indicated in national hydrogen strategies are:

- Reduction of emissions,
- Decarbonization of heavy industry,
- Zero-emission transportation,
- Diversification of directions of energy supplies,
- Supporting economic growth,
- Supporting the development of domestic technologies, Integration of renewable energy sources, Development of hydrogen export capabilities[VI].

In November 2021, the Polish hydrogen strategy until 2030 with an outlook until 2040" was adopted (Polish Hydrogen Strategy). It specifies six main goals:

- Implementation of hydrogen technologies in the power and heat production sectors,
- Use of hydrogen as an alternative fuel in transport,
- Supporting the decarbonization of industry,
- Hydrogen production in new facilities,
- Efficient and safe transmission, distribution and storage of hydrogen,
- Creation of a stable regulatory environment.

Quantitative targets have also been identified, which include:

- 50 MW of installed capacity of all hydrogen production facilities by 2025 and 2 GW by 2030, 100-250 hydrogen buses by 2025, 800-1000 hydrogen buses by 2030,
- At least 32 hydrogen filling stations by 2025,
- 5 hydrogen valleys by 2030.

In the national context, an important role will be played by the so-called Constitution for Hydrogen[VII], a legislative package intended to regulate and support the creation of a hydrogen economy in Poland.

I. Ibid.
II. Institute of Power Engineering, Faculty of Management of the University of Warsaw, Institute of Ecology of Industrial Areas, "Analiza potencjału technologii wodorowych w Polsce do roku 2030 z perspektywą do 2040 roku" (Analysis of the potential of hydrogen technologies in Poland until 2030 with an outlook until 2040), 2020 [31 July 2023],
III. Institute of Power Engineering, Faculty of Management of the University of Warsaw, Institute of Ecology of Industrial Areas, "Analiza potencjału technologii wodorowych w Polsce do roku 2030 z perspektywą do 2040 roku" (Analysis of the potential of hydrogen technologies in Poland until 2030 with an outlook until 2040), 2020 [31 July 2023],
IV. Institute of Power Engineering, Faculty of Management of the University of Warsaw, Institute of Ecology of Industrial Areas, "Analiza potencjału technologii wodorowych w Polsce do roku 2030 z perspektywą do 2040 roku" (Analysis of the potential of hydrogen technologies in Poland until 2030 with an outlook until 2040), 2020 [31 July 2023],
V. International Energy Agency, Hydrogen. Energy system overview, 2022 [31 July 2023],
VI. Institute of Power Engineering, Faculty of Management of the University of Warsaw, Institute of Ecology of Industrial Areas, "Analiza potencjału technologii wodorowych w Polsce do roku 2030 z perspektywą do 2040 roku" (Analysis of the potential of hydrogen technologies in Poland until 2030 with an outlook until 2040), 2020 [31 July 2023],
VII. Ministry of Climate and Environment, another stage of work on the "Constitution for hydrogen", 2023 [31 July 2023],

According to the analysis[I], the most favorable support mechanism for the hydrogen market would be a hydrogen contract for difference. An auction mechanism for hydrogen producers and consumers has also been proposed, which will minimize the risk of imbalance in hydrogen supply and demand.

Colors of hydrogen

It is commonly accepted to use colors to indicate the type and method of hydrogen production. The following typology is most commonly used:

- **Green:** Produced through electrolysis of water using renewable energy (looking forward, for example, photolysis). Renewable hydrogen can also be produced by biogas reforming / biochemical conversion of biomass.
- **Yellow:** Produced through electrolysis of water using solar energy; often classified as one of the subtypes of green hydrogen.
- **Purple:** Produced through electrolysis of water using electricity produced at nuclear power plants.
- **Blue:** Produced in processes using fossil fuels, supplemented by carbon capture, storage or processing technologies (sometimes also called pink).
- **Grey:** Produced by reforming natural gas or other hydrocarbons obtained from crude oil refining.
- **Brown:** Produced in the process of gasification of lignite.
- **Black:** Produced in the process of gasification of hard coal.
- **Turquoise:** Produced using methane pyrolysis or processing of waste plastics.
- **White:** Produced from natural geological resources.

It is worth noting that there is a trend to move away from nomenclature based on hydrogen colors to precise determination of the emission level of a specific technology.

Classification of hydrogen production methods

- Electrolytic hydrogen: hydrogen produced using water electrolysis technology. Water electrolysis technology involves the production of hydrogen in an electrolyzer using electricity as a fuel regardless of its source. The level of emissions is determined by the way in which electricity used in the process is generated.
- Renewable/clean/zero-carbon hydrogen: hydrogen produced through electrolysis of water, except that the electricity used in the process is generated from RES. Emissions are very low, hence the product is also referred to as "zero-emission". The process can use solar power, wind power generated at onshore

I. Esperis, Analysis of financial support instruments for the development of the hydrogen market in Poland. Executive summary, 2023 [31 July 2023], or offshore facilities, and possibly nuclear power in the future.

- Hydrogen from fossil fuels (non-renewable): hydrogen produced using conventional energy sources, mainly in the process of steam reforming. This type of hydrogen is environmentally unsustainable as its production generates carbon dioxide emissions. This is the main type of hydrogen that is currently produced and used.
- Hydrogen from fossil fuels with carbon capture: hydrogen produced using conventional energy sources, such as fossil fuels, with the provision that the production process involves pyrolysis or CCS – carbon capture and storage and CCUS – carbon capture, usage/utilization and storage technologies. This type of hydrogen is seen as a transition solution towards full decarbonization of the hydrogen sector.
- Low-carbon hydrogen: hydrogen produced using conventional energy sources, but lower emissions are generated in the process. It can be produced from fossil fuels using CCS technology, RES, or by water electrolysis, irrespective of the source of electricity. The key feature is that this hydrogen ensures a significant reduction in greenhouse gas emissions compared to hydrogen production using fossil fuels. This type of hydrogen is seen as a transition solution towards full decarbonization of the hydrogen sector.
- Synthetic fuels: gaseous and liquid fuels based on hydrogen and CO_2. Synthetic fuel is produced from renewable hydrogen and carbon dioxide captured in petrochemical processes, which produce synthetic hydrocarbons. They are considered as potential alternative fuels that can reduce greenhouse gas emissions.

Ultimately, two categories of hydrogen will prevail in the widely used nomenclature, i.e. zero-carbon hydrogen and low-carbon hydrogen.

Global value chain

A global value chain is a group of interconnected elements that must cooperate with one another to provide users with access to hydrogen. The elements of the value chain can be divided into 5 areas[I]:

- Production,

Fig. 2.2 Simplified hydrogen value chain

Source: in-house analysis based on IEn, "Analiza potencjału technologii wodorowych w Polsce do roku 2030 z perspektywą do 2040 roku" (Analysis of the potential of hydrogen technologies in Poland until 2030 with an outlook until 2040), 2020.

I. Ibid.

- Transmission, distribution and transport,
- Storage,
- Transport applications,
- Stationary applications.

Production

Hydrogen can be produced from fossil fuels, biomass and water. The main current and potential production methods are:

- Steam reforming,
- Reforming as part of refining processes,
- Water electrolysis,
- Gasification of solid fuels (coal, biomass, waste and other).

As an alternative to the above methods biological production can be used, because hydrogen is also produced through natural processes, including fermentation. Scientists have developed a combination of photosynthesis and fermentation processes using algae and cyanobacteria, which in certain conditions can break down molecules of water into hydrogen and oxygen. Work is currently underway on improving the efficiency of biological methods[I].

Approximately 95 million tons of hydrogen are consumed globally each year (data for 2022), and the volume is growing at an average rate of 3% year on year. 99% is non-renewable hydrogen (produced from fossil fuels and accounting for 900 Mt of carbon dioxide emissions[II]. This amount constitutes several percent of the world's energy demand and is enough to power, for example, all of Germany[III]. The largest producer of hydrogen is China[IV], with an output of about 32 million tons of hydrogen per year[V].

Hydrogen production is expected to be carried out in two main models: central and distributed. Central production will be focused around large wind or photovoltaic farms, while distributed production will consist of local units located near smaller towns, cities and agglomerations.

In 2022, the share of low-carbon hydrogen in global hydrogen production was less than 1%[VI], with most of it produced from solar energy, wind energy (except in Chile, which produces almost all of its green hydrogen using wind energy), and a negligible amount with energy generated by offshore wind farms[VII].

Increasing the output of low- and zero-carbon hydrogen requires infrastructure components for its production, primarily electrolyzers. The rate of development of the potential for low- and zero-carbon hydrogen production started to pick up particularly rapidly in the second decade of the 21st century. Global production capacity in 2005 was less than 5 MW, and in 2010 it was already more than 40 MW, in 2015 almost 100 MW, and in 2020 – 304 MW[VIII]. In 2022, the value exceeded 1,000 MW (1 GW), and it is forecast that by the end of 2023 the capacity will reach 5,517 MW (over 5.5 GW)[IX].

Distribution

The method of hydrogen delivery depends primarily on the distance and the amount of hydrogen that is transported, for example:

- Cylinders and small tanks,
- Road transport (on shorter and longer distances),
- Pipelines (when demand is very high),
- Maritime transport.

The use of pipelines implies two main scenarios: construction of hydrogen pipelines or using already existing gas pipelines by blending hydrogen with natural gas. In Germany, up to 10% of hydrogen content in gases is allowed (this does not apply to natural gas, in which case EU regulations recommend blending hydrogen into natural gas of up to 2% by volume[X]), while the characteristics of hydrogen create higher requirements in terms of tightness and pressure[XI]. If this idea worked on a larger scale, there would be no need to build an extensive network of pipelines for the transmission of hydrogen. Europe's largest network is operated by Air Liquide. Its pipelines are approximately 1,000 km long, stretching from northern France to Rotterdam and connecting several production facilities and customers in northern France, Belgium and southwestern Netherlands[XII].

Maritime transport currently plays a marginal role, but its importance may increase due to plans to develop the international hydrogen market. It is believed that the first sea vessel transported hydrogen in 2021, from Australia to Japan. The vessel built to support

I. Wodorowy świat, "Biologiczne metody pozyskiwania wodoru" (Biological methods of hydrogen production), 2021 [31 July 2023],
II. International Energy Agency, Hydrogen. Energy system overview, 2023 [11 October 2023],
III. International Renewable Energy Agency, Hydrogen, 2022 [31 July 2023],
IV. Center for Strategic and International Studies, China's Hydrogen Industrial Strategy, 2022 [31 July 2023],
V. International Energy Agency, Hydrogen. Energy system overview, 2023 [11 October 2023].
VI. International Energy Agency, Hydrogen. Energy system overview, 2022 [31 July 2023],
VII. International Energy Agency, How much will renewable hydrogen production drive demand for new renewable energy capacity by 2027? 2022 [31 July 2023],
VIII. International Energy Agency, The Future of Hydrogen. Seizing today's opportunities, 2019 [31 July 2023],
IX. International Energy Agency, Electrolysers. Technology deep dive, 2022 [31 July 2023],
X. EU Council, Member States set their position on future gas and hydrogen market, 2023 [31 July 2023],
XI. Wysokienapięcie.pl, "Polska energetyka gaz zastąpi wodorem? To nie takie proste" (Will Poland's energy market replace gas with hydrogen? It's not that easy), 2023 [31 July 2023],
XII. Institute of Power Engineering, Faculty of Management of the University of Warsaw, Institute of Ecology of Industrial Areas, "Analiza potencjału technologii wodorowych w Polsce do roku 2030 z perspektywą do 2040 roku" (Analysis of the potential of hydrogen technologies in Poland until 2030 with an outlook until 2040), 2020 [31 July 2023],

the cooperation between the two countries carries hydrogen in a liquid state[I].

Storage

Storage methods are related to distribution methods. Steel cylinders and small tanks are mainly used for research applications and where production volumes are smaller. Larger tanks, such as those at filling stations or in heavy trucks, are made using a different technology.

Hydrogen storage poses significant challenges. In its gaseous state, hydrogen must be kept under relatively high pressure, even up to 970 bar. Maintaining hydrogen in a liquid state requires expending a significant energy to keep it at a temperature of about -250°C. Changing the state of hydrogen significantly affects its volume. For example, 4 kg of liquid hydrogen occupies a volume of 57 liters, while under a pressure of 200 bars the same amount of hydrogen has a volume of 110 liters[II].

Underground storage facilities (including salt caverns) are optimal for storing large quantities of hydrogen. A salt cavern is an empty space in a salt deposit that, if it meets the right requirements, is subject to leaching and fracturing, after which gas is injected.

The size of the caverns can be impressive, for example, the storage facility operated by Aces Delta in Utah, USA, is 800 meters deep and wide. Such a large tank could hold a supply of hydrogen capable of powering 150,000 homes for an entire year. In Poland, two salt caverns are actively used: Mogilno and Kosakowo. They currently store 880 million m^3 of natural gas. When combined, the capacity of these storage facilities is sufficient to cover about 5% of Poland's annual natural gas consumption[III],[IV].

Applications of hydrogen

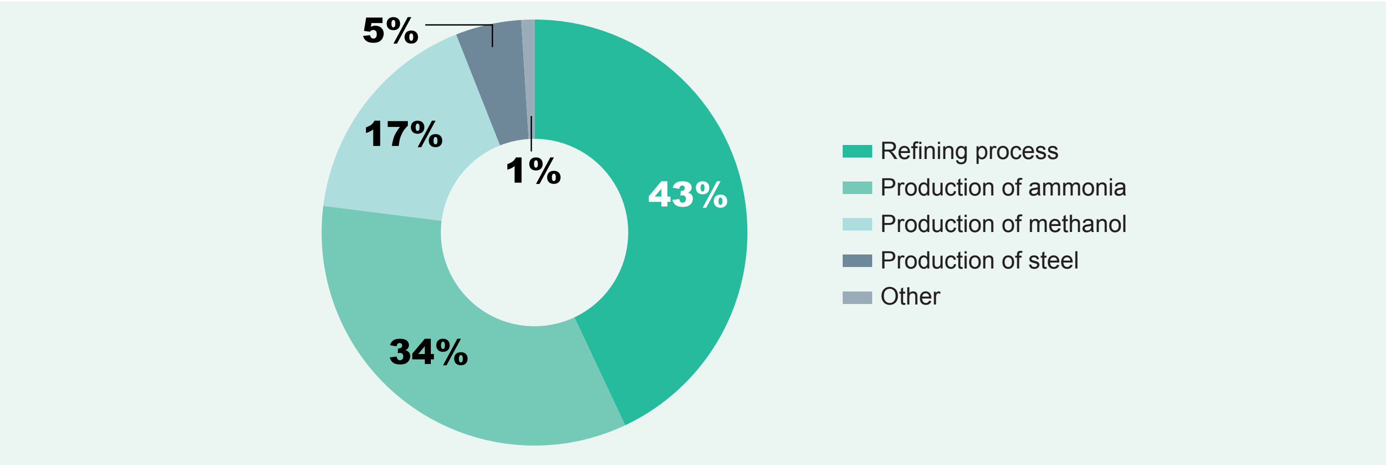
Hydrogen is often referred to as an energy carrier that will help reduce the adverse impact of human activity on the environment. Currently, hydrogen is used primarily as a raw material in the engineering industry. The demand for hydrogen is generated mostly by industrial applications. Its two main areas of application in 2022 are as follows[V]:

- Chemical sector (51%):
  - Production of fertilizers,
  - Production of nitric acid,
  - Hydrogenation processes other than ammonia production and refining processes,
- Refining sector (43%):
  - Production of diesel oil and jet fuel,
  - Hydrotreatment – treatment of products and semi-finished products from petroleum refining.

Other applications:

- Metallurgy:
  - steel production (hydrogen as an agent for converting iron ore to steel),
  - reducing phosphorus and sulfur content of steel (which changes its properties),
- Transport,
- Electricity production (including co-firing of hydrogen in gas turbines),
- Production of building materials (mainly in cement plants),
- District heating,

Fig. 2.3 Areas of hydrogen application worldwide in 2022



Source: In-house analysis based on International Energy Agency, Hydrogen. Energy system overview, 2023 [11 October 2023].

I. Reuters, World's first hydrogen tanker to ship test cargo to Japan from Australia, 2022 [11 October 2023],
II. Zuttel A., Hydrogen-storage materials for mobile applications, "Nature" (414)6861,2001, pp 353-358 [31 July 2023],
III. Polish Economic Institute, https://pie.net.pl/wp-content/uploads/2020/06/PIE-WP7.pdf, 2019 [accessed on 31 July 2023],
IV. PGNiG, https://pgnig.pl/podziemne-magazyny-gazu, 2023 [accessed on 31 July 2023],
V. International Energy Agency, Hydrogen. Energy system overview, 2023 [11 October 2023],

- Synthetic fuel production,
- Food industry.

It is expected that hydrogen use will increase in transport (railway, buses, passenger cars and trucks, maritime transport), steel industry (replacement of process streams based on fossil fuels with hydrogen in the production process), non-ferrous metals industry (mainly the production of copper and silver), energy storage (hydrogen as an energy carrier) and heating.

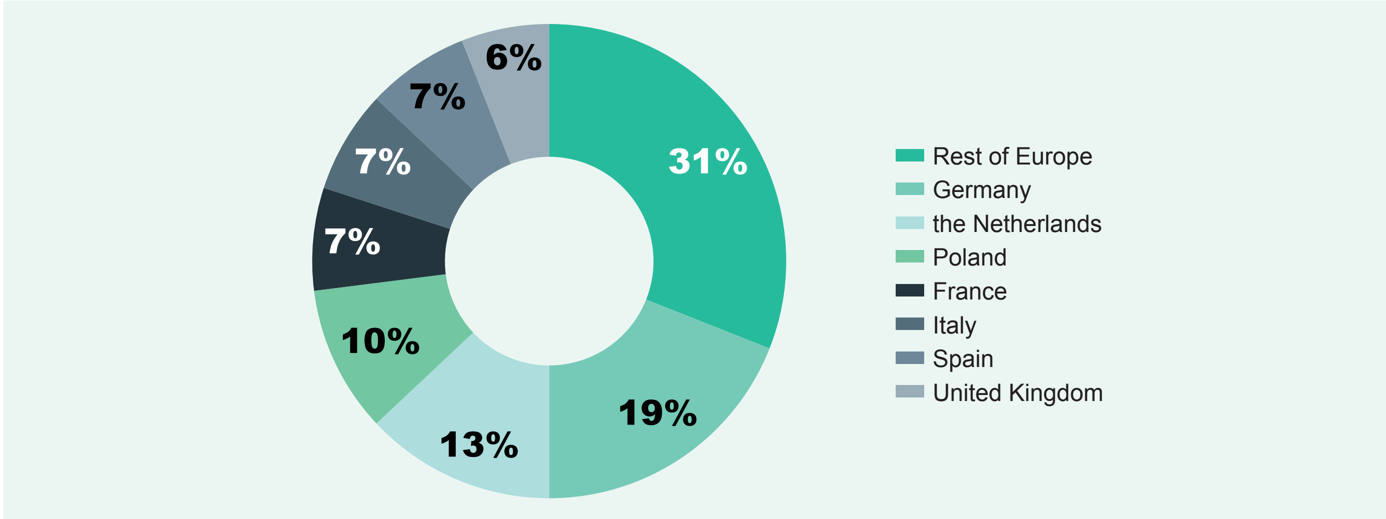
European countries

Analyzing the European context, it is clear that Poland is one of the most important players in the hydrogen market. Data shows that the top 5 hydrogen producers in Europe are:

- Germany,
- the Netherlands,
- Poland,
- Italy,
- France.

In 2022, European countries produced about 11.4 million tons of hydrogen, or nearly 31 tons of hydrogen per day[I].

Fig. 2.4 Share of hydrogen production in Europe (% of 11.4 million tons of hydrogen in 2020)



Source: In-house analysis based on Fuel Cells and Hydrogen Observatory, Chapter 2. 2022 Hydrogen Supply Capacity and Demand [31 July 2023].

The hydrogen strategy for a climate neutral Europe focuses on two primary sectors: industry and transport, and on the assumption that hydrogen production will be based on electrolysis. This is a vision of the future – in 2022, low-carbon (CCS/CCU) and zero-carbon methods of hydrogen production (electrolysis using RES) accounted for about 1% of total generation capacity. However, this capacity has been expanded consistently. The growth rate of electrolysis capacity in 2018-2021 in Europe was over 30-50% per year[II].

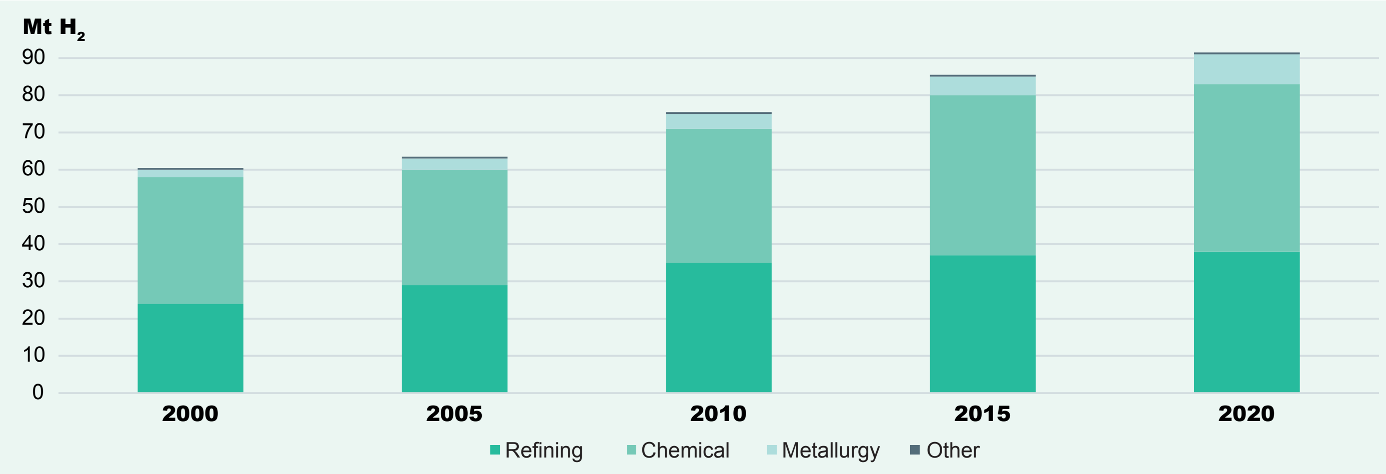
Development in European countries is happening relatively fast. According to FleishmanHillard experts, France has the most developed legal system in the area of hydrogen in Europe, and the Netherlands has the largest number of large-scale hydrogen projects. In its ranking, the company indicated as many as 15 countries, including Poland, as the "frontrunners". 10 countries (e.g. Italy, Ireland) were rated as "developers", while Cyprus, Latvia, Malta and Slovenia were described as "laggards"[III].

The hydrogen market is attracting large investments in production, sales, research, development and education. In 2022, the value of the global hydrogen market was estimated by PIE at approximately PLN 600 billion[IV]. Its value could triple by 2050 as a result of decarbonization of the global economy[V].

Demand for hydrogen is on the rise. In 2000, it was about 60 million tons of hydrogen, in 2020 –

I. Fuel Cells and Hydrogen Observatory, Chapter 2. 2022 Hydrogen Supply Capacity and Demand [31 July 2023],
II. Institute of Power Engineering, Faculty of Management of the University of Warsaw, "Łańcuch wartości gospodarki wodorowej w Polsce" (The value chain of hydrogen economy in Poland), 2023 [31 July 2023],
III. FleishmanHillard, National Hydrogen Strategies In The EU Member States. A FleishmanHillard overview of national hydrogen strategies, 2022 [31 July 2023],
IV. Centrum Informacji o Rynku Energii, PIE: In 2022, the value of the global hydrogen market will reach PLN 600 billion, 2020 [31 July 2023],
V. Centrum Informacji o Rynku Energii, The value of the hydrogen production market will triple by 2050, 2021 [31 July 2023],

Fig. 2.5 Hydrogen demand by sector



Source: In-house analysis based on International Energy Agency, Hydrogen. Energy system overview, 2023 [11 October 2023].

approximately 90 million tons[I], and it is forecast that in 2030 demand will be some 150 million tons[II].

Domestic hydrogen market

Poland has particular potential to contribute to the development of the hydrogen economy. 1.3 million tons of hydrogen are produced in the country per year. It is the third largest production volume in the European Union (after the Netherlands and Germany, which produce respectively 1.5 and 2.5 million tons). Globally, Poland is the fifth largest producer of hydrogen[III].

The largest annual production is recorded by Grupa Azoty S.A. (190,000 tons in Puławy, 77,000 tons in Kędzierzyn Koźle and 88,000 tons in Police). If we look at the petrochemical industry, the most hydrogen is produced annually by Orlen S.A. – about 140,000 tons – and Grupa Lotos (currently owned by Orlen) – some 59,000 tons. The combined hydrogen output of two largest coking

Fig. 2.6 The largest producers and consumers of hydrogen in Poland

Source: In-house analysis based on EY, Hynfra, "Zielony wodór – rewolucja czy przejściowa moda? Szanse i wyzwania dla polskiej gospodarki" (Green hydrogen – revolution or temporary rush? Opportunities and challenges for the Polish economy), 2023 [31 July 2023].

I. Deloitte, Hydrogen. Making it happen, 2023 [31 July 2023],
II. International Energy Agency, Hydrogen. Energy system overview, 2022; McKinsey & Company, Global Hydrogen Flows: Hydrogen trade as a key enabler for efficient decarbonization, 2022 [31 July 2023],
III. BOŚ Bank, Hydrogen in the domestic and foreign markets, 2021 [31 July 2023],

plants in Poland – Zdzieszowice and Przyjaźń – was 149,000 tons (2015 data)[I]. The vast majority of hydrogen produced in Poland comes from fossil fuels and is used for industrial processes – in refining processes in the production of fertilizers and methanol.

Stakeholders of the Polish hydrogen economy

The major entities and institutions involved in the creation of the Polish hydrogen market can be divided into several main categories:

- Industry – companies, including companies owned by the State Treasury,
- Research and academic organizations,
- Governmental agencies,
- Supporting organizations,
- Industrial actors,
- Networks and associations,
- Hydrogen valleys.

Networks

Entities operating in the hydrogen economy are creating their own structures to facilitate cooperation, attracting investors, winning contracts, or influencing the state policy.

European networks in which Polish entities participate include:

- Hydrogen Europe,
- Hydrogen Europe Research,
- European Energy Research Alliance, Fuel Cells and Hydrogen,
- International Energy Agency, Annex 32 Advanced Fuel Cells,
- European Clean Hydrogen Alliance.

The nationwide networks primarily include:

- Izba Gospodarcza Gazownictwa (Chamber of the Natural Gas Industry),
- Polskie Stowarzyszenie Energetyki Wiatrowej (Polish Wind Energy Association),
- Polska Izba Paliw Płynnych (Polish Chamber of Liquid Fuels),
- Polska Izba Magazynowania Energii (Polish Chamber of Energy Storage),
- Polskie Stowarzyszenie Paliw Alternatywnych (Polish Alternative Fuels Association),
- Krajowa Izba Gospodarcza (Polish Chamber of Commerce),
- Polska Izba Przemysłu Chemicznego (Polish Chamber of Chemical Industry).

The local networks include:

- Gdański klaster wodorowy (Gdańsk hydrogen cluster),
- Wieluński klaster energii (Wieluń cluster of energy),
- Stowarzyszenie Polski Wodór (Polish Hydrogen Association),
- Hydrogen valleys.

Hydrogen valleys

Hydrogen valleys are regions that were selected as areas where local markets of the hydrogen economy would be created. They concentrate in one place the efforts of the local government, government representatives, local entrepreneurs and the local community. The purpose of a hydrogen valley is to maintain the entire "life cycle" of hydrogen in a given region, i.e. hydrogen should be locally produced and locally consumed.

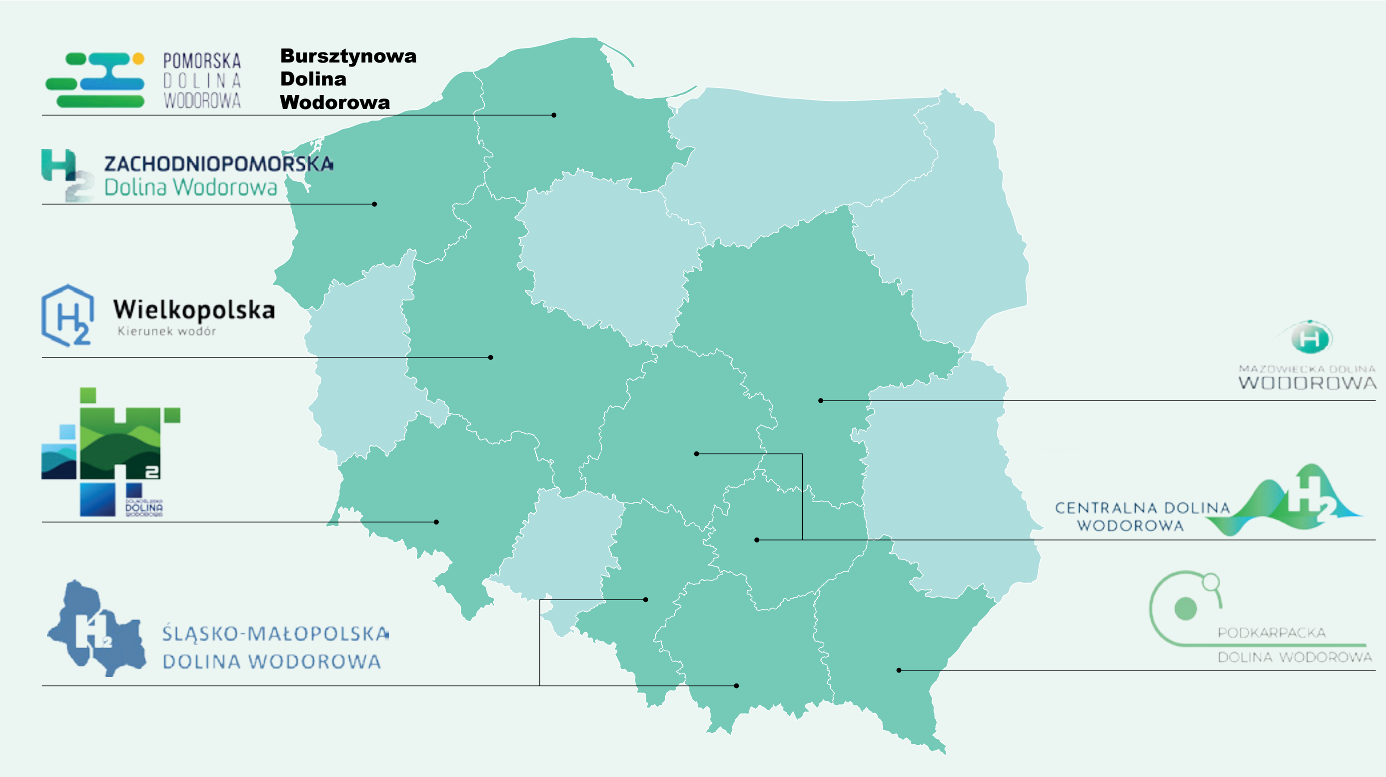
Hydrogen valleys are intended to demonstrate Polish hydrogen technologies developed through the cooperation of regional entities and stakeholders, including research units and businesses. Hydrogen valleys will play an important role in mobilizing private funds for green investments implemented as part of the European Green Deal[II].

At present (as at September 2023), 9 hydrogen valleys are being developed across Poland:

- Lower Silesian Hydrogen Valley,
- Mazovian Hydrogen Valley,
- Central Hydrogen Valley,
- Silesian-Lesser Poland Hydrogen Valley,

I. Polish Economic Institute, "Kierunki rozwoju gospodarki wodorowej w Polsce" (Directions of development of hydrogen economy in Poland). Working Paper 7/2019, [31 July 2023],
II. Industrial Development Agency, https://arp.pl/pl/jak-dzialamy/doliny-wodorowe/, 2023 [accessed on 31 July 2023],

Fig. 2.7 Map of hydrogen valleys in Poland (18 July 2023)



Source: In-house analysis.

- Subcarpathian Hydrogen Valley,
- Pomeranian Hydrogen Valley,
- Amber Hydrogen Valley,
- Greater Poland Hydrogen Valley,
- West Pomeranian Hydrogen Valley.

In addition, it is worth mentioning an international hydrogen valley – the Baltic Sea Hydrogen Valley. The Lower Silesian Hydrogen Valley joined the consortium that associates 37 entities from the Baltic Sea basin[I]. The Amber Hydrogen Valley is the only certified hydrogen valley in Poland that has been established to implement a full hydrogen ecosystem in the Pomeranian Province[II].

Government agencies

Public institutions in are involved in the development of the hydrogen economy at several levels. The most apparent outcome of this work is the already published Polish Hydrogen Strategy. Its development was overseen by the Interministerial Committee on Hydrogen Economy, which included representatives from the Ministry of State Assets, the Ministry of Climate and Environment, the Ministry of Development, the Ministry of Infrastructure and the Ministry of Education and Science[III]. On the initiative of the Ministry of Climate and Environment, on 14 October 2021 the Sector Understanding on the Development of Hydrogen Economy came into effect, whose signatories were the stakeholders of the development of the Polish hydrogen economy. The understanding is a continuation of the work started by the Ministry of Climate and Environment in 2020 with the signing of a letter of intent to establish a partnership for the establishment of a hydrogen economy and the execution of a hydrogen sector understanding[IV].

Research organizations

The effort related to development of hydrogen technologies is undertaken by institutes from across Poland which primarily operate in chemical and energy sectors. The Institute of Power Engineering (IEn) is considered to be the main institution involved in Polish research and development activities related to hydrogen. The structure of the institute includes the Center for Hydrogen Technologies (CTH2), which was the first center of this type in Poland (established in 2020). CTH2 employees are responsible, *inter alia*, for research and development work related to high-temperature electrolyzers, the supply of electrolysis units and their integration with industrial facilities and nuclear power plants, burners for combustion and co-combustion of hydrogen, and auxiliary technologies. There are similar units in the structures of Polish universities. The Warsaw University of Technology operates the Center for Hydrogen and Fuel Cells, the Wrocław University of Science and Technology

I. Ibid.
II. Money.pl, https://www.money.pl/gospodarka/wodor-w-grupie-orlen-6908937632307840a.html, 2023 [accessed on 31 July 2023],
III. Polish Economic Institute, https://pie.net.pl/wp-content/uploads/2021/01/PIE-PP_Wodor.pdf, 2020 [accessed on 31 July 2023],
IV. MKiŚ, https://www.gov.pl/web/klimat/podpisano-porozumienie-sektorowe-na-rzecz-rozwoju-gospodarki-wodorowej-w-polsce, 2023 [accessed on 31 July 2023],

– the Center for Hydrogen and Renewable Energy Technologies (CTW_OZE), and the Gdańsk University of Technology – the Center for Hydrogen Technologies.

On behalf of the Polish Academy of Sciences work is conducted, among others, by the Institute of Molecular Physics of the Polish Academy of Sciences, the Institute of Chemical Engineering of the Polish Academy of Sciences and the Institute of Physical Chemistry of the Polish Academy of Sciences. In the Łukasiewicz Research Network, hydrogen technologies are developed by, among others, Łukasiewicz – Institute of Industrial Chemistry (e.g. production of hydrogen from waste, fuel cells), Łukasiewicz – Institute of Electrical Engineering (e.g. fuel cells), Łukasiewicz – Institute of New Chemical Syntheses (production of low- and zero-carbon hydrogen at production plants of Grupa Azoty), and Łukasiewicz – Poznań Institute of Technology (application of hydrogen in rail vehicles). Other active institutions include the Central Mining Institute – National Research Institute, the Oil and Gas Institute, the Institute of Energy and Fuel Processing Technology and the Institute of High Pressure Physics[I].

Example hydrogen projects in Poland

HYDROGIN project – the second life of the Elbląg CHP plant[II]

The project is intended to give a new role to centrally dispatched generating units through storage of excess energy in hydrogen. Centrally dispatched generating units are the core facilities of Poland's power industry, but their output is regularly limited and their operation is frequently stopped (from dozens to more than a hundred times per year). Frequent halts accelerate the wear of power plant components and increase emission rates.

The boilers of power units fired by coal, biomass (as in the case of the BB20p unit at the Elbląg CHP Plant) or other fuels are designed to produce a large amount of steam that drives a turbine that generates electricity. When the unit's load is reduced, the amount of steam is lower and the unit produces less power. The limit value for reducing the power of the unit is the so-called technical minimum, below which the operation of the unit is halted.

An alternative is to divert excess steam and/or use electricity to power a high-temperature electrolyzer. This will enable significant improvement of the flexibility of the power unit, which, instead of being stopped, can continue to operate under optimum conditions with the generated steam and/or electricity feeding the electrolyzer. When biomass is used, as was the case in the HYDROGIN project, the hydrogen produced in the fixed-oxide electrolyzer has no carbon footprint. An additional feature of this unique, world's first installation combining an electrolyzer with a CHP plant, was the ability to switch the electrolyzer (10kW) to fuel cell (SOFC) mode. This makes it possible to increase the output of the hybrid system (CHP plant + fuel cell) at times of increased demand for electricity. The fuel for the SOFCs in the case of this plant was hydrogen that had been previously produced and stored on site.

Hydrogen-powered locomotive by PESA[III]

Electric locomotives are operated on electrified lines and diesel locomotives are used where railway lines are not electrified. No power supply on sections of the railway networks requires the use of domestic rolling stock with internal combustion engines, which generates carbon dioxide emissions.

An alternative could be an electric drive based on an on-board power generator with hydrogen fuel cells. To meet that challenge, a new type of locomotive (SM42-6Dn) was design and first presented in 2021. The PESA shunting locomotive has a fuel cell stack with the power of 170 kW and tanks that can hold up to 175 kg of hydrogen. The locomotive is powered by a set of four traction motors with a total power of 720 kW coupled to a traction battery. At the end of 2022 – as the first vehicle of this type in the world – it successfully passed approval tests. The locomotive will first be operated at Petrochemia ORLEN in Płock.

It is assumed that the experience gained in the development of the SM42-6Dn locomotive can be used in the next 5 years to develop hydrogen-powered hybrid vehicles for passenger transport. The placement of the SM42-6Dn locomotive into service at a petrochemical plant will also enable the creation of a local hydrogen ecosystem that will include elements for fuel generation, storage and use for decarbonized transport within a single industrial facility.

Hydrogen Eagle project – low-carbon transport network

In 2021, ORLEN S.A. launched the Hydrogen Eagle project. This is an infrastructure project composed of several stages, which consists in the construction of an international network of hydrogen hubs[IV] powered by renewable energy sources and facilities for converting municipal waste into low-carbon hydrogen. The project also includes the construction of more than 100 hydrogen refueling stations for individual, public and cargo transport. The entire project is connected with the plans involving the construction of hydrogen refueling stations in Poland, Czechia, Slovakia and Germany. Hydrogen is to be obtained by converting wind energy and municipal waste.

I. Polish Economic Institute, https://pie.net.pl/wp-content/uploads/2021/01/PIE-PP_Wodor.pdf, 2020 [accessed on 31 July 2023],
II. The project is co-financed by the National Center for Research and Development. Carried out by the Faraday Research and Development Center, Energa S.A., the Orlen Group in consortium with the Szewalski Institute of Fluid-Flow Machinery of the Polish Academy of Sciences and in cooperation with the Institute of Power Engineering - National Research Institute, whose team was the author of the concept, designed and built the installation and supplied own-produced stacks of solid oxide electrochemical cells.
III. A joint project between PKP, ORLEN and PESA. The solution is the result of a cooperation between many entities, including ABB, Ballard (fuel cell stack supplier), Worthington, Luccini, Rawag, TSA and CADD.
IV. A large redistribution center.

HYDROGEN IN THE THREE SEAS REGION (3 SEAS INITIATIVE – "3SI")

For the 3SI countries, hydrogen technologies are one of the elements of energy security policy, as well as an opportunity to implement climate policy, decarbonization of energy supply or improving its security. Hydrogen is gaining importance especially now, amid the changing geopolitical conditions in the region. The energy security policy of the 3SI countries is gaining importance in the face of Russian aggression against Ukraine. The growing significance of hydrogen as an energy carrier is also observed in the context of accelerating the development of RES and improving energy efficiency.

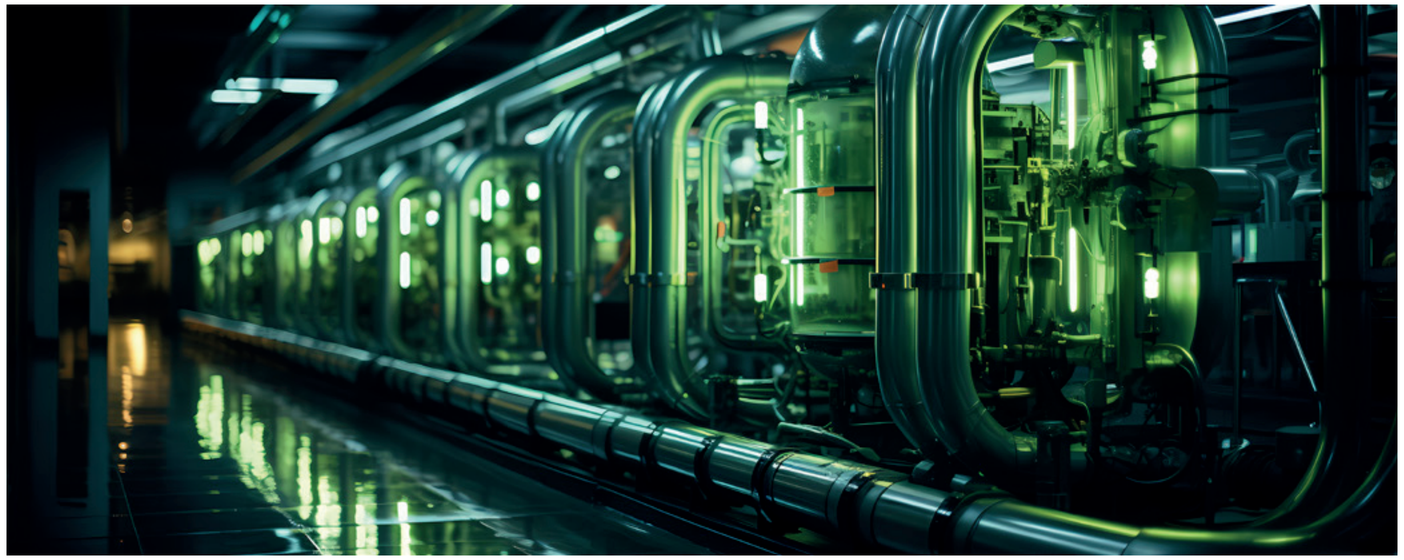
During the sixth 3SI summit in Sofia held in 2021, it was pointed out that hydrogen was considered in a broad perspective of energy security with particular focus on three strategies for its development:

- Ensuring the continuity of energy supply,
- Diversification of energy sources,
- Achieving the goals related to transition to climate neutrality[I].

In the declaration of the 3SI countries it was indicated that member countries would support development of hydrogen technologies that would allow its production from renewable sources. These projects are seen as supporting and implementing the EU's climate and energy security policies.

Hydrogen in projects pursued by the 3SI

National hydrogen technology development projects and international efforts to modernize the infrastructure for the transit of energy are paramount priorities. The importance of the 3SI countries in ensuring Europe's energy security was highlighted in March 2023 in the Partnership for Transatlantic Energy and Climate Cooperation (P-TECC)[II]. Member countries seek to make the entire region independent of Russian supplies within two decades by strengthening the capacity of geothermal and hydrogen technologies. In the case of hydrogen, strong financial support is envisaged for the integration of transmission infrastructure.



I. Joint Declaration of the Sixth Summit of the Three Seas Initiative (Sofia, 8-9 July 2021) [31 July 2023],
II. U.S. Department of Energy, The Partnership for Transatlantic Energy and Climate Cooperation (P-TECC) Statement of Principles - 2023 [31 July 2023],

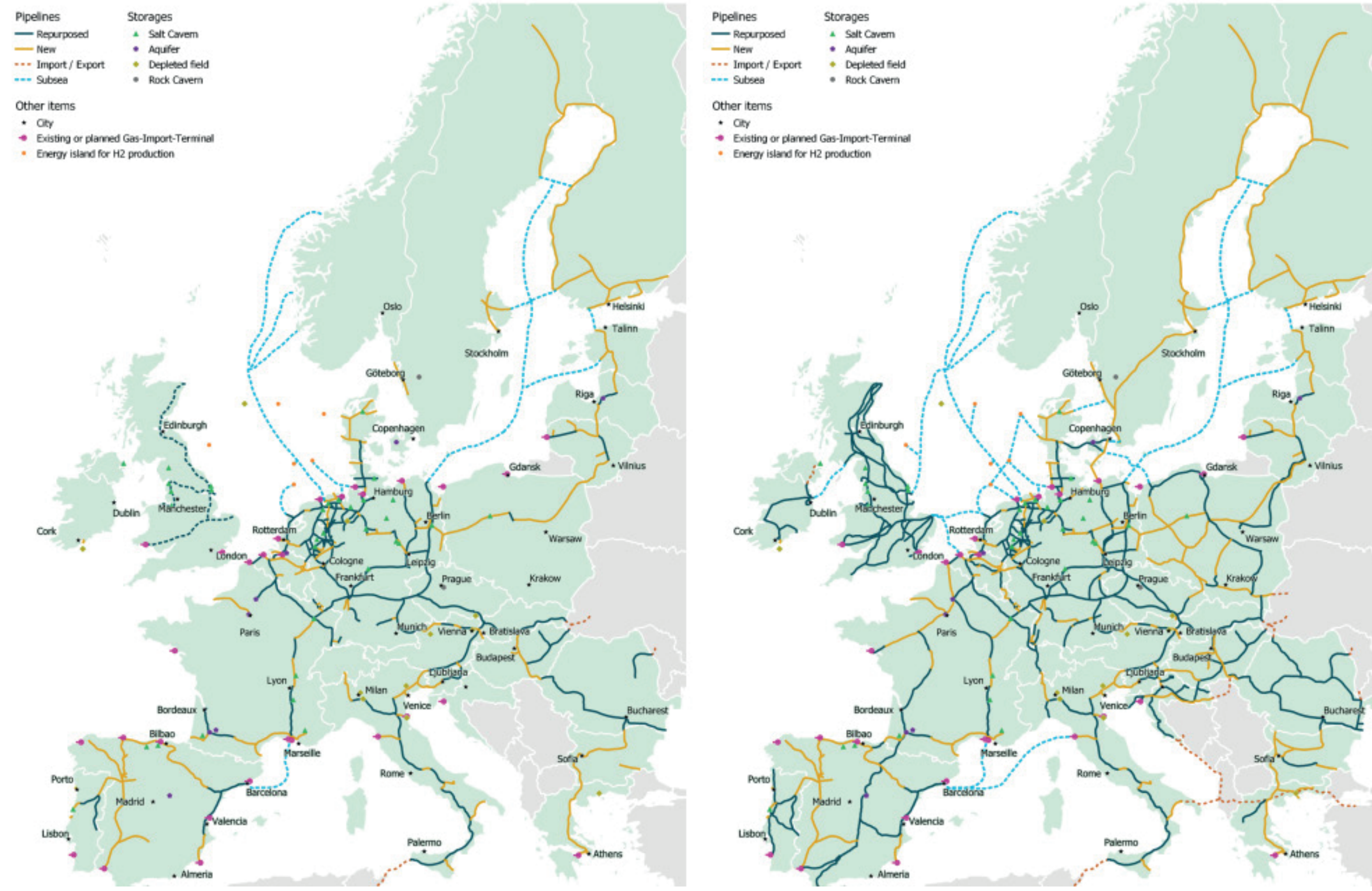
An example of the implementation of the hydrogen policies of the 3SI countries are the first projects launched internationally or in cooperation with external actors, e.g.: *Projects Launching a Hungarian-American pilot project in Hungary*. The project involves exploring the use of hydrogen in Hungary in cooperation with the new US hydrogen technology sector. Project goals: the opening of a hydrogen research center and the establishment of a hydrogen production company in Hungary – the two will implement the climate and diversification policies in the country. According to Hungary's energy strategy, 6,000 MW of capacity is to be provided by solar power plants by 2030. Hydrogen will act as energy reservoir and balance the energy system. The assumptions of this project are part of the efforts to: ensure the security, diversification and development of hydrogen as a carrier and source of energy. Hungary's dependence on Russian hydrocarbon supplies is a major threat both on a national and regional level. The actions of the 3SI countries indicate solidarity in providing assistance in this area[I].

Another example of the development of hydrogen technology in the 3SI region is the conclusion of an agreement between Transgaz of Romania and the 3SI Investment Fund for the development of gas transmission infrastructure with the integration of hydrogen transportation. The project value is estimated at PLN 2.7 billion[II].

The importance of 3SI countries for the development of hydrogen technologies

The importance of the 3SI countries for the development of hydrogen technologies has been growing consistently, which results from geopolitical changes and energy security requirements, as well as technological developments in the production and use of hydrogen in the power sector. The European Hydrogen Backbone Initiative has updated its map of future expansion of the hydrogen transmission pipeline network. Changes in hydrogen pipelines are driven by national and regional policies on the development of hydrogen technologies. Taking them into account in the period from mid-2022 to 2023 allowed the authors of the European Hydrogen Backbone Initiative to update their vision for hydrogen development across Europe. The main changes in the intensity of development of hydrogen technologies are emerging in the 3SI area: in Poland, Czechia, Romania and Bulgaria.

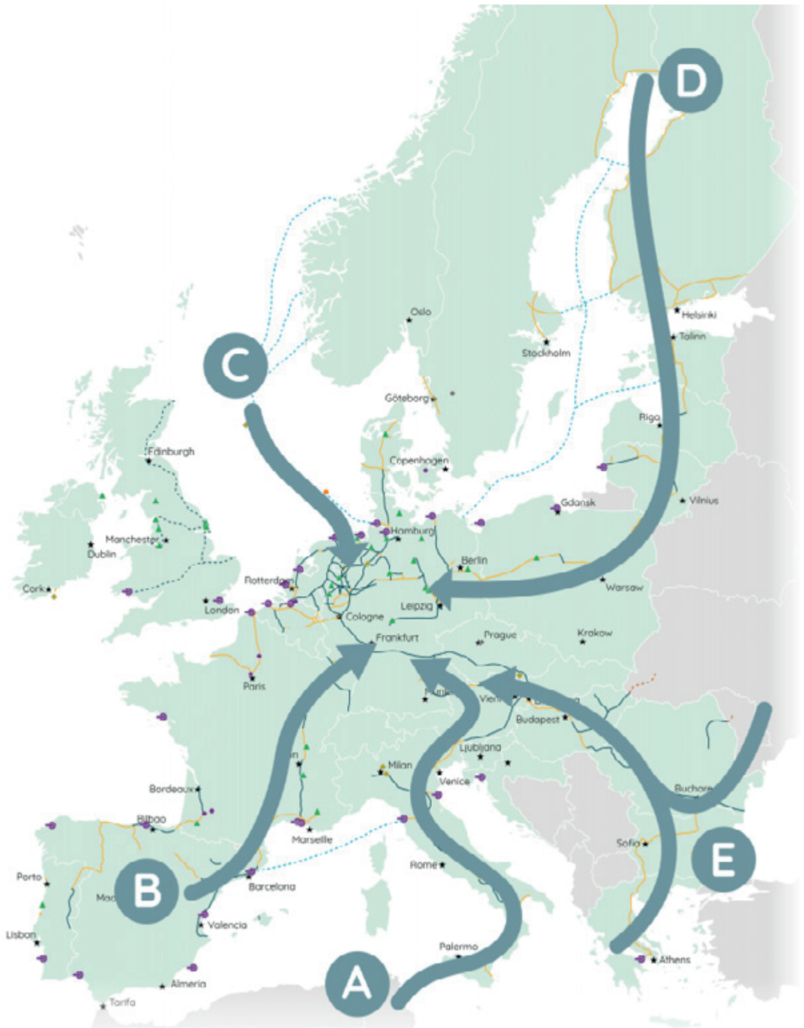
Fig. 2.8 Update of the EHB infrastructure map in line with EHB development vision



Source: European Hydrogen Backbone, EHB Infrastructure Maps Update February - including latest feasibility estimates and PCI submissions, 2023 [31 July 2023].

I. 3seas, Launching a Hungarian-American pilot project in Hungary [31 July 2023],
II. Transgaz, Three Seas Initiative Investment Fund signs agreement to invest in greenfield gas infrastructure in Romania [31 July 2023],

Fig. 2.9 EHB transmission corridors



Source: European Hydrogen Backbone, EHB publishes five potential hydrogen supply corridors to meet Europe's accelerated 2030 hydrogen goals, 2022, [31 July 2023],

Under the RePowerEU program, two important hydrogen transmission corridors will lead through the 3SI countries: from the Nordic and Baltic regions and from Eastern and South-East Europe to Germany. All transmission corridors lead in one direction – to Germany, but only after the demand of regional economies is adequately saturated around 2030[I].

A particularly important part of the project from the Polish perspective is the Nordic-Baltic corridor, through which hydrogen from onshore and offshore wind farms will be transported. In this area, hydrogen will play a special role in decarbonization processes, the development of steel production, e-fuels and the chemical industry. In the case of the southern 3SI countries, hydrogen will be produced using solar energy and will be an energy carrier for both industrial and retail customers. The 3SI region will also receive hydrogen from North Africa, whose accessibility will pose a challenge to the countries of the region in terms of competitiveness of its local counterpart[II]. It may turn out that the 3SI project intended to link economies in the north-south axis will be so energy-intensive that hydrogen generated in the region will be used to develop regional economies instead of supporting the German economy. Decarbonization and diversification processes may force increased involvement of hydrogen as a carrier to stabilize energy balances of individual countries.

3 Seas Hydrogen Council

To secure the interests of the 3SI countries in the area hydrogen energy, the 3SI Hydrogen Council was established[III]. A relevant agreement was signed in Poznań in 2023 by representatives of hydrogen

I. European Hydrogen Backbone, Five hydrogen supply corridors for Europe in 2030. Executive Summary, 2022, [31 July 2023],
II. CIRE, "Inicjatywa 2 x 40 GW szansą dla dekarbonizacji Europy" (The 2 x 40 GW initiative as an opportunity for decarbonization of Europe) [31 July 2023],
III. Cluster of Hydrogen Technologies, 3 Seas Hydrogen Council. A hydrogen council is established, consisting of Central European and Baltic States, 2023 [31 July 2023],

organizations from Poland, Czechia, Estonia, Lithuania, Latvia, Slovakia, Slovenia, Hungary and Ukraine. The task of the 3SI HC is to complement the business, technological and political competencies of its members, in particular: international business cooperation of signatory countries, conducting dialogue and developing a common position towards the European Commission, the Council and the European Parliament.

The 3SI HC highlights the main deficits, dependencies and converging goals of the 3SI countries in the area of hydrogen economy. They are driven by conditions such as:

- Common past and experience of 3SI countries, comparable energy structure, similar climate conditions,
- Seasonal increase in demand for electricity and heat,
- Regional and global importance of manufacturing in 3SI countries.

The 3SI countries have a high potential for change, which the 3SI Hydrogen Council is expected to realize through:

- Activities to reduce the share of fossil fuels in the national energy balance, Promotion of labor market restructuring policies, Promotion of national and regional solutions, companies and technologies focused on hydrogen,
- Fostering legal changes in the EU with special consideration and respect for the specifics
- of the region of the 3SI countries,
- Supporting initiatives financing the creation of a joint hydrogen ecosystem,
- Acting as a platform for the exchange of expertise, experience and good practices,
- Developing an efficient cross-border hydrogen economy in the region, ensuring a sustainable regional energy system,
- Developing innovative energy technologies.

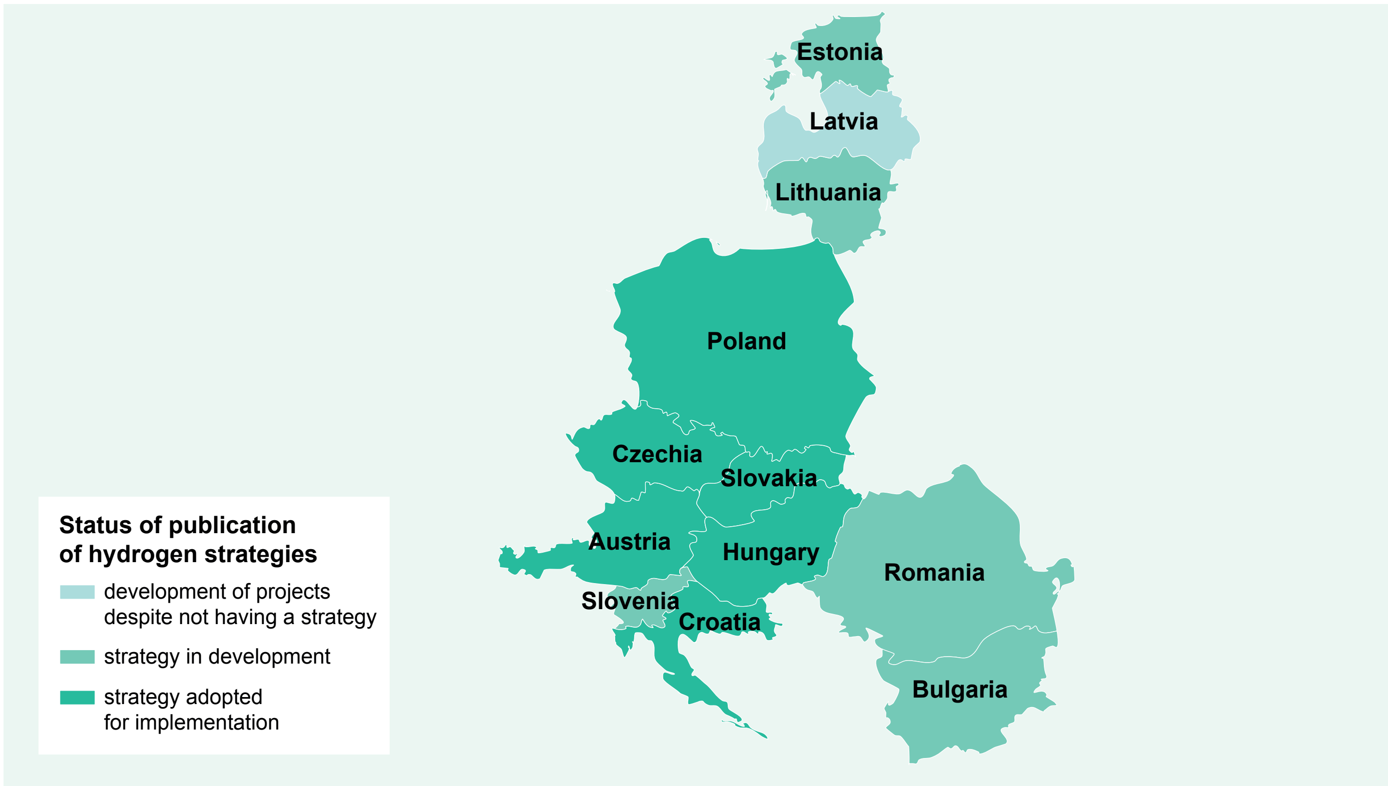
Hydrogen in strategic documents of 3SI countries

Strategies

The 3SI countries do not have a coherent strategy for the development of the hydrogen economy. All of the 3SI countries pledge to meet the EU policy goals set out in the EU Hydrogen Strategy. The activities of the 3SI countries promote bilateral cooperation and the development of cross-border hydrogen transmission in the 2030-2040 horizon.

Not all 3SI countries have strategies, programs or roadmaps for the development of hydrogen technologies by 2030. The map below shows the advancement of the hydrogen strategy in each of the 3SI countries.

Fig. 2.10 Map of hydrogen strategies in 3SI countries (as at 17 July 2023)



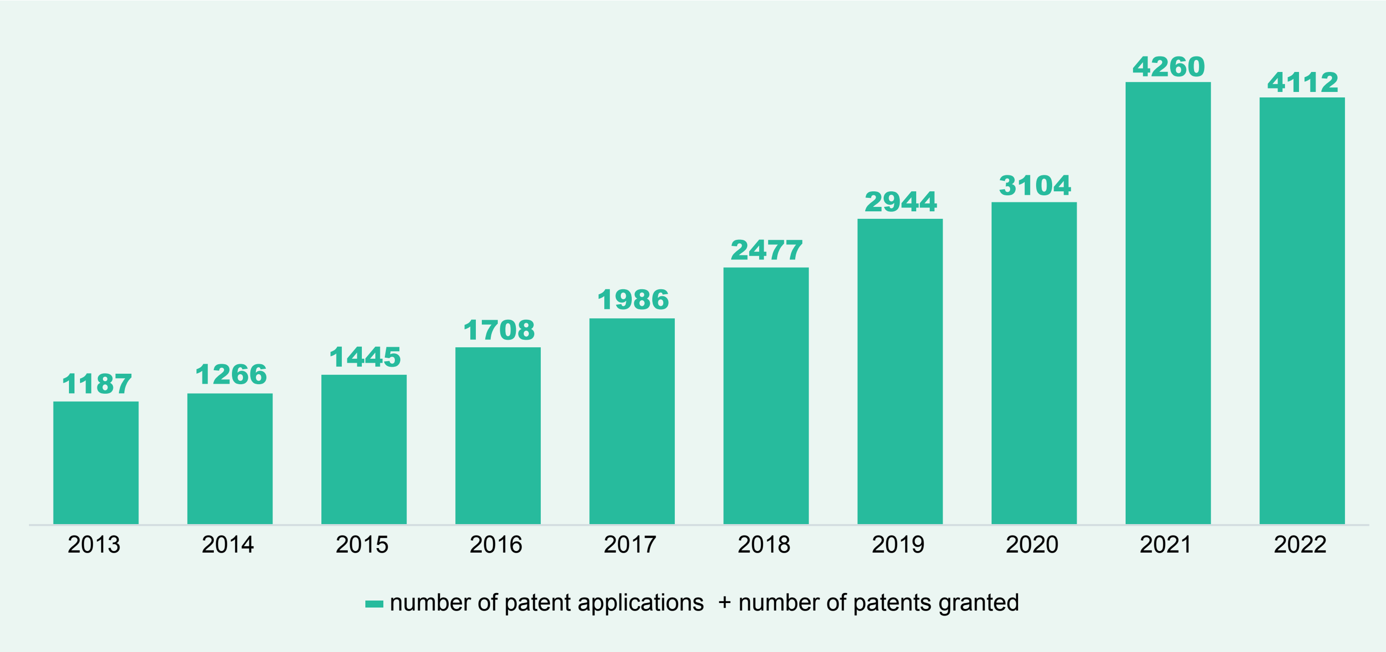
Source: In-house analysis.

RESEARCH AND PATENTS

Comparing the differences between geographic areas (world, 3SI, Poland) allows us to assess the overall level of innovation in the area of hydrogen technologies. Patent activity (understood as the sum of all patent applications and patents granted) indicates significant differences between countries in hydrogen production, storage and transport.

Global patent activity

Fig. 2.11 World – patent activity in the area of hydrogen technologies



Source: In-house analysis based on PatSnap® Analytics

The global patent activity related to hydrogen technologies has been growing rapidly for 10 years. In 2020, patent activity related to hydrogen technologies exceeded 3,000 patent applications and patents granted per year, which warrants a statement that hydrogen technologies have become an area of significant interest for inventors worldwide[I].

The table below sets forth value of all hydrogen patents worldwide recognized in 2013–2020. This value is an estimate made using the[I] PatSnap analytical tool based on a number of economic factors, i.e. the financial condition and value of entities applying for a patent, as well as market trends and the degree of commercialization of patents.

Table 2.1 World – estimated value of patents by technology area

area	total value of patents	average patent value
production	USD 523,996,400	USD 59,282
storage	USD 306,533,700	USD 70,081
transport	USD 15,480,500	USD 123,844
Total/average:	USD 846,010,600	USD 63,429

source: In-house analysis based on PatSnap® Analytics

The average value of patents related to hydrogen production is the lowest, but their total value exceeds USD 500 million, accounting for two-thirds of the market. In turn, the average value of – a small group – of "transport" patents, is as much as twice that of "production" patents, confirming their attractiveness from the point of view of commercial applications. It can be assumed that these patents are attractive not only in terms of selling IP property, but especially in terms of their commercialization (technology implementation).

Table 2.2 World – TOP5 countries by number of applications

position	country of origin	number of applications
1	China	10,562
2	Japan	1,987
3	USA	1,032
4	Korea	950
5	France	224
15	**Poland**	**45**

source: In-house analysis based on PatSnap® Analytics

The leader in hydrogen-related innovation is China, were as many as two-thirds of all patents worldwide were filed between 2013 and 2022. France is the only European country taking one of the top spots. In this ranking Poland is ranked in a high 15th place, before such developed countries as Israel, Sweden and Canada.

I. In all patent databases, the number of patents granted (as at the end of 2021 and 2022) is lower than actual because patent applications are still being processed. These figures are updated retroactively on the date of recognition/rejection of the patent right.

I. Although PatSnap makes estimates using learning algorithms (AI) whose accuracy is unknown, this valuation is sufficient to calculate and compare average values for hydrogen production, storage and transport.

TRENDS IN THE GLOBAL HYDROGEN MARKET

Socio-economic

- **Hydrogen production costs:** dependent on many factors (cost of electrolyzer production, energy crisis, access to RES, scale of hydrogen production, natural gas and electricity prices, regulatory changes). Technological costs are declining and the scale of production is regularly increasing contributing to lower costs, but macroeconomic conditions are difficult to foresee with certainty.
- **Investment in hydrogen technology:** regularly increased. Investments are moving away from the planning phase to implementation activities (production methods, infrastructure). The market requires integrators and risk takers (large companies and local governments). The investment cycle in the clean energy sector lasts about 25 years, hence most of the energy investment will be carried out in this decade.
- **Demand for hydrogen:** economic plans that involve the use of hydrogen are published by the world's main superpowers, and most forecasts predict that demand will grow. Hydrogen can be competitive particularly in local value chains.
- **Benefits of implementing hydrogen technologies:** up to 30 million jobs globally, 1 million in Europe.
- **Hydrogen-related products:** hydrogen cars as a complementary product to electric vehicles.
- **Growth of cooperation:** new hydrogen technologies enable the development of international and cross-sector cooperation among many countries.
- **Raising public awareness:** the development of hydrogen technology is raising energy awareness and commitment to energy saving measures.

Technological

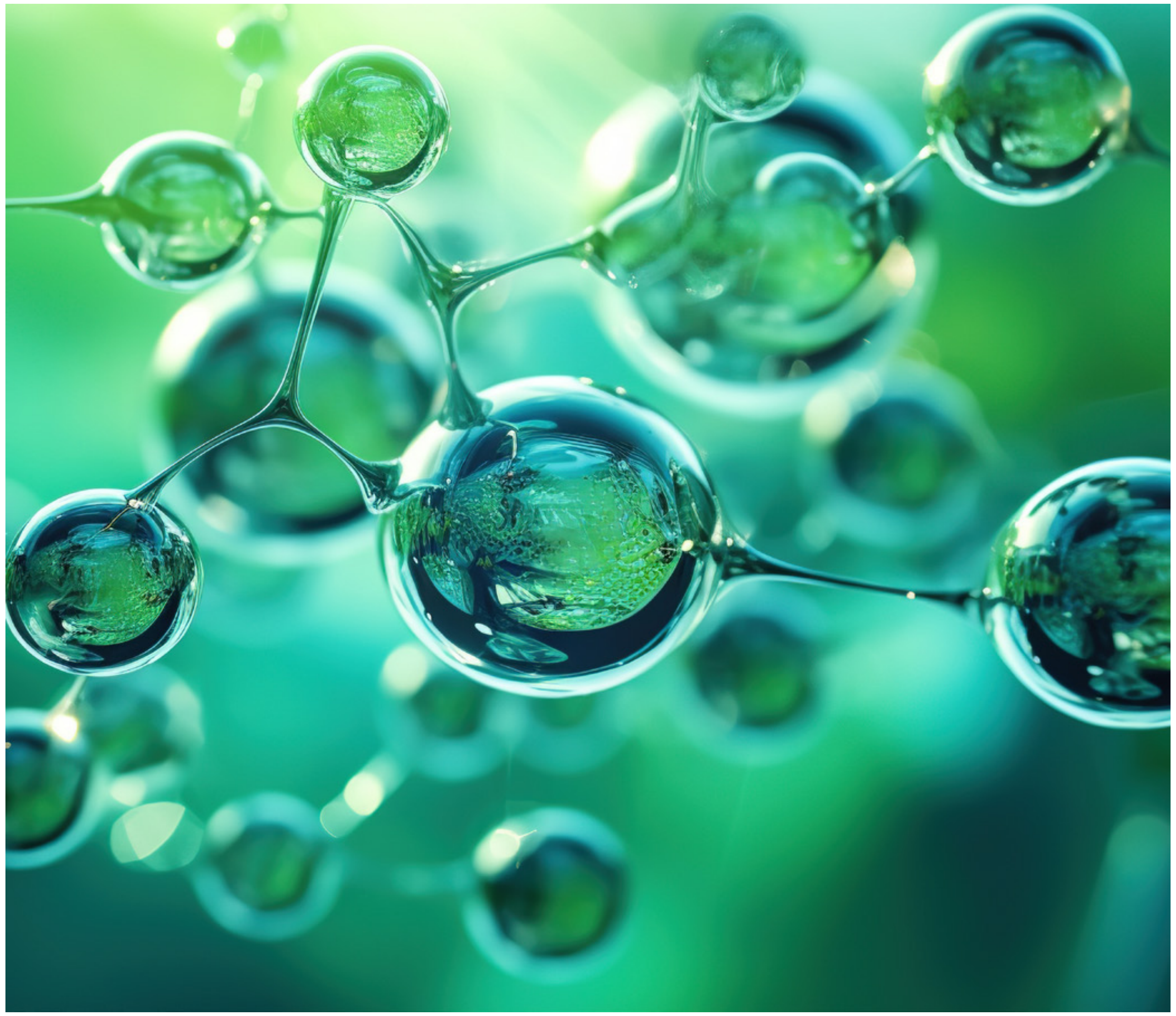
- **Decarbonization:** hydrogen from electrolysis promotes decarbonization, which is why it is applied in various sectors, such as production of cement and ammonia, in glass, iron and steel works, in transport (shipping, rail, public transport, municipal vehicles) and in heating of buildings.
- **A bottleneck in the development of hydrogen production:** interest in hydrogen has exceeded the availability of e.g. electrolyzers. Fulfillment of orders for electrolyzers is currently late by about 3-4 years. This affects the extension of infrastructure.
- **Energy system:** hydrogen will be used as a carrier or reservoir for excess power from RES, and electrolyzers will be installed next to demand points, such as refineries, steel mills and chemical complexes. If needed, the hydrogen will serve as a buffer, enabling energy to be transported over longer distances or postponing its consumption.
- **Hydrogen production technologies:** advancement in the area of anaerobic fermentation, biomass gasification, electrolysis based on energy generated from renewable sources, photo-biological methods.
- **Outlook for infrastructure:** hydrogen transport is possible by mixing it with natural gas. The hydrogen refueling infrastructure in Europe currently consists of 120 stations and is planned to be expanded – sixfold by 2025. Hydrogen is stored in smaller cylinders, tankers and in larger underground storage facilities, such as salt caverns.

Political and regulatory

- **Financing:** a shift towards financing green investments (e.g. EU Taxonomy). Hydrogen technologies will require a significant increase in funding, including support from public funds, for investment (PLN 600 billion by 2030), research and development or standardization of hydrogen.
- **Sustainable development goals:** hydrogen is currently the main political tool that can make it possible to address climate change, competitiveness of economies and security of resources.
- **International market:** dominant countries seek to establish an international hydrogen trade market. They enter into intercontinental cooperation agreements focusing on trade, investment and scientific development. In the case of the EU, cooperation ties are also expected to cover Ukraine and the Eastern Balkans, as well as North Africa.
- **Energy strategy:** energy management is to be carried out through a sector coupling strategy. Energy will primarily flow between the industry, transport and construction sectors.
- **Waiting for regulations:** definitions related to the hydrogen economy are being established, e.g. as part of regulatory sandboxes, which are environments that allow testing of products not yet regulated by law. Waiting for regulations increases investment risk.

Environmental

- **Cleaner air:** the use of hydrogen will reduce air pollution, especially in cities.
- **Reduction of emissions:** the European Union's objective is to make the energy system climate-neutral – thanks to hydrogen and RES, among other things.
- **Waste management:** solid waste – hydrogen production through pyrolysis. Municipal wastewater can be used in hydrogen production through electrolysis and as a medium for anaerobic fermentation, pyrolysis or activated sludge gasification.
- **Increased production of raw materials:** increased use of critical raw materials in hydrogen production equipment.
- **Dominance of fossil fuels:** in the first half of 2023, despite the increased use of RES, more than 90% of hydrogen was produced from fossil fuels.



CONCLUSIONS AND RECOMMENDATIONS

Summary

The convergence of goals and many different national measures means that the acceleration of hydrogen technology development is highly foreseeable.

The need to develop synergies in the hydrogen economy is evident. It is a multifaceted effort on a local and international level. In local operations, synergy entails coordinating the resources and potentials of individual countries in hydrogen production and use. The international dimension of synergy implies support in the creation of projects of a cross-border nature. Examples of such activities are the Baltic Hydrogen Valley and the North Adriatic Hydrogen Valley (Croatia, Slovenia, Italy)[I].

Initiating and supporting such activities is essential for the further development of the 3SI countries' hydrogen technology and economy. A major role in creating directions for the development of strategies for the Three Seas Initiative member countries is played by the Three Seas Initiative Investment Fund, the co-founder of which is Bank Gospodarstwa Krajowego, which supports hydrogen projects in individual countries[II].

In many cases, there are different models for the development of the hydrogen economy: centralized (mainly in small countries) or decentralized (e.g. in Poland). Some countries without a strategy do not define a development model (e.g. Slovenia).

Priorities for further development in the area of hydrogen in Poland

The results of a study carried out by the Delphi method in 2023 as part of the project "Strategy for Poland's hydrogen technology security for 2022-2030" indicate three key factors that could significantly affect the development of the hydrogen economy in Poland:

I. NAHV, https://www.clean-hydrogen.europa.eu/system/files/2023-03/2.%20North%20Adriatic%20cross-border%20Hydrogen%20Valley%20%28NAHV%29.pdf, 2023 [accessed on 31 July 2023],
II. Hydrogen Europe, https://hydrogeneurope.eu/clean-hydrogen-monitor2022/, 2022 [accessed on 31 July 2023],

1. **Legislation that reduces investment risk in the area of hydrogen by 2030;**

   Experts see this as a key element that can accelerate the development of low-carbon hydrogen production. It will be important to create a stable regulatory environment for low-carbon hydrogen, which will help minimize investment risks, accelerate the establishment of the value and supply chains, and improve the balance of demand and supply. In addition, national regulations should allow pilot projects related to the use of specific hydrogen technologies in different sectors of the economy (e.g.: transport, industry, heating). All types of local initiatives, such as hydrogen valleys, may soon prove to be remarkably successful.

2. **Financial instruments supporting Polish companies until 2030;**

   The establishment of appropriate financial instruments, such as the European Hydrogen Bank, could significantly accelerate the development of the hydrogen market. Lack of funding makes it difficult for Polish companies to enter the low-carbon hydrogen market on their own. It is important to determine the strategic direction and level of financing of projects and the expected measurable effects until 2030-2035. The lack of a clear trajectory – with potential changes driven by political and market factors – limits the willingness of many players to initiate and implement large-scale projects that can make a real difference to the economy and the establishment of a hydrogen ecosystem.

3. **Securing public funds for the energy transition until 2030;**

   This is an important aspect for the development of the hydrogen economy. Experts stress the need for financial support, especially for initial projects. However, there is concern that the amount of available public funds may be insufficient, and the conflict with the EU and a lack of internal agreement regarding the directions of the transition may pose a risk to ensuring full availability of these funds.

Both regulation and financial support are key to accelerating the development of the hydrogen sector in Poland. It is necessary to take measures to ensure the right investment and financial conditions, so that Poland can effectively use the potential of hydrogen technology to decarbonize the economy.

In addition, the following factors are important:

- **Synergy with climate and national policies**
  Hydrogen as a resource of the future is viewed from the perspective of broader economic contexts, which include decarbonization, green transformation and the tackling climate change. Hydrogen is the common denominator of a number of political and social initiatives in these areas and is an element of many different political strategies. The identification and standardization of hydrogen policies at national and regional levels will make it possible to more fully utilize and highlight the changes that are taking place in the local and global environment under the influence of hydrogen technologies.
- **Access to mineral resources and analyses**
  It is recommended that analyses be performed on the availability of mineral resources that are sufficiently

alkaline for the purposes of CO_2 sequestration as well as analyses of the cost-effectiveness of using such resources. If such analyses demonstrate opportunities in terms of significant availability and potential economic opportunities, the next step should be the development of research programs involving – in the first stage – the analysis of feasibility of using raw materials for CO_2 sequestration and – subsequently – the development and implementation of the resulting technologies.

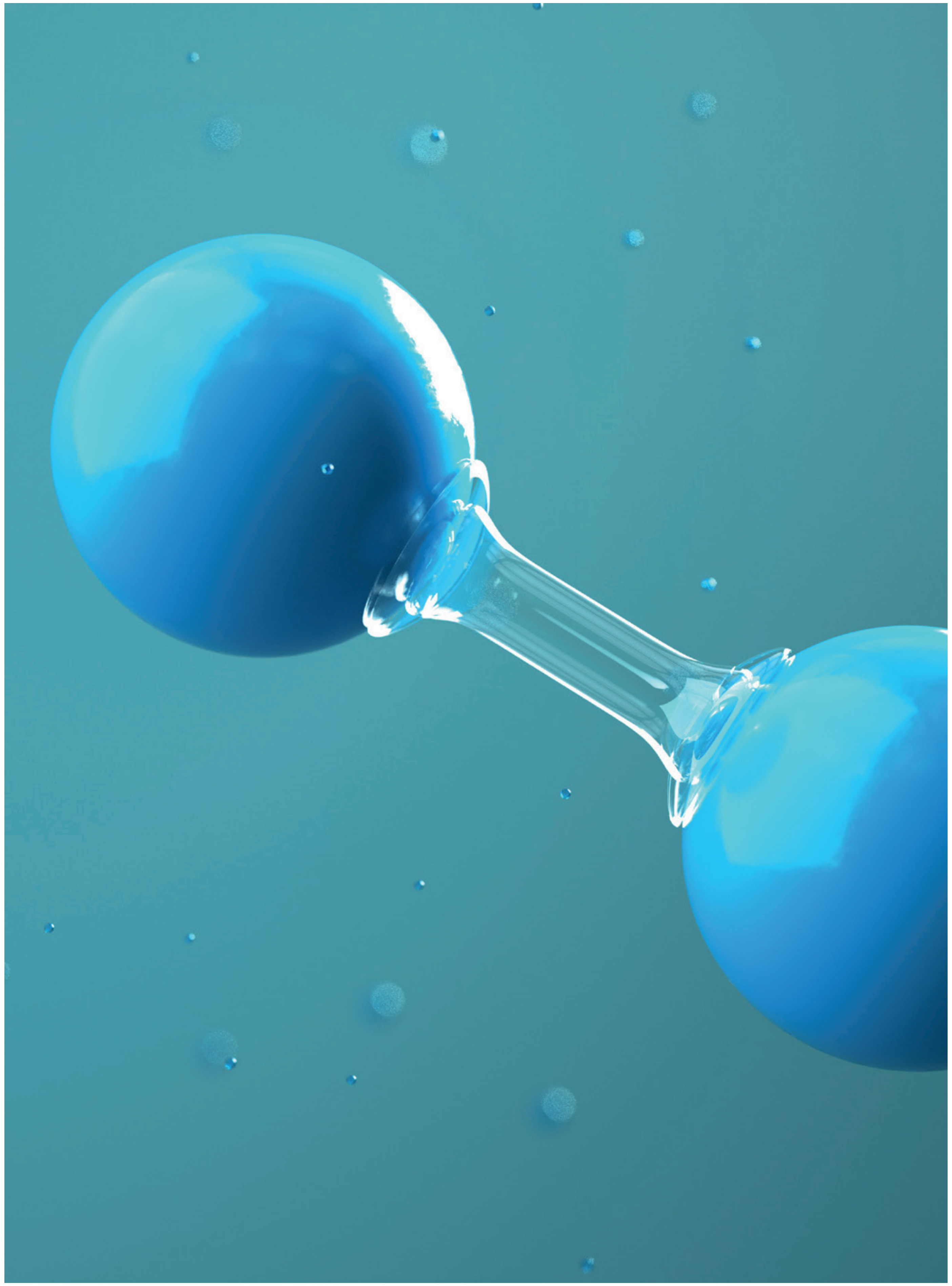
Another recommended measure is an analysis of the total carbon footprint of urea production under different scenarios.

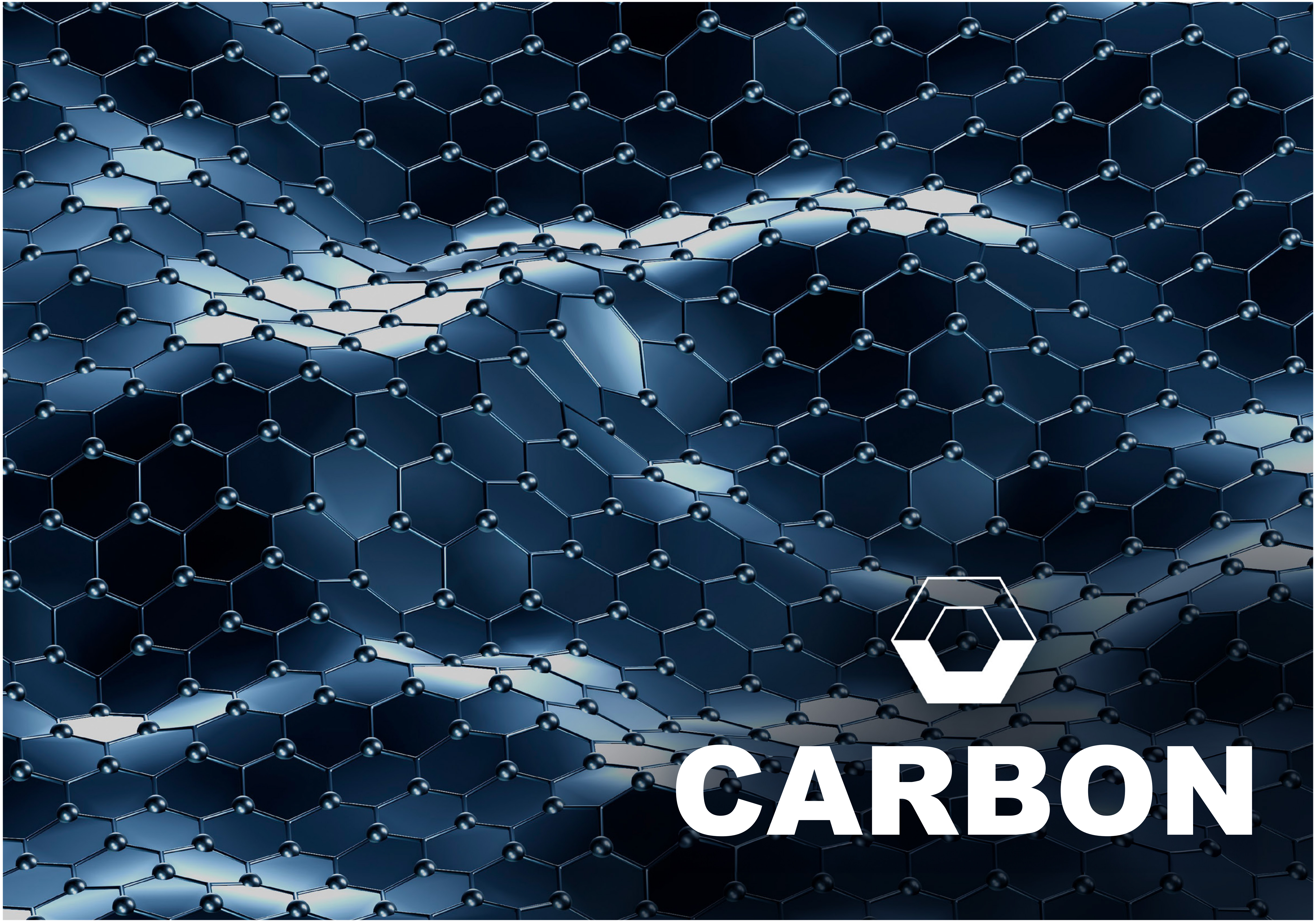
- **Establishment of research and development programs**
  Continued research and experimental development activities in hydrogen technologies is crucial. It is necessary to continuously monitor the development progress and analyze the challenges, opportunities and threats related to hydrogen in the technological, political, social and cultural aspects. In addition, it will be necessary to increase investment in new innovations, streamline processes and seek more efficient technological solutions. In particular, it is recommended that programs be established in the following areas:
  - support of technology projects related to the use of hydrogen in copper ore reduction processes,
  - development of low-cost methods for treatment of water sourced from rivers so that it meets the requirements for water electrolysis technologies,
  - carrying out analyses and establishing a program to identify and, if necessary, develop and implement technologies for the use of oxygen produced in electrolysis (or photolysis in the future) of water, with particular regard to logistics,
  - establishment of a program related to photolysis of water covering all required elements, with due regard to the complementarity of equipment needs with the scope of the required research work.
- **Development of electrolyzer production capacity in Poland and planning their higher availability in the Polish economy**
  The availability of electrolyzers, in particular the lead time for new ones, is a challenge already today. Long waiting times and delays in deliveries can adversely affect the development of investments and the pace of growth of the hydrogen economy. What is important in this regard is to analyze the possibility of creating electrolyzer production capacity to satisfy Polish needs and to develop a plan of ensuring access to those devices.
- **Development of the green steel sector in Poland**
  In the steel sector decarbonization is difficult and cost-intensive, but most needed. It is important to create conditions in which foreign corporations will be willing to invest in the use of hydrogen in steel production earlier than in other competing countries where they have their facilities. This could help increase the international competitiveness of this sector of the Polish economy and prevent the closure of branches of foreign companies in Poland.

What measures should be taken in the context of a multistrategy for 3W?

The most important and the most urgent needs for action:

1. Standardization and linking the strategies of EU Member States so that they define key realistic objectives, take into account the potential and capabilities of individual economies, the availability of relevant resources and means.
2. Building international partnerships and cooperation with a view to implementing regional strategies to boost the hydrogen economy and technologies.
3. Taking sector-specific measures, accounting for the role of hydrogen in various areas of the economy (power generation, heating, transport, etc.), with due consideration of the effect of synergy and seeking its achievement in the development of hydrogen.
4. Development of R&D and pilot projects in individual countries and sectors of the economy to verify the potential of hydrogen technologies and solutions.
5. Education of different sections of society, especially building public awareness of hydrogen technologies; education and information activities are important for the acceptance and development of this industry. Informing the public about the advantages and potential of hydrogen as a green fuel will help earn more support and interest.




CARBON

INTRODUCTION

When asked about coal, we first think of fossil fuel, a sedimentary rock that was formed from the transformation of plant remains and contains carbon, oxygen, hydrogen, nitrogen and sulfur, among other elements. This raw material had its part in the industrial revolution and has accompanied humanity for many decades as an energy carrier, but also, as we observe more and more clearly, as one of the causes of climate change and pollution of the environment in which we live.

Carbon and many of its varieties is used, *inter alia*, in technologies supporting sustainable development and contributing to the reduction of some of the negative effects caused by civilizational development, including the widespread use of fossil fuels. Paradoxically, if it was not for the adverse connotation with the fossil, we would be talking about coal and carbon today as a hope for a modern and clean tomorrow for us and for future generations.

Carbon, is still a new and promising subject of research and new applications, for example in materials technology. There are more and more cases of commercialization of discoveries and in many cases we do not realize that everyday items contain carbon elements derived from these new discoveries. The existing achievements inspire great optimism and we continue to discover new features of carbon that open up further potential directions of study and application.

The diverse properties of carbon enable its versatile use in virtually every area of the global economy, from construction, e.g. as an additive to cement, through electronics – in the manufacture of displays, medicine – as a drug carrier in targeted therapy, to the space industry, the military industry and even in the manufacture of sports equipment.

This clearly translates into interest in modern carbon technologies in the world's most advanced economies, as evidenced by numerous patents, and in the international arena, which can be seen, among other things, in numerous initiatives pursued by joint research teams from different countries. Poland also contributes to this process and it has the potential to make the new industry a catalyst for rapid growth.

In this report, due to the extensiveness of the expression "carbon technology market", we do not address the coal mining and processing industry and the metallurgy and casting industries. Therefore, with the term "carbon technologies" we refer to other applications and technologies that use carbon in one of its molecular and chemical forms, as well as composite materials containing allotropic forms of carbon.

SUMMARY

Most forms of carbon have appeared in our environment relatively recently. Studying their properties requires financial resources, adequate laboratory facilities and time, which makes this area of expertise still new, promising but also requesting significant commitment.

1. Science continues to discover new allotropic forms of carbon. Diamond and graphite were joined by fullerenes, carbon nanotubes, graphene and cyclocarbon. Scientists have predicted and described the characteristics of more carbon varieties (e.g. graphidyne (GDY), which, similarly to graphene, will have a two-dimensional structure), more than 500 hypothetical carbon allotropes based on infinite 3D networks are waiting to be synthesized[I].
2. Graphene is a unique material made of carbon atoms that form one atom thick sheets. It is almost transparent and a sheet that would cover an area of 1 km^2 weighs less than 1 kg.
3. Electrons move 200 times faster in graphene than in silicon. This opens up new prospects for electronics and computer hardware development. Until now, to increase the speed of a transistor, it had to be made smaller. Next-generation transistors based on graphene will be faster by definition and will replace silicon in the future[II].
4. Fullerene C_{60} and its derivatives have potential antiviral activity, for example, in the treatment of HIV infection. Experimental observations confirmed the inhibitory effect of C_{60} on HIV-P and its effectiveness is attributed to its antioxidant properties and molecular structure that induces a hydrophobic interaction with the active site of the virus[III].
5. According to analyses conducted by Precedence Research[IV], the global carbon nanomaterials market was worth about USD 3.6 billion in 2022. Growth is expected to continue at a CAGR[V] of 27.5% from 2023 to 2032, reaching approximately USD 40.71 billion in 2032.
6. The Asia and the Pacific region accounted for 38% of the global value of this market in 2022, followed by: Europe (29%), North America (23%) and Latin America (6%)[VI].
7. Global concrete production causes approximately 8% of global CO_2 emissions. If they were compared to emissions generated by individual countries, “concrete would be the third largest carbon dioxide emitter in the world”, surpassed only by China and the US[VII]. The introduction of the new concrete worldwide could reduce global CO_2 emissions by about 2%.
8. The US and China, as the world’s two largest economies, are competing for technological superiority and innovation in this area. The new leader from 2017 is China. Competition can lead to increased investment in R&D and result in more patents.
9. In May 2022, the European Chemicals Agency (ECHA) conducted a study covering the European Economic Area and Switzerland[VIII]. Based on the study, the market for nanomaterials, defined in accordance with the European Commission’s recommendation, was estimated at 140,000 tons in volume and EUR 5.2 billion in value terms in 2020.
10. Poland is the fourth largest market in the EU and the largest market in Central and Eastern Europe, which is why it can stand for the leader in nanocarbon technology.

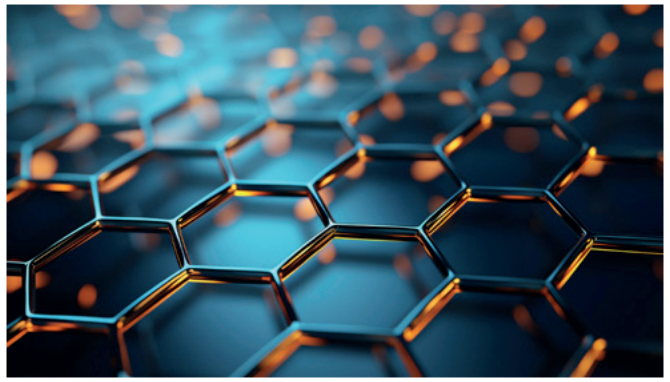
I. Bulletin of the Chemical Society of Japan, 2021, Vol.94, No.3, 798-811, (https://www.journal.csj.jp/doi/10.1246/bcsj.20200345)
II. Aranca: https://www.aranca.com/knowledge-library/articles/ip-research/is-graphene-the-new-silicon
III. https://www.cd-bioparticles.com/
IV. A Canada/India based company specializing in providing strategic market insights, with a registered office in Ottawa.
V. Compound Annual Growth Rate – an indicator used to calculate the average annual growth of a certain value over a given period.
VI. Ibidem
VII. https://www.theguardian.com/cities/2019/feb/25/concrete-the-most-destructive-material-on-earth
VIII. ECHA (European Chemicals Agency): Study of the EU market for nanomaterials, including substances, uses, volumes and key operators, May 2022

CARBON AND ITS ALLOTROPES

The outstanding variety of physical and chemical properties is attracting the attention of the world of science and business to carbon. This is because it has an interesting property called allotropy, namely, as a chemical element it can exist in the same physical state in different forms.

The most commonly recognized allotropy is found in the gaseous form of oxygen: the two-atom form that we use for breathing and the three-atom form (ozone), which has strong photochemical oxidation, antiseptic, but also toxic properties. Allotropic forms of an element may differ in their crystalline structure or the number of atoms in a molecule.

Small differences mean that the same carbon can be extremely hard as diamond, and with a slightly differently organized structure – it can create graphite, which is very soft and easily breakable.



Graphene is an unusual material that was discovered in 2004 by a group of physicists at the University of Manchester. The existence of graphene had been anticipated earlier, but it was assumed that due to its single-atom “thickness” it would be unstable and hence hard to produce. Andre Geim and Konstantin Novoselov used graphite and took Scotch tape to peel off its subsequent layers. They did this until they were left with a single layer of carbon atoms, which was graphene[I].

For the discovery of graphene its inventors were awarded the Nobel Prize in Physics “for groundbreaking experiments on two-dimensional graphene material” in 2010. The discovery has opened up new opportunities for the design and production of ultralight and ultrastrong materials.

Graphene has the appearance of honeycomb with a hexagonal lattice structure, whose thickness is only 1 carbon atom layer. It is extremely light (1 km^2 weighs less than 1 kg), harder than diamond, up to 200 times stronger than steel, and perfectly conducts heat and electricity. It can be stretched by 20% without damaging its structure, it is almost transparent, resistant to cutting and abrasion. These mechanical properties make it an ideal construction material or component of such structures. Adding graphene to concrete increases its load-bearing capacity, reduces its weight and the industry’s environmental impact.

Graphene can be successfully used in:

- production of transparent, rollable touch displays, sensitive image converters, energy-efficient light sources (LEDs),
- production of more efficient photovoltaic cells, high-performance batteries by increasing their capacity and charging speed, in medicine in the creation of artificial tissues that are tolerated by the human body and having antibacterial and antioxidant properties,
- adding new properties to plastics – graphene can turn them into conductors and combined with aluminum it can be used to build modern power grids[II].

Electrons move 200 times faster in graphene than in silicon. This enables the development of breakthrough electronic devices. Until now, to increase the speed of a transistor, it had to be made smaller. Next-generation transistors based on graphene will be faster by definition and will replace silicon in the future[III]. Transistors based on graphene are revolutionary single-electron devices that operate on the nanometer scale, allowing the flow of only one electron at a time.

I. U.S. Energy, Office of Science, https://science.osti.gov/Science-Features/News-Archive/Featured-Articles/2011/03-25-11
II. https://materialyinzynierskie.pl/
III. Aranca: https://www.aranca.com/knowledge-library/articles/ip-research/is-graphene-the-new-silicon

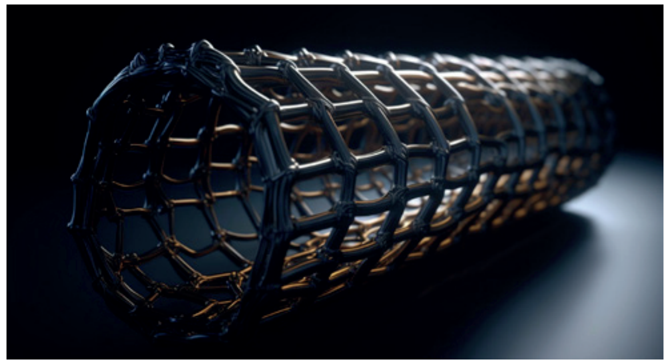
Graphene, due to its excellent electrical conductivity, high form factor and ability to efficiently disperse particles, is superior to traditional materials used in cathodes, as it can be used in lithium-ion batteries, lithium-sulfur batteries, supercapacitors and other electrical components.

Composites based on nanocarbon (such as graphene) are playing an increasingly important role in modern industries. They are used especially where strength and weight are crucial, such as in the aerospace industry.

A membrane from oxidized graphene is impermeable to gases, even helium atoms, while being fully permeable to water (H_2O). This makes it possible to use it for filtration at room temperature.

Graphene-based sensors can record phenomena at the molecular level, which can be used, among other things, in monitoring – in particular in environmental protection.

Graphene is a material that has the potential to change our present and future. It has not yet been two decades since its discovery and there already are thousands of potential applications. At the same time, it should be noted that the production of graphene is expensive. A piece of graphene with the size of 10x10 cm and 10 µm thick costs more than EUR 13[I].



Carbon nanotubes (CNT) are structures that resemble hollow seamless cylinders, which consist of thin carbon walls with diameters in the order of a few nanometers and lengths of a few micrometers to a few millimeters. The wall is composed of coiled graphene and the surface of a wall in a carbon nanotube has the appearance of honeycomb with a hexagonal and pentagonal lattice structure.

It is widely recognized that their inventor was a Japanese scientist Sumio Iijima, who in 1991 published a paper on carbon nanotubes in Nature[II]. He made the discovery by examining material extracted from solids that formed at the ends of carbon electrodes after a discharge under conditions of C_{60} formation. It should be noted that nanotubes had been known in the world of science several decades earlier.

Carbon nanotubes are among the most fascinating carbon structures, possessing unique mechanical, electrical and magnetic properties. There are single-walled carbon nanotubes (SWCNT) and multi-walled carbon nanotubes (MWCNT), i.e. tubes whose walls have more than one layer.

Carbon nanotubes are hydrophobic materials that exhibit heterogeneous diffusion in biological environments, but giving appropriate characteristics to their surfaces may mitigate this limitation. When exposed to oxidizing agents, they form carboxylated surfaces. Carboxylated CNT are materials that can be filled with drugs.

The special and stable porous structure of carbon nanotubes has a wide range of potential applications, for example as membranes for removing contaminants from water, *inter alia*, in the adsorption of heavy metals, antibiotics or oil. Filters containing CNTs can effectively trap and neutralize bacteria and viruses. CNTs can also be used to remove surfactants.

Carbon nanotubes have a large surface area comparable to that of activated carbon, which makes it possible to use them in filters, for gas storage or in monitoring – in sensors of environmental parameters, e.g. for ammonia detection.

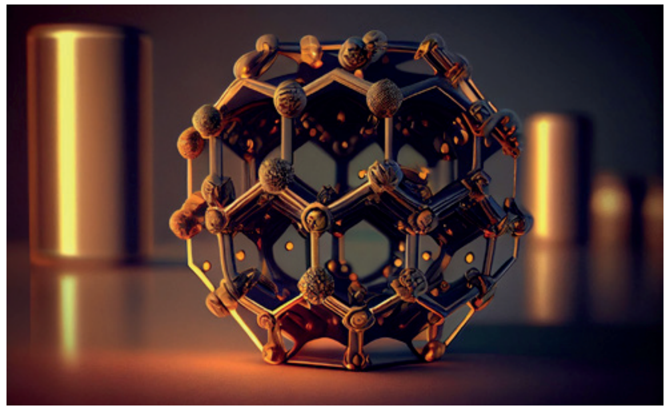
In medicine, carbon nanotubes can be used to introduce drugs into the body as part of targeted therapies. They can penetrate cell membranes and deliver medicinal substances to specific sites, which is crucial for the effectiveness of treatment and reducing unwanted adverse effects, e.g. in chemotherapy. Modified carbon nanotubes can also support diagnostics. After acquiring new properties, such as glowing in a predefined color, for example they can help detect places where cancer markers have appeared[III].

In electronics, nanotubes can be used to make nanowires and nanodiodes. With semiconductor and magnetic properties, they can be used to manufacture computer memory and sensors. The strong electrical conductivity of nanotubes is used in antennas, which increases performance by about 20 times compared to conventional antennas. The same property is used to shield electromagnetic radiation.

Batteries using nanotubes as electrodes increase energy density by 10 times and can withstand extreme temperatures.

I. https://nanografi.com/graphene/graphene-sheet/ [accessed on 20 October 2023]
II. Iijima, Sumio (1991), "Helical microtubules of graphitic carbon", Nature, 354 (6348): 568, Bibcode:1991 Natur.354...56I, doi:10.1038/354056a0, S2CID 4302490
III. https://biotechnologia.pl/technologie/swiecace-klik-nanorurki-pomoga-diagnozowac-choroby-serca-i-nowotwory,21907

The electron properties of CNTs are of great importance for their applications in a variety of industries: chemical, electronics, food, textile, as well as pharmaceuticals, medicine, construction, agriculture, aerospace and defense[I].



Fullerene is another allotrope of carbon, characterized by an even number of atoms and a three-dimensional form taking the shape of a closed and hollow body. Fullerenes are black solids with a metallic luster. They were discovered in the mid-1980s by two independent teams of scientists from the University of Sussex in Brighton (UK) and Rice University in Houston (Texas, US), for which they received a Nobel Prize in Chemistry in 1996[II].

The most recognizable example of this allotrope of carbon is fullerene C_{60}, which consists of patches with a pentagonal and hexagonal shape, resembling a football.

The structure of fullerene is unique in that it has no dangling bonds or unpaired electrons. These characteristics distinguish fullerene from other crystalline structures, such as graphite or diamond, which have edges with dangling bonds and electrical charges. Fullerene is chemically reactive and can be added to polymer structures to form new copolymers with specific physical and mechanical properties[III].

Fullerene derives its name from an American architect Buckminster Fuller, who invented hall coverings in the form of domes, with trusses in the shape of regular polygons. Interestingly, the structure was used to design a pattern of a ball played in football (Buckminster Ball), approved by FIFA and used for 36 years (1970-2006).

Fullerene C_{60} and its derivatives have potential antiviral activity, for example, in the treatment of HIV infection. Experimental observations confirmed the inhibitory effect of C_{60} on HIV-P and its effectiveness is attributed to its antioxidant properties and molecular structure that induces a hydrophobic interaction with the active site of the virus[IV].

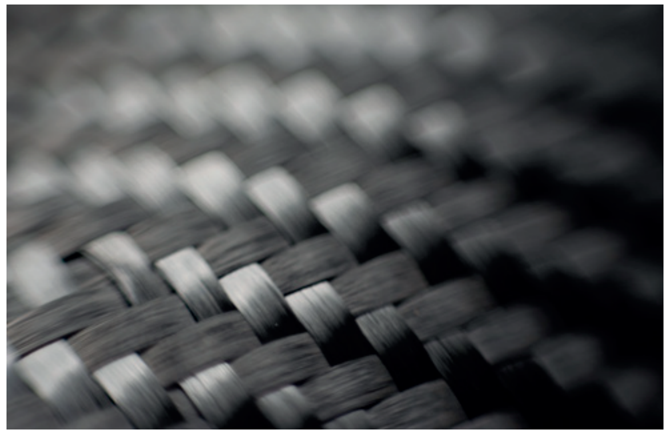
The subject of intensive research and exploration is a safe carrier of drugs or genes, capable of their precise delivery to the intended site in the body. Fullerenes can be dissolved in water and can carry drugs and genes to deliver them directly to cells. A fullerene-based peptide was successfully synthesized and its ability to penetrate the skin was observed[V]. Hence, fullerenes can easily penetrate cell membranes and cell walls and serve as drug delivery systems.

Conjugated fullerenes may be used for localized drug delivery, which avoids damage to other body organs. Ibuprofen is a common prescribed drug for pain relief and inflammation, but it can cause side effects. Research is carried out on the use of fullerenes as ibuprofen carriers, which will help minimize the risk of adverse effects.

Fullerene is a powerful antioxidant that reacts easily and quickly with free radicals, which can cause cell damage or death.

When filled with the right charge (e.g. metal ions), fullerenes can be of great importance for diagnostics. Their studies have been made as a radioactive tracer for imaging diseased organs and killing cancer tumors. They outcome demonstrated that a carbon layer is stable and resistant to human metabolism and the radioactive metal fulfilled its function by marking cancer cells. It was also found that metal fullerenes are non-toxic, remain in the body for about an hour and can help with cardiovascular imaging[VI].

I. [1] Robert W., Kelsall R.W., Hamley I.W., Georhegan M. (ed.), trans.: Kurzydłowski K., "Nanotechnologie" (Nanoscale science and technology), PWN, Warsaw, 2009. [2] Cademartiri L., Ozin G.A., trans.: Kłonkowski A.M., "Nanochemia. Podstawowe Koncepcje" (Concepts of Nanochemistry), PWN, Warsaw 2011. [3] Pietrasz A., "Zastosowanie nanorurek węglowych w medycynie" (Application of carbon nanotubes in medicine), in: Wawer I., Trziszka T. (ed.), "Ziołolecznictwo, biokosmetyki i żywność funkcjonalna" (Herbal medicine, biocosmetics and functional food). Research materials of the 1st International Conference "Herbal medicine, biocosmetics and functional food", Krosno 18-19 April 2013, p. 57
II. https://pl.wikipedia.org/wiki/Laureaci_Nagrody_Nobla_w_dziedzinie_chemii
III. https://www.cd-bioparticles.com/
IV. https://www.cd-bioparticles.com/
V. Rouse, J. G., Yang, J., Ryman-Rasmussen, J. P, Barron, A. R., & Monteiro-Riviere, N. A. (2007). Effects of mechanical flexion on the penetration of fullerene amino acid-derivatized peptide nanoparticles through skin. Nano letters, 7(1), 155-160.
VI. NANOTECHNOLOGY FOR TARGETED DELIVERY IN CANCER THERAPEUTICS, https://studylib.net/doc/13307993/editorial-article-nanotechnology-for-targeted-delivery-in...



Carbon fibers (CF) are produced, *inter alia*, in the process of pyrolysis, e.g. of polyacrylonitrile[I] (PAN), and usually occur in the form of fabrics woven from single fibers, which gives them an unusual, prestigious appearance. We have known and used them for more than one and a half century; as early as in 1880, Thomas Edison used them as filaments for electric light bulbs[II]. They owe their greater popularity to their widespread use in the defense (aerospace) and space industries in the 1960s.

Carbon fibers generally have excellent tensile properties, low densities, high thermal and chemical stabilities in the absence of oxidizing agents, and good thermal and electrical conductivities. They have been used in composites in the form of woven textiles, continuous fibers, and chopped fibers. The composite parts can be produced through filament winding, tape winding, liquid molding, and other methods[III]. Reinforced carbon fiber can be up to 5 times stronger than steel having only one-fifth of its mass.

Some of the more important applications of carbon fiber include:

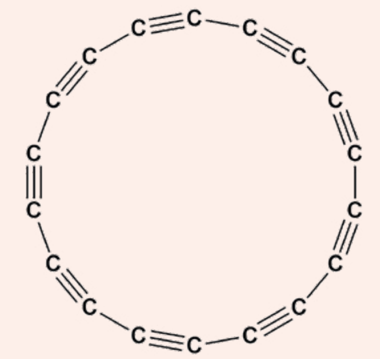
- aerospace industry – construction of aircraft parts, e.g. wings, fuselages, tails. Reduced weight of an aircraft means savings in fuel consumption,
- sports equipment – creating lightweight and durable equipment such as tennis racquets, golf clubs, fishing rods and bicycles, and especially yachts and racing boats. Reduced weight of equipment enables improved performance,
- medical equipment – manufacturing, e.g. of limb prostheses or dental braces. The key parameters are also lightness and durability.

Space exploration is one of the industries where rapid technological progress is absolutely essential. Thanks to the use of new technologies or materials, we are pushing the boundaries of what is discovered, while giving impetus to solutions that make our daily lives easier.

Carbon composites are commonly used in rocket construction. NASA uses carbon composite engine blades and hull plating for its spacecraft. Carbon composites are also used to make heat shields in rovers. The high temperature resistance and high strength of carbon fiber make it an excellent protective material when it heats up as it flies through the atmosphere.

Carbon can also be used in the production of advanced space electronic components, for example, silicon carbide is used to make LEDs, which are used in indicators and lighting systems on spacecraft.

It is worth mentioning the synergistic (from the point of view of use of 3W resources) use of carbon fibers in the construction of hydrogen pressure vessels. Here, carbon fibers are used as a reinforcing element, wrapped around the tank in a precisely defined way[IV]. Type V pressure vessels offer the lightest weight and feature a fully composite construction reinforced primarily with carbon fiber[V].



Cyclocarbon consists of n-atoms of carbon and has the shape of a ring. Each carbon atom only bonds to two neighboring atoms with alternating triple and single bonds. Researchers have been trying for years to obtain such a structure in the solid phase, but they did not succeed until 2019. This was done by a team of scientists from the University of Oxford and IBM Research – Zürich, who for the first time synthesized and characterized a ring consisting of n=18 carbon atoms[VI]. It is worth noting that the research on the production of a new carbon allotrope was participated by a Pole – Przemysław Gaweł, PhD, from the University of Oxford[VII].

Studies of its structure indicate that it acts like a semiconductor, which mean that it can have potential applications in electronics, which in the next stage could allow further miniaturization of solutions. Cyclocarbon has so far been obtained only under strictly controlled conditions at a very low temperature of five kelvins, which is about minus 268 degrees Celsius. It is uncertain whether the compound will be stable at higher temperatures. Due to its recent discovery, this carbon allotrope is not yet well recognized.

I. The process of polymer decomposition at high temperature under oxygen deficiency
II. https://dragonplate.com/a-brief-history-of-carbon-fiber
III. National Center for Biotechnology Information, https://www.ncbi.nlm.nih.goV/pmc/articles/PMC5513585/#B1-materials-02-02369
IV. Clean Energy, Volume 7, Issue 1, February 2023, Pages 190-216, https://doi.org/10.1093/ce/zkad021
V. https://www.compositesworld.com/articles/infinite-composites-type-v-tanks-for-space-hydrogen-automotive-and-more
VI. https://www.sci.news/physics/cyclocarbon-07503.html
VII. https://www.gov.pl/web/edukacja-i-nauka/diament-grafen-grafit-fulereny-i-cyklokarbon-zaobsen/vowano-nowa-odmiane-wegla

Diamond is perhaps the most recognizable carbon allotrope, mainly because of its unique appearance that is desired regardless of geographical boundaries and cultural differences. Many myths have been created around diamonds, but there is no doubt that this variety of carbon also has remarkable qualities that make it attractive not only for the jewelry industry. The most important uses of diamonds, beyond the jewelry industry, include[I]:

- industrial use – most diamonds mined lack the quality necessary to become gemstones and 80% of all rough diamonds go towards industrial uses. Because diamonds are so hard (scoring a 10 on the Mohs Hardness Scale)[II], they have long been used for cutting, drilling and polishing. Very small diamond particles are embedded into saw blades, drill bits and grinding wheels to increase their ability to cut tough materials. Diamond powder, made into a diamond paste, is used for polishing or for very fine grinding. In the automotive industry, diamond saws and drill bits cut and finish car body and engine components and diamond-coated grinding wheels bevel and polish the glass in windows.
- applications in the optical industry – diamond windows are made from very thin diamond membranes and used to cover openings in lasers, vacuum chambers and x-ray machines. Diamond membranes are very durable, resistant to heat and abrasion and are transparent.
- medical applications – medical research indicates that nanodiamonds (tiny diamond particles) may be an indicator of the effectiveness of cancer medication, allowing doctors to monitor the progression of the cells. Researchers are also looking into using diamonds to help the visually impaired, and testing diamonds as a potential material for bionic eyes and eye implants. Many dental tools include diamond tips to help dentists drill with maximum efficiency and without worrying about breaking instruments.
- music industry – diamond is a very stiff material, which can vibrate rapidly without deforming, a quality that has been used in high-quality speakers. Diamonds are also used in record player needles and DJ equipment.
- future uses – through continuous research, scientists are finding other, more sophisticated uses for nanodiamonds, e.g. in super lasers, surgical tools, medical devices and next generation computing.

The family of carbon allotropes continues to expand. Diamond and graphite that we have known for centuries have been joined in the past decades by fullerenes, carbon nanotubes, graphene and cyclocarbon. Scientists characterized subsequent carbon allotropes (such as graphidyne (GDY), which will be another 2D carbon allotrope). More than 500 hypothetical carbon allotropes based on infinite 3D networks are waiting to be synthesized[III].

I. Minerals Council South Africa: https://www.miningforschools.co.za/lets-explore/diamond/uses-of-diamonds
II. The Mohs Hardness Scale is based on a scale of 1 to 10, with diamond being the hardest material with the highest score of 10. Materials are tested against each other and if one scratches the other it gives the material a higher value.
III. Bulletin of the Chemical Society of Japan, 2021, Vol.94, No.3, 798-811, (https://www.journal.csj.jp/doi/10.1246/bcsj.20200345)

MARKET OF CARBON NANOMATERIALS

The carbon nanomaterials industry has seen rapid growth in recent years. This is a consequence of the increasing number of applications for both these materials and related technologies.

According to analyses conducted by Precedence Research[I], the global carbon nanomaterials market was worth about USD 3.6 billion in 2022. Growth is expected to continue at a CAGR[II] of 27.5% from 2023 to 2032, reaching approximately USD 40.71 billion in 2032.

The Asia and the Pacific region accounted for 38% of the global value of this market in 2022, followed by: Europe (29%), North America (23%) and Latin America (6%). The dominance of the Asia and Pacific region results from the increasing use of carbon nanomaterials in the following industries: automotive (to reduce the weight of vehicles and in electric vehicle batteries), aerospace (according to the estimates of the U.S. planemaker Boing, China would need 8,560 new planes by 2042)[III], energy industry, as well as in the production of displays, phones and other electronics.

The same analysis estimates the value of the global carbon nanotube market at USD 2 billion in 2022 and forecasts it will reach about USD 7.71 billion by 2032, with a CAGR of 14.50% between 2023 and 2032.

The global graphene market size was valued at USD 175.9 million in 2022 and is expected to grow at a compound annual growth rate (CAGR) of 46.6% from 2023 to 2030. Growth will be driven by the electronics industry in emerging economies and composite applications. Graphene production is also expected to see significant growth due to increasing demand for research and development purposes[IV].

According to the Grand View Research report for 2022, nearly 70% of the value of the graphene market was generated by the Asia and Pacific region (including China, India, South Korea, Japan and Australia). Graphene was used mainly in the production of electronics (approximately 37%), composites (about 35%), solutions in the area of energy (some 13%) and in other applications

In the coming decades, the market for carbon nanomaterials is also expected to grow rapidly with applications in medicine, including precision drug delivery, diagnostics, and the creation of specialized therapies that take advantage of the properties of different carbon allotropes (including antioxidant, electrical, optical, etc.).

One of the challenges in estimating the nanomaterials market is defining what exactly a “nano” material is. For that purpose, usually the European Commission Recommendation (2011/696/EU)[V] of 2011 is used, based on which 92 materials, substances and mixtures that meet the definition of nanomaterials have been identified. 19 of them, or more than 20%, are based on carbon, and they include respectively fullerenes (6), graphene (5), carbides (3), carbon-based (2), diamonds (1), other (2).

In May 2022, the European Chemicals Agency (ECHA) conducted a study covering the European Economic Area and Switzerland[VI]. Based on the study, the market for nanomaterials (defined in accordance with the European Commission’s recommendation) was estimated at 140,000 tons in volume and EUR 5.2 billion in value terms in 2020. Carbon nanomaterials account for more than 14% of the value.

In 2020, 790 tons of carbon nanotubes were produced in Europe, which brings the estimate of the market value to about EUR 452.47 million. The graphene

I. Precedence Research: Carbon Nanotubes Market - Global Industry Analysis, Size, Share, Growth, Trends, Regional Outlook, and Forecast 2023-2032, September 2023
II. Compound Annual Growth Rate – an indicator used to calculate the average annual growth of a certain value over a given period.
III. https://www.reuters.com/business/aerospace-defense/boeing-says-china-will-need-8560-new-planes-over-next-20-years-2023-09-20/
IV. GRAND VIEW RESEARCH: Graphene Market Size, Share, Growth & Trends Report, 2030
V. https://eur-lex.europa.eu/legal-content/PL/TXT/?uri=CELEX%3A32011 H0696
VI. ECHA (European Chemicals Agency): Study of the EU market for nanomaterials, including substances, uses, volumes and key operators, May 2022

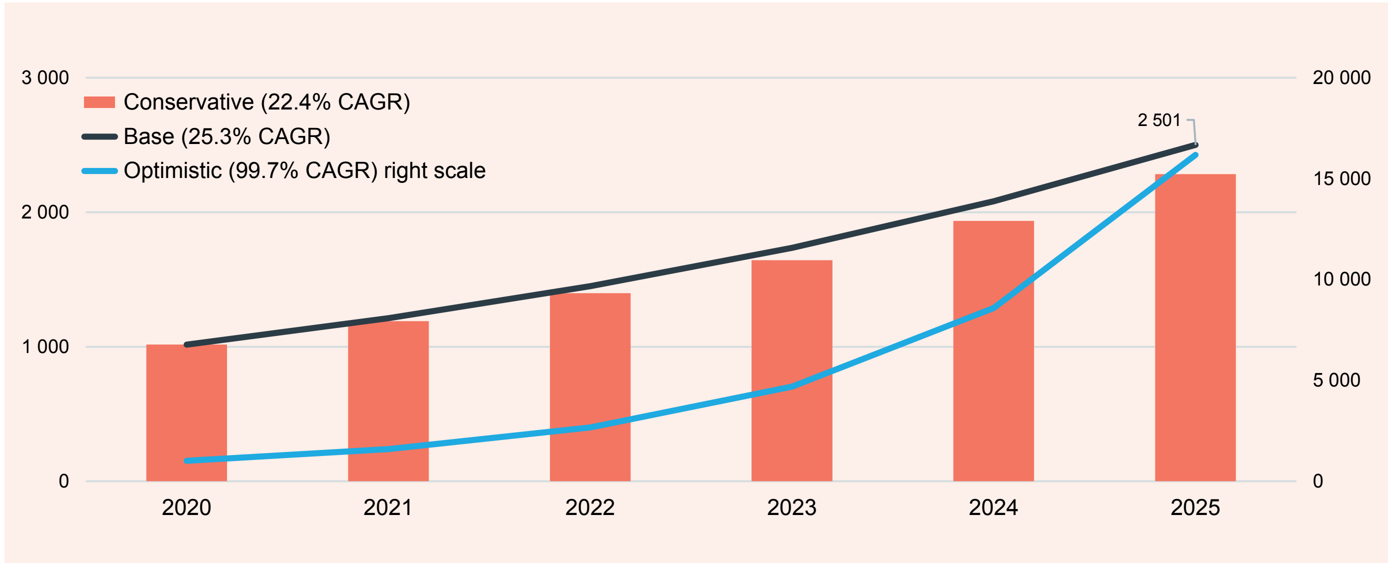
market was estimated at 40 tons, which was equivalent to EUR 92.9 million, while the fullerene market at 20 tons, i.e. about EUR 470 million[I].

In the horizon of 2025, assuming baseline growth scenarios for the carbon nanomaterials market in Europe (carbon nanotubes, graphene and fullerenes), the production volume will reach 2,150 tons and the market value will exceed EUR 2.5 billion.

Overview of the Polish carbon technology market.

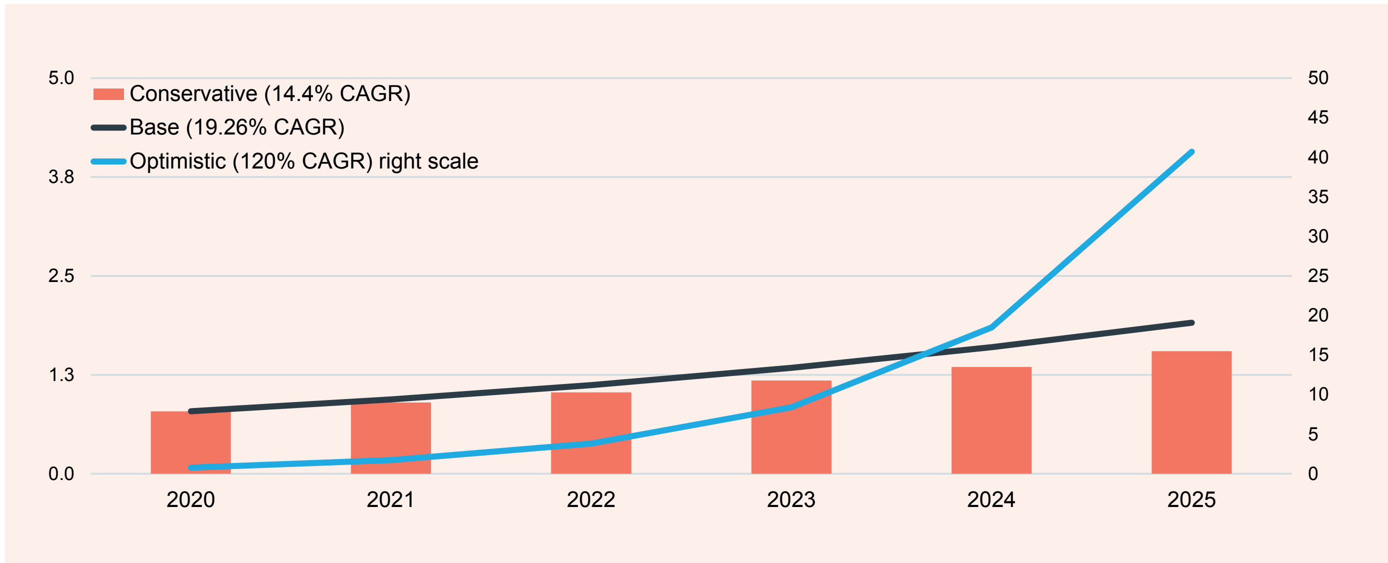
In the first quarter of 2023, in Poland there were about 90 companies implementing projects with the use or support of technologies based on carbon allotropes (including nanocarbon)[II]. Only 20 of them specialize directly in the area of carbon and develop technologies in this regard. These mainly include small and medium-sized enterprises and start-ups.

Fig. 3.1 Estimated output of carbon-based nanomaterials in the EU in the period 2021-2025 (thousand tons) (carbon nanotubes, graphene, fullerenes)



Source: ECHA: Study of the EU market for nanomaterials, including substances, uses, volumes and key operators, May 2022

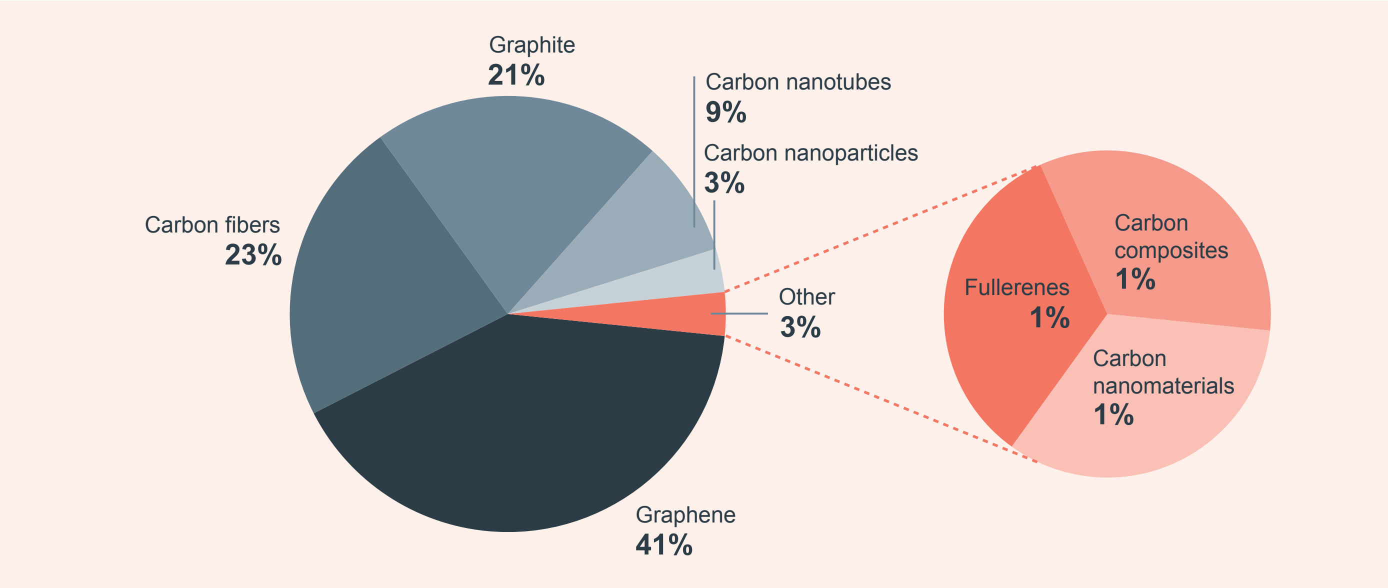
Fig. 3.2 Estimated value of production of carbon-based nanomaterials in the EU in the period 2021-2025 (EUR m) (carbon nanotubes, graphene, fullerenes)



Source: ECHA: Study of the EU market for nanomaterials, including substances, uses, volumes and key operators, May 2022

I. Ibidem
II. Based on: 3W Idea 2023 Report, Nanonet: Carbon

Fig. 3.3 Projects related to carbon nanomaterials implemented in Poland in 2022

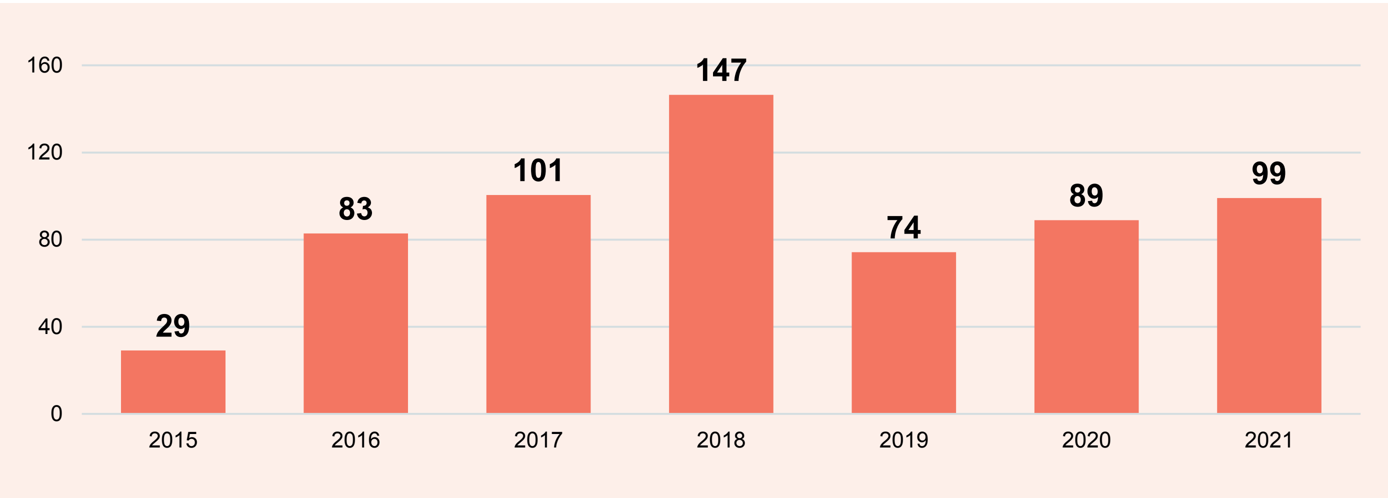


Source: In-house analysis of Nanonet.

Most companies focus on the synthesis and production of carbon raw materials, such as graphene flakes in the form of powder or suspension, carbon nanotubes, graphite, diamond or amorphous carbon. They have been very active in conducting research on innovations in the production process of carbon nanomaterials. In turn, the market for carbon fiber and carbon fiber composites, due to its relative maturity, is focused on product sales and, to a lesser extent, R&D projects. Composite materials produced in Poland are used in the automotive, aerospace, construction and building industries, among others.

Based on data from the Polish Agency for Enterprise Development (PARP), the National Center for Research and Development (NCBiR) and statistics published by individual companies, the estimated value of investment in R&D related to carbon technologies in 2021 was about PLN 100 million[I].

Fig. 3.4 Estimated value of investment in R&D related to the development of carbon technologies in 2015-2021 (PLN m)



I. Based on: 3W Idea Report 2023, Nanonet: Carbon – Compilation of data from the Ministry of Funds and Regional Policy, NCBR and PARP

RESEARCH AND PATENTS

Geopolitics plays a significant role in the development of competition and cooperation between countries in the area of carbon nanomaterials. The US and China, as the world's two largest economies, are competing for innovation and technological superiority in this area.

This competition can lead to increased investment in R&D and yield more patents.

The United States has for many years been the leader in the number of registered patents in the field of

Fig. 3.5 Cumulative number of patents in 2014–2023 (carbon nanotubes and nanofibers, graphene, graphite, fullerene)

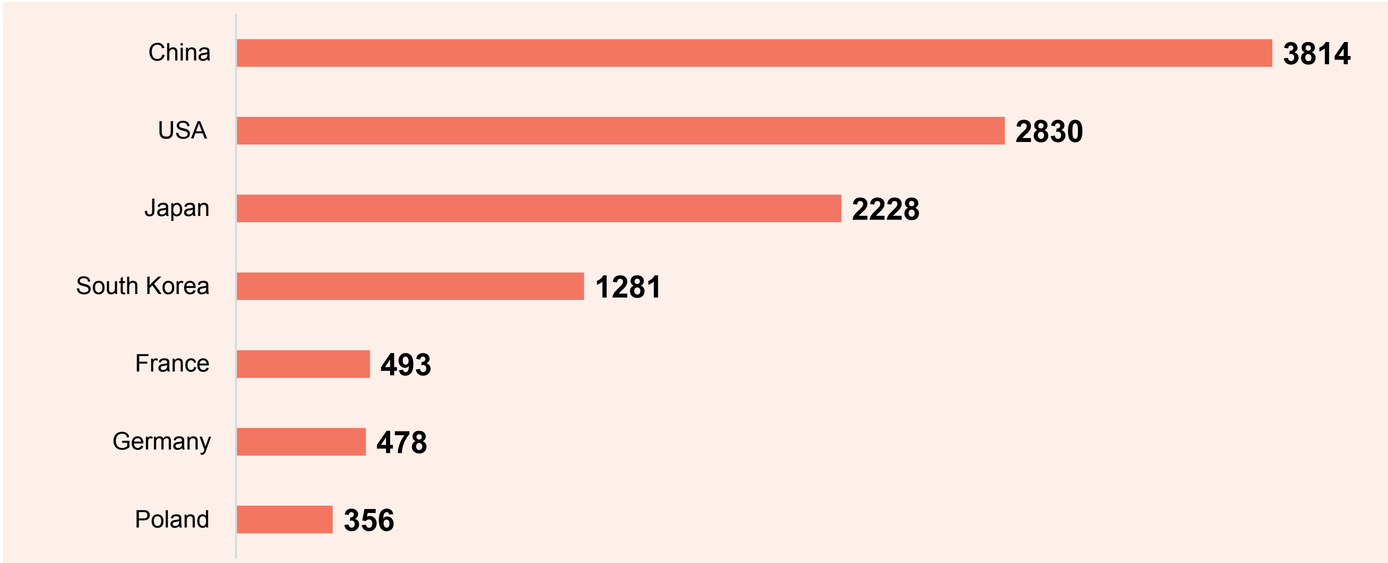
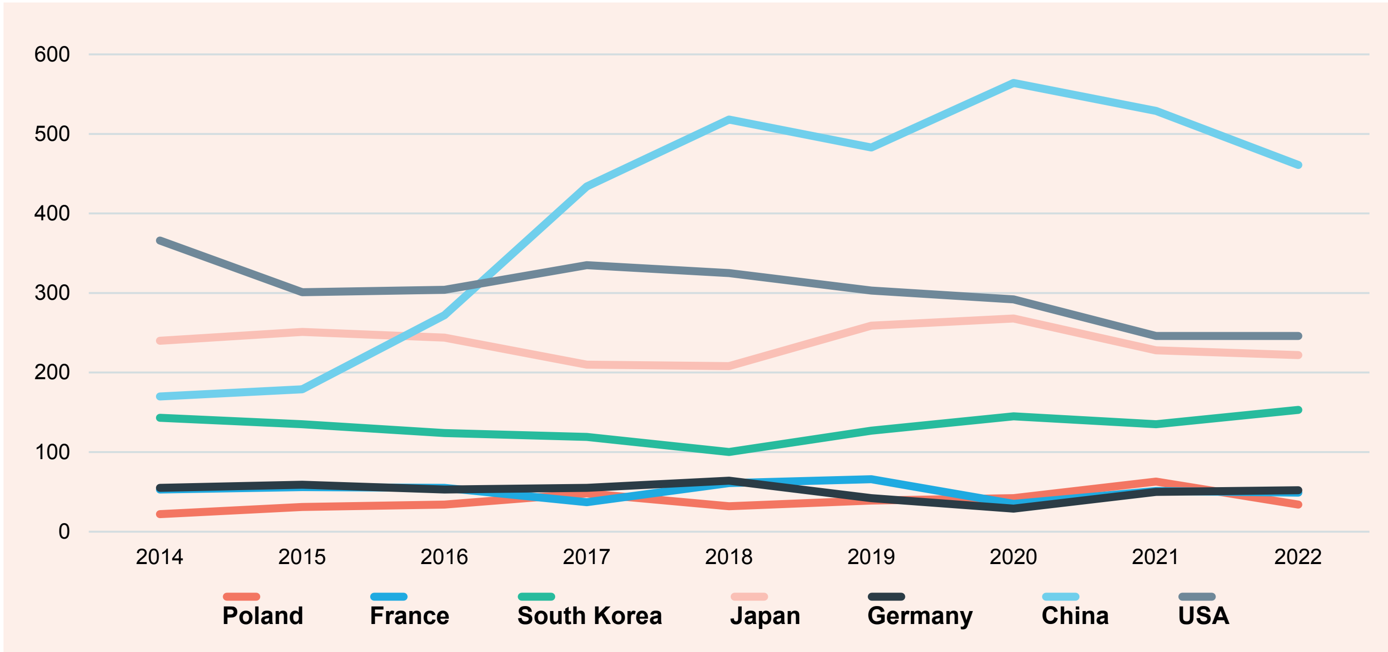


Fig. 3.6 Number of patents per year in the period 2014-2022



carbon nanotechnology, but since 2017 it has been outperformed by China. In the last 10 years, the number of patents in that area significantly increased[I].

Japan and South Korea are also among the world leaders, while in Europe France and Germany play a key role. Poland's position is high, but it is clearly behind these countries in terms of the number of patents in this field, registering an average of 30-40 patents per year. It should be noted that the number of patents in Europe is significantly lower than in Asia, which corresponds to the economic statistics referred to earlier.

According to a report prepared by StatNano , Poland is the 21st country in the world in terms of the number of nanotechnology publications in 2023. In Europe, it takes the seventh place – behind Germany, the United Kingdom, France, Spain, Italy and Russia. The number of publications is strongly related to the level of technology development in the country.

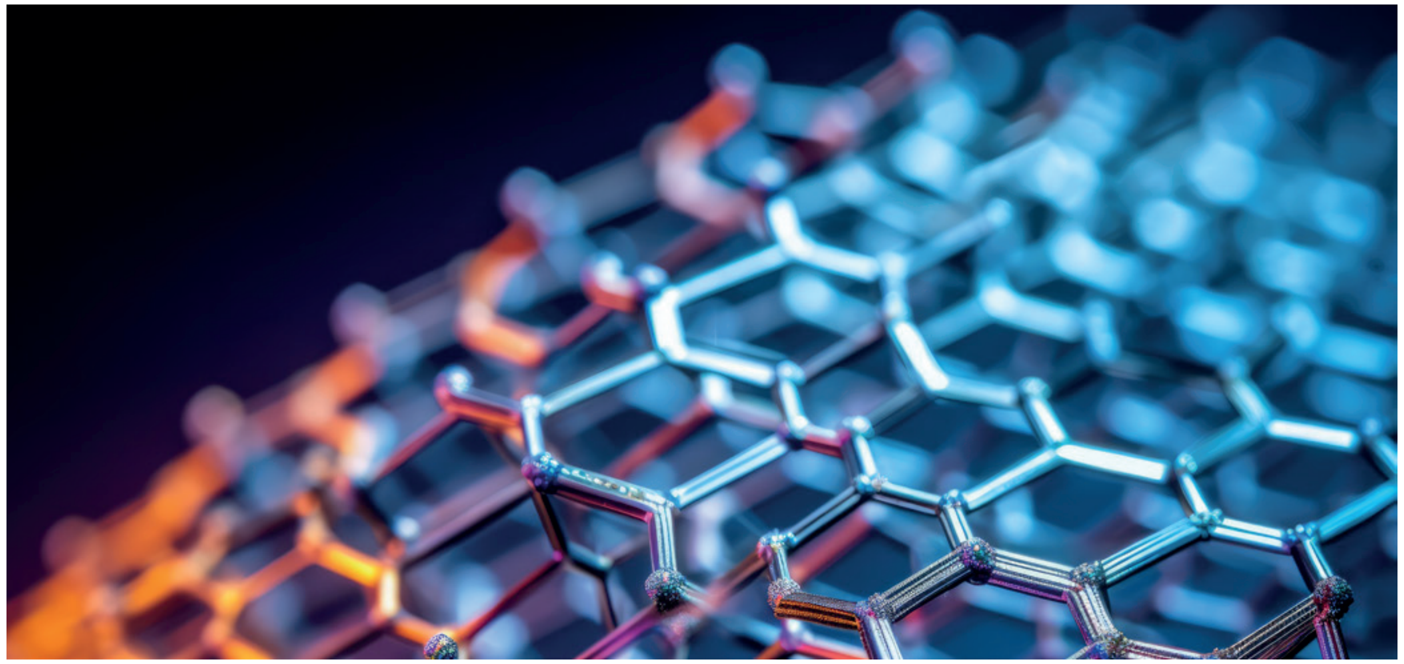
The reference database for monitoring the number of Polish publications covering a particular topic is the Polish Scientific Bibliography. Considering the keyword "graphene", in 2023, the leader in terms of the number of publications until September was the University of Warsaw (Faculty of Chemistry) and the National Academy of Sciences (however, in the case of the Polish Academy of Sciences articles were published by different institutes – the Institute of Catalysis and Surface Chemistry, the Institute of Physical Chemistry, the Centre for Polymer and Carbon Materials of the Polish Academy of Sciences, the Institute of High Pressure Physics).

Many Polish universities are involved in the development of carbon nanotechnologies (in particular graphene). One of them is the University of Lodz – in 2022, it was the main organizer of the conference "Graphene and other two-dimensional materials". The conference was co-organized by the Faculty of Physics at the University of Warsaw. The previous editions were organized by: University of Wrocław and the West Pomeranian University of Technology in Szczecin. Major centers that conduct research on graphene are the Warsaw University of Technology with its Graphene Laboratory and the Lodz University of Technology.

In addition to universities, the scientific institutes of the Polish Academy of Sciences and the Łukasiewicz Research Network also conduct active research.

I. Ibidem

APPLICATIONS OF CARBON TECHNOLOGIES



Nanotechnology has shown remarkable progress in the past decade, resulting in a wide range of applications in various sectors of the economy. Our understanding and knowledge of the properties of carbon allotropes has been improving, which translates into more effective use of their physical and chemical properties, which include conductivity, electrical activity, durability, stretchability and many others. What are the specific applications of nanomaterials?

Most of all, carbon materials are used in the electronics and sensors industry (production of high-performance electronic systems, sensors for gas detection), aerospace industry (production of lightweight and durable structures), automotive industry (anti-corrosion coatings, reinforced structures), energy industry in energy production and storage (photovoltaic cells, batteries), medicine (drug delivery, targeted therapies, diagnostics), environmental protection (treatment of water and air), incremental technologies and functional materials (printed electronics, production of materials with specific properties).

Interesting applications of carbon technologies

Graphene concrete – already in ancient times people realized that adding various ingredients to bricks, e.g. straw, increased their strength and thermal performance. Using straw (de facto cellulose, which consists of the elements carbon, hydrogen and oxygen), the builders of the time used the first "carbon fibers". They gained this knowledge empirically, experimenting with the materials available at the time. They did not suspect that a few thousand years later their technology would be used again in modern and environmentally sustainable construction[I].

A joint venture between graphene specialists at the University of Manchester and alumni-led construction firm Nationwide Engineering has developed a product that could revolutionize the concrete industry and its impact on the environment.

I. DNA samples from an ancient brick | Science in Poland

In a world-first for the sector, the team has laid the floor slab of a new gym in Amesbury, Wiltshire with graphene-enhanced concrete, removing 30% of material and all steel reinforcement, which generated approximately 20% of savings in raw materials used[I].

Global concrete production causes approximately 8% of global CO_2 emissions. If they were compared to emissions generated by individual countries, "concrete would be the third largest carbon dioxide emitter in the world", surpassed only by China and the US[II].

Adding small amounts of graphene strengthens concrete by about 30%, which means that to achieve equivalent structural characteristics significantly less concrete is required. According to scientists, the introduction of the new concrete worldwide could reduce global CO_2 emissions by about 2%.

The **Boeing 787** makes greater use of composite materials in its structure than any previous Boeing commercial airplane. Boeing engineers specified the optimum materials for specific applications. The result is an airframe comprising nearly half carbon fiber reinforced plastic and other composites. This approach ensured weight savings by approximately 20% compared to conventional aluminum designs. In addition, experience with the previous model (Boeing 777) proves that composite structures require less scheduled maintenance than non-composite structures[III].

Airbus A350 – the French aircraft manufacturer used composite materials for the first time in its A300's vertical stabilizer more than 50 years ago. In today's A350 XWB more than half of the aircraft's structure is composite. An example of application of a composite material is carbon-fiber reinforced plastic (CFRP), in which microscopic carbon fibers are locked into place with resin. Most of the wing (including its upper and lower covers) is comprised of the lightweight carbon composites. Measuring 32 meters long by six meters wide, these are among the largest single aviation parts ever made from carbon fiber[IV].

Source: https://www. wbgroup.pl/produkt/bezzalogowy-system-powietrzny-klasy-taktycznej-flysar/

FlySAR – based on Polish technology, it is a tactical, unmanned aerial system featuring simple logistics and operation. It is designed to carry large and heavy operating payload and sensors[V]. Its light structure made of carbon fiber enabled achieving relatively low mass, with high resistance to in-flight G-loads.

I. https://www.manchester.ac.uk/discover/news/greener-and-cheaper-graphenemanchester-solves-concretes-big-problem/
II. https://www.theguardian.com/cities/2019/feb/25/concrete-the-most-destructive-material-on-earth
III. https://www.boeing.com/commercial/aeromagazine/articles/qtr_4_06/article_04_2.html
IV. https://www.airbus.com/en/newsroom/news/2017-08-composites-airbus-continues-to-shape-the-future
V. https://www.wbgroup.pl/produkt/bezzalogowy-system-powietrzny-klasy-taktycznej-flysar/

Unmanned technologies have been developed for many years and the number of their applications is expected to continue to grow, not only in the military industry, but also civilian. Weight is a key parameter affecting flight time and range. The use of lightweight carbon nanomaterials or composites will be an obvious choice for designers.

Carbon nanomaterials are used for storage and transport of hydrogen. Due to the large surface area of the structure, they can serve as a carrier, which contributes to increased storage capacity and efficiency. In addition, they can be used as catalysts in hydrogen-related reactions such as water electrolysis and reduction reactions.

Source: https://3dprinting.com/wp-content/uploads/ image3-67.png

Type V hydrogen tanks – Infinite Composites (Oklahoma, US) supplies tanks sized 5 to 325 liters for use in, among other areas, spacecraft, aviation and ground transportation. The company has tanks certified for space systems and is conducting further work to develop Type V tanks. It primarily uses carbon fiber reinforcements, e.g. Japanese Toray T800 and T1100 fibers[I].

In the field of water, carbon nanomaterials have applications in treatment and disinfection processes. Thanks to their large surface area, they can effectively absorb and remove contaminants, such as heavy metals, pesticides and organic compounds. In addition, their antibacterial properties can be used to disinfect water, eliminate bacteria and pathogens.

Treatment of water from chemical contaminants – dyes are a very numerous and diverse group of compounds that are produced in quantities reaching millions of tons per year. Dye-contaminated water can be treated using new nanoporous carbon materials (NPCs) derived from various polymer precursors. Research results are very promising, as these materials have large surface areas, often up to 1000 m^2/g, and in some cases even 2000 m^2/g[II].

Supercapacitors – they have sometimes been heralded as replacements for lithium-ion batteries. They offer a variety of compelling advantages, including increased safety, faster charging/discharging, and longer lifetimes. Traditional batteries have a high energy density but low power density (slower energy discharge), making them suitable for long-term applications. Supercapacitors have a lower energy density but a higher power density (faster energy discharge). As a result, they cannot store as much energy as batteries but can be charged and discharged much faster. This property makes them more suitable for applications in which quick bursts of energy are needed and where they can be readily recharged, e.g. as complementary energy storage devices, particularly in the transportation sector[III].

Polish graphene in water treatment technology – scientists from the Institute of Materials Science and Engineering at the Lodz University of Technology have developed an innovative technology for obtaining graphene electrodes for water treatment. Composite electrodes made from carbon fibers coated with cross-linked, reduced graphene oxide exhibit high resistance to degradation associated with gas evolution at the cathode and anode, as well as high chemical and electrochemical stability over a wide pH range and resistance to oxidation. They are characterized by low resistance, fast sorption and desorption of ions, as well as low susceptibility to organic contamination. Moreover, the use of carbon fiber preimpregnates as a support substrate provides greater durability and gives the possibility to form and retain the formed shapes of the electrodes by epoxy resin polymerization without the need for additional molds[IV].

I. https://www.compositesworld.com/articles/infinite-composites-type-v-tanks-for-space-hydrogen-automotive-and-more
II. Ochrona Środowiska (2017, No. 2), Marzena Czubaszek, Jerzy Choma: Adsorpcja wybranych barwników z roztworów wodnych na nanoporowatych materiałach węglowych otrzymanych z prekursorów polimerowych (Adsorption of selected dyes from aqueous solutions on nanoporous carbon materials obtained from polymeric precursors)
III. https://www.cas.org/resources/cas-insights/sustainability/supercapacitor-technologies-graphene-finally-living-its-full
IV. https://p.lodz.pl/uczelnia/aktualnosci/grafen-z-pl-w-technologii-uzdatniania-wody

IS THE CARBON STRATEGY NECESSARY?

Technological advancement depends heavily on rare earth elements (REE), which are beginning to be referred to as strategic raw materials. The market for these materials represents a small percentage in terms of production, but its role is vital due to the use of REEs, inter alia, in electronics, energy transition processes and defense.

The uneven distribution of these elements on Earth can cause their limited availability during times of political tension. It becomes necessary to look for alternative solutions that would make technological progress less dependent on geopolitics. Carbon and carbon-based materials can be produced locally and their properties are often better than that of rare earth elements.

Poland is an important European market and the largest market in the CEE region, as a result of which it has the potential to become a key player in the development of carbon technology. However, it is necessary to develop a strategy that takes into account the scientific and research potential of Polish research centers and improves the commercialization of new discoveries.

Developing a strategy for carbon will help identify the most promising development directions, those that have the potential to build Poland's competitive advantage in the region and globally. Such a strategy should set specific goals and indicators that will enable effective development of carbon materials.

It should take into account the current trends related to energy transition, energy security, and sustainable development as well as the EU's goals in this regard.

An important area covered by the strategy should be the support for research and development and innovation activities. It is necessary to define financial support programs and non-financial forms of support for projects developing carbon technologies. It is important to focus on projects with high implementation readiness and strong potential for market commercialization. This includes promoting the establishment and development of startups and spin-offs that can accelerate the innovation process in the sector.

One of the goals of the strategy must be enhancing the competitiveness of Polish technological solutions in the international arena. This could involve the promotion of Polish achievements, international cooperation, e.g. through participation in international research projects. The carbon strategy should be consistent with the principles of sustainable development and emphasize its importance, which entails ensuring the balance between economic development and environmental protection.

Implementation of such a strategy can contribute to the transformation of Poland's coal sector and be beneficial to both the economy and the environment.

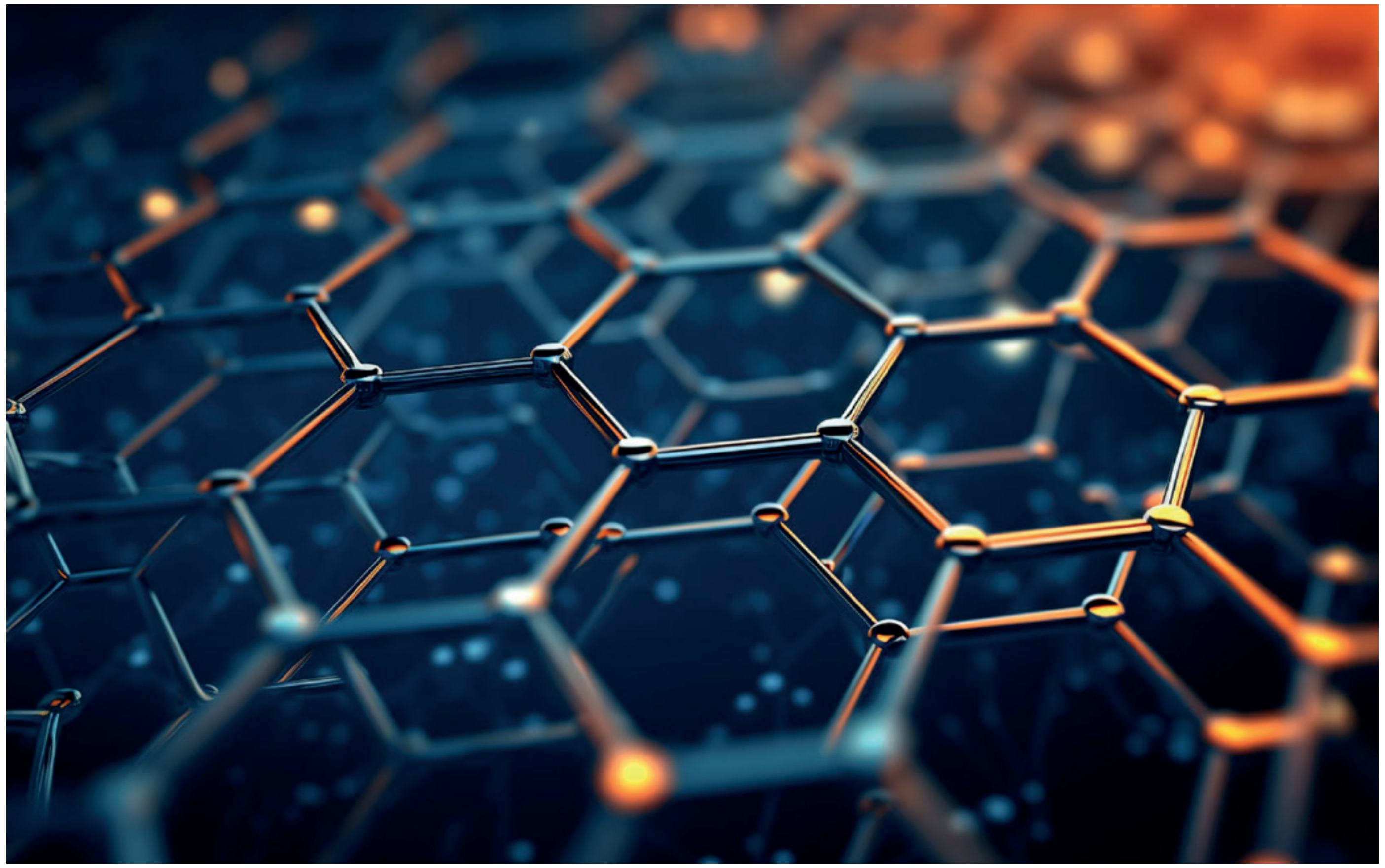
OUTLOOK ON THE FUTURE

New discoveries encourage the worlds of science and business to commit their resources to thoroughly examine the new knowledge and assess its potential implications, e.g. for further research and commercial applications. The process is tedious, but at some point there is a breakthrough and the effect of the discovery brings to life new products, technologies and innovations. An example are computer technologies, which just 50 years ago were only available to research centers, but have since been commercialized and are present in our everyday lives.

Nanotechnology is an emerging science whose rapid and strong growth in the future is expected. It is anticipated that in the coming decades it will make a significant contribution to economic growth and creation of new jobs in the EU[I].

Unquestionably, carbon nanotechnologies, due to the variety of properties of the different carbon allotropes, will be a key element in the progress of nanotechnology. The available medical procedures will become much more effective, new therapies will be developed to effectively treat diseases currently incurable. New graphene-coated medical devices will be used, exhibiting antibacterial properties, and graphene will also be used in the production of surgical implants[II].

We can expect more intensive use of carbon nanotechnologies in construction. Not only to reduce the weight of structures, but also to increase strength, tensile strength and durability. Long bridges are already being designed that will be suspended on cables made of carbon nanotubes (CNTs). In turn, a Japanese company Obayashi Corporation plans to build by 2050 a space elevator climbing 36,000 km above the Earth's



I. European Union Observatory for Nanomaterials: https://euon.echa.europa.eu/pl/the-future-of-nanotechnology
II. Technavio: Graphene Market by Product, End-user, and Geography – Forecast and Analysis 2023-2027

surface[I], that will be operated with the use of a carbon nanotube cable.

Electronics will be the main beneficiary of development of nanocarbon technologies. Graphene will replace silicon, which will lead to further miniaturization, development of faster processors, and reduction of energy consumption in electronic devices etc.[II]

The high surface area, electrical conductivity and mechanical strength of graphene will lead to the development of more efficient energy storage devices. It will become possible to produce supercapacitors and high-density batteries that will enable fast charging and longer battery life and will transform the energy storage industry.

Graphene's sensitivity to external stimuli makes it suitable for use in sensory solutions such as environmental monitoring and biomedical diagnostics, offering the ability to detect subtle environmental changes with exceptional precision and sensitivity.

Environmental applications will undoubtedly be the next major challenge, which carbon nanomaterials will certainly meet. Graphene is already being successfully used in water pollution sensors and water treatment processes (e.g. filters). In the future, there will be more efficient and commonly available solutions for testing and treatment of water whenever and wherever it is needed[III].

The space industry will use graphene to build satellites, spacecraft components (including propulsion systems), radiation shielding and in life support systems in space and more[IV].

In the coming decades, we are certainly facing a revolution in the area of nanomaterials, in which carbon allotropes will play an important role. We cannot yet imagine how much this will change our lives. It will certainly have a positive impact on the environment and will help, among other things, accelerate the global energy transition and improve the quality of life for people facing serious health issues.

But before that can happen, scientists need to solve problems related to the efficiency and cost-effectiveness of producing graphene and other carbon allotropes. In turn, manufacturers are confronted with serious challenges related primarily to ensuring high quality material on a large scale, low cost and a guaranteed repeatable supply.

I. https://www.obayashi.co.jp/en/news/detail/the_space_elevator_construction_concept.html
II. https://www.fierceelectronics.com/electronics/beyond-silicon-exploring-new-materials-future-electronics
III. https://graphene-flagship.eu/materials/sustainability/
IV. https://www.siliconrepublic.com/machines/uses-of-graphene-space-wearables

CONCLUSIONS AND RECOMMENDATIONS

The observed statistics and trends confirm that the World has recognized the potential of carbon technologies. Bold growth projections and ambitious research and business ventures are clear evidence of this. The increased research activity in major economies guarantees good prospects for applications of allotropes of carbon.

Carbon is becoming a more common subject of debate despite the fact that carbon technologies development has started only a few decades ago. It is clear that a young market faces multiple constraints, such as the high unit costs of production resulting from its low scale and the still imperfect technologies for producing individual carbon allotropes. However, it is already evident that the market growth rate will be overwhelming and we can already observe its beginning.

Collaborative in innovation ecosystem – cooperation between stakeholders at the international level enables the exchange of expertise and best practices. This facilitates faster technological progress and increasing the potential of technology application in the industry.

Thanks to its versatility, carbon is becoming not only important, but also instrumental in ensuring a better future. Poland excels in the region in conducting research on the development work related to carbon materials and their applications and can build a significant competitive edge not only in Europe, but also globally.

Carbon undoubtedly has enormous research and economic potential and capturing this opportunity properly will be of great importance for the quality and length of life in the future, for accelerating the processes of transformation in the energy and automotive sectors, and for facilitating space exploration.

It is necessary to properly define the key challenges and create a system framework to address them. Carbon nanotechnologies should become an important part of the national research agenda, which should be confirmed by appropriate support programs and, above all, the creation of a strategy for carbon.

Public education and awareness are equally important. Public entities should take up this challenge and promote the use of carbon technologies in everyday life, advocate for inventions developed in Polish research organizations and by enterprises by implementing education and information campaigns.

Businesses conducting research and development activities in the area of carbon technology and materials should make greater use of existing or create new networks of cooperation to exchange expertise and experience, jointly seek solutions to challenges encountered, and integrate the environment.

Despite numerous incentives for cooperation between enterprises and research organizations in the form of dedicated publicly funded support programs or additional points during project assessment for enterprises cooperating with research organizations, the level and scope of such cooperation is still insufficient. Additional mechanisms for cooperation and know-how transfer should be developed. An example of an instrument fostering cooperation is the initiative of the Łukasiewicz Research Network – "Łukasiewicz Challenges", in which free support is offered in the form of ideas and expert recommendations for technological problems submitted by businesses.

Research should give more consideration to the application aspect of projects. Already at the early stages of research, potential practical applications in the economy should be defined clearly and be one of the main goals of research projects.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