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ЗМІСТ

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PROSPECTS FOR THE DEVELOPMENT OF HYDROGEN ENERGY: INNOVATIVE TECHNOLOGIES AS THE KEY TO REDUCING THE PRICE OF "GREEN" HYDROGEN

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The article considers the prospects for the development of hydrogen energy, in particular, the application of hydrogen production technology based on water splitting using the latest electrolysis technologies. Particular attention is paid to the innovative methodology proposed by the Israeli company H2Pro, which promises a significant reduction in the cost of "green" hydrogen by 2030 to the level of less than $1 per kilogram. This reduction in hydrogen prices by 60-80% will make it more competitive in the energy market, which can lead to widespread adoption of hydrogen technologies in various sectors of the economy.

The technology developed by H2Pro uses the E-TAC (Electrochemical Thermally Activated Chemical Water Splitting) method, which consists of a two-step process for the production of hydrogen and oxygen. The first stage involves cold electrochemical splitting of water, which generates hydrogen and oxidizes the anode, while the second stage, thermally activated, regenerates the anode by releasing oxygen, without the need for additional electricity consumption. This technology makes it possible to reduce energy costs and increase the efficiency of the process, reaching an efficiency of 95%, which is a significant achievement in the field of hydrogen energy.

The author of the article also draws attention to the importance of this achievement for the global transition to renewable energy sources. In particular, reducing the cost of hydrogen production with the help of such technologies can provide cheaper energy production than traditional energy carriers such as gasoline and diesel, and also become a key factor in the implementation of ambitious environmental initiatives aimed at reducing carbon dioxide emissions.

In addition to technological innovation, the article also discusses the need for infrastructure development for the storage, transportation and use of hydrogen, which remains one of the main barriers to its large-scale use. However, thanks to the efforts of companies such as H2Pro, which are actively working on improving production processes and reducing costs, hydrogen energy has a great chance of becoming an integral part of the energy system of the future.

Thus, the development of hydrogen energy technologies, such as E-TAC, is an important step on the way to ensuring a clean and sustainable energy supply, which will contribute to reducing the environmental impact and ensuring the sustainable development of the world economy in the face of global climate change.

Key words: *hydrogen, hydrogen energy, green hydrogen, electrolysis, E-TAC technology, thermally activated chemical splitting of water, energy efficiency, reducing the cost of hydrogen, environmental technologies, renewable energy sources, hydrogen technologies.*

Fig. 7. Ref. 8.

1. Problem formulation

Recent decades have been characterized by global changes in the energy sector, which are due to the need to solve two key challenges: reducing environmental pollution and finding alternatives to traditional fossil energy resources. In this context, electric and fuel cell vehicles have become one of the main contenders for the role of environmentally safe transport of the future. Despite the popularity of electric vehicles, vehicles based on hydrogen technology remain an important alternative, with both unique advantages and certain challenges. Hydrogen is the most common chemical element in the universe, and its energetic properties have long attracted the attention of scientists and industrialists. Due to its high energy intensity and environmental safety of use, interest in hydrogen technologies has grown significantly in recent decades. Hydrogen can ensure zero carbon dioxide emissions because the only byproduct of its use is water. However, its use requires taking into account not only efficiency, but also the impact on materials, in particular, hydrogen resistance.

Modern energy is trying to find a balance between environmental friendliness, efficiency and economic expediency. Although electric vehicles are now widely used, their technological limitations, such as charging time and energy density of batteries , leave room for the development of alternatives. Hydrogen cars can cover longer distances, refuel faster and provide greater mobility compared to many electric cars. At the same time, their widespread implementation requires the creation of a developed infrastructure for the production, storage and transportation of hydrogen [1].

It is important to note that neither hydrogen nor electric cars are independent sources of energy. Their environmental friendliness depends on the source of primary energy, which is used to produce hydrogen or charge batteries . Thus, the transition to mass use of these technologies requires integration with renewable energy sources such as solar or wind farms. Particularly promising is the use of hydrogen as a means of energy storage, which allows smoothing out irregularities in the production of energy from renewable sources.

This introductory overview highlights the key aspects of using hydrogen as an alternative fuel, as well as its advantages and disadvantages compared to electric vehicles. The future of the automotive industry is likely to be based on the symbiosis of these technologies, which together create conditions for more environmentally responsible transport.

The use of hydrogen as an energy source is one of the promising technologies in the modern energy and transport industry. However, for the introduction of hydrogen technologies into widespread use, it is necessary to solve a number of technical, economic and environmental problems related to the production, storage, transportation and application of hydrogen. One of the key advantages of hydrogen is its high energy density per unit weight. In particular, hydrogen has an energy index of 143 MJ/kg, which is more than three times higher than the similar index for gasoline (47 MJ/kg). Hydrogen also outperforms modern electric batteries in this respect, providing twice as much energy for the same weight. However, the main challenges arise in the storage and transportation of this chemical element. The most effective form for such purposes is liquid hydrogen, however, its liquefaction is possible only at extremely low temperatures (-253°C), which requires the creation of a specialized infrastructure that requires significant capital investments [1, 2].

The economic aspect also remains a key obstacle for the mass application of hydrogen. Current technologies for the production and storage of hydrogen are extremely expensive, and market parity with traditional fossil fuels can only be achieved if the cost of hydrogen is reduced by a factor of about five. The Japanese experience shows the need for government support, significant investment and infrastructure development to stimulate the transition to hydrogen fuel. Despite the high costs, Japanese government programs show the possibility of gradually increasing the availability of hydrogen through infrastructure development, subsidizing hydrogen fuel cell transportation and expanding the network of filling stations.

In addition, the issue of environmental cleanliness of hydrogen production remains relevant. Existing technologies for the production of "black" and "gray" hydrogen are accompanied by significant emissions of carbon dioxide, which contradicts the idea of environmental friendliness of this fuel. Although "blue" hydrogen involves partial carbon capture , only "green" hydrogen produced using renewable energy sources can be considered truly sustainable. However, the share of "green" hydrogen is currently only 0.1% of the total production, which requires a significant reduction in the costs of renewable energy sources and the development of electrolysis technologies.

Other technical aspects, such as the effect of hydrogen on materials used for storage and transportation, also require detailed study. The ability of hydrogen to penetrate the structure of materials and affect their strength is a serious problem for the development of hydrogen systems.

Thus, in order to realize the potential of hydrogen, it is necessary to solve a number of complex issues related to production, storage, transportation, environmental friendliness and economic feasibility. These challenges become the object of research by scientists and specialists in various fields, including Ukrainian scientists who are actively studying hydrogen technologies and their impact on materials. Integrating hydrogen into the global energy system and transport infrastructures requires a multi-level approach that combines innovative technologies, government support and international cooperation.

2. Analysis of recent research and publications

The modern development of the transport industry is aimed at finding alternative types of fuel that contribute to reducing the ecological burden on the environment. One of the promising directions is the introduction of hydrogen as the main energy resource for cars. In developed countries, technologies are being actively developed to ensure the efficiency and availability of hydrogen cars, and the corresponding infrastructure for their maintenance is also being created.

The latest research suggests the division of hydrogen cars into three main classes, each of which is characterized by its technical features and level of environmental friendliness.

Cars with an internal combustion engine running on hydrogen or hydrogen mixtures.

This type of car combines a traditional design with the use of hydrogen as a fuel. The advantage is an increase in the efficiency of the engine and a significant reduction in the level of harmful emissions: carbon monoxide (CO), hydrocarbons (CHx) and nitrogen oxides (NOx). This technology was tested back in the 1970s and 1980s, but due to its high complexity and costs, it is only a transitional stage to more advanced solutions [3].

Hybrid cars with an electric drive and a hydrogen engine.

This type involves the use of an electric drive that receives energy from a battery. The battery is charged by an internal combustion engine running on a hydrogen mixture. Thanks to the high efficiency of electric motors (90-95% efficiency), the overall efficiency of the vehicle increases significantly, and fuel consumption and emissions are significantly reduced. Such cars allow meeting the highest environmental standards, including Euro-4. Hybrid technologies are being actively implemented by leading manufacturers such as Mercedes-Benz .

Real hydrogen cars with fuel cells.

The most modern class of cars is based on the use of fuel cells to generate energy from hydrogen. The fuel cell converts the chemical energy of hydrogen directly into electrical energy, which powers the electric motor. The efficiency of fuel cells reaches 75–85%, which is more than twice that of the best internal combustion engines. In urban conditions, such cars can provide up to a five- to six-fold advantage in terms of efficiency compared to gasoline or diesel cars. This opens up new opportunities for reducing dependence on fossil fuels.

Despite significant advances in the development of hydrogen cars, studies show that the mass adoption of this technology requires significant investment in infrastructure development, including refueling stations and hydrogen storage facilities. In addition, hydrogen storage and ensuring its safe transport remain important technical challenges. The use of low-temperature technologies and the adaptation of hydrogen systems to existing standards are the object of active scientific research [4] .

Thus, recent research confirms that hydrogen cars have significant potential to transform the transportation industry, but require improvements in hydrogen production, storage, and use technologies. This opens up prospects for further scientific developments and the introduction of innovations in the field of sustainable transport.

3. The purpose of the article

The purpose of the research is a comprehensive analysis of the possibilities of using hydrogen as an alternative energy source, studying its impact on the properties of materials during storage and transportation, as well as substantiating the prospects for the introduction of hydrogen technologies in the transport and energy sectors. This involves the development of approaches to overcome the technical, economic and environmental challenges associated with the production, storage and use of hydrogen in order to ensure its widespread use as an environmentally clean, efficient and affordable energy source.

4. Results of the researches

Modern hydrogen production technologies show significant progress, but remain far from perfect, which prevents its widespread adoption as an alternative energy source. About 500 billion m³ of hydrogen is produced annually in the world, half of which is used for the production of ammonium fertilizers, and the rest - in the production of steel, glass, margarine and other products.

The main methods of obtaining hydrogen.

The most common and relatively cheap method is methane steam reforming. At a temperature of 900°C, in the presence of a nickel catalyst, methane reacts with water vapor, forming hydrogen. This technology remains the main one due to its efficiency and relative economy , but it is accompanied by significant emissions of CO_2, which reduces its environmental friendliness.

A promising method is the processing of biomass, which can be heated to 500–600°C to obtain alcohols (methanol, ethanol), which are further converted into hydrogen. At a temperature of 1000°C, biomass is completely gasified, forming a mixture of H_2 and CO. Although this method has environmental advantages, it requires large volumes of raw materials. In particular, according to calculations, even using the entire fertile territory of France to grow biomass would not cover the country's needs for hydrogen fuel.

Electrolysis is one of the simplest methods of hydrogen production. In the process of electric splitting of water, hydrogen and oxygen are formed. However, the efficiency of this method still remains low: to obtain 1 m³ of hydrogen, it is necessary to spend 4 kWh of electric energy , which provides only 1.8 kW of energy during hydrogen combustion. Improvement of electrolysis is possible by carrying out the process at elevated temperatures or pressure, as well as due to the use of renewable energy sources or excess energy of nuclear power plants in periods of low load [5] .

An innovative direction is the production of hydrogen using biological processes. Some types of algae and bacteria can decompose water during photosynthesis, releasing hydrogen. The problem is that this process occurs only in the absence of oxygen, which significantly limits its duration. Research by the University of California in Berkeley showed that under conditions of lack of sulfur and oxygen, algae actively produce hydrogen. The use of green algae such as Chlamydomonas is promising reinhardtii , which are able to obtain hydrogen from seawater or sewage.

Hydrogen has been successfully used in industry for many years (Fig. 1), and the estimated value of the hydrogen raw material market is about $115 billion and, according to forecasts, will reach $155 billion by 2022. Its applications cover a wide range of industries, including energy , chemical production, metallurgy and transport.

Despite technological progress, hydrogen technologies need further development to ensure their economy, efficiency and environmental safety. This includes the optimization of production processes, the development of new methods of obtaining and the development of infrastructures for the storage and transportation of hydrogen.

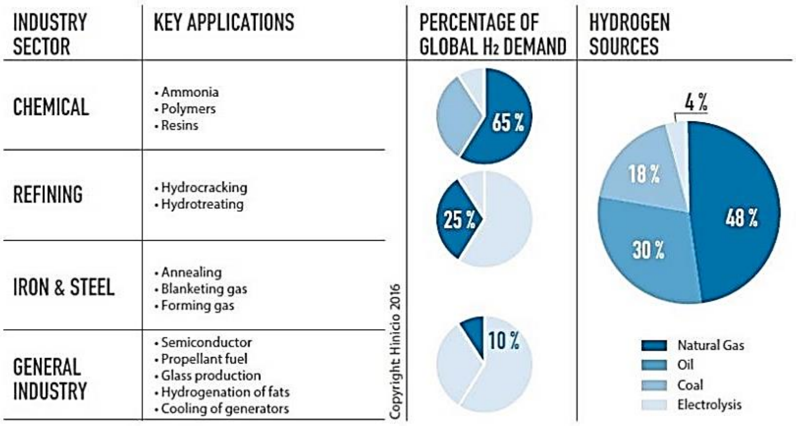

Fig. 1. World demand and sources of hydrogen production. Hydrogen from renewable power.

Low gas prices in the Middle East and North America provide some of the lowest costs for hydrogen production. Gas importers, especially South Korea, Japan, China and India, are forced to compete with rising prices for gas imports, which leads to an increase in hydrogen production costs (Fig. 2).

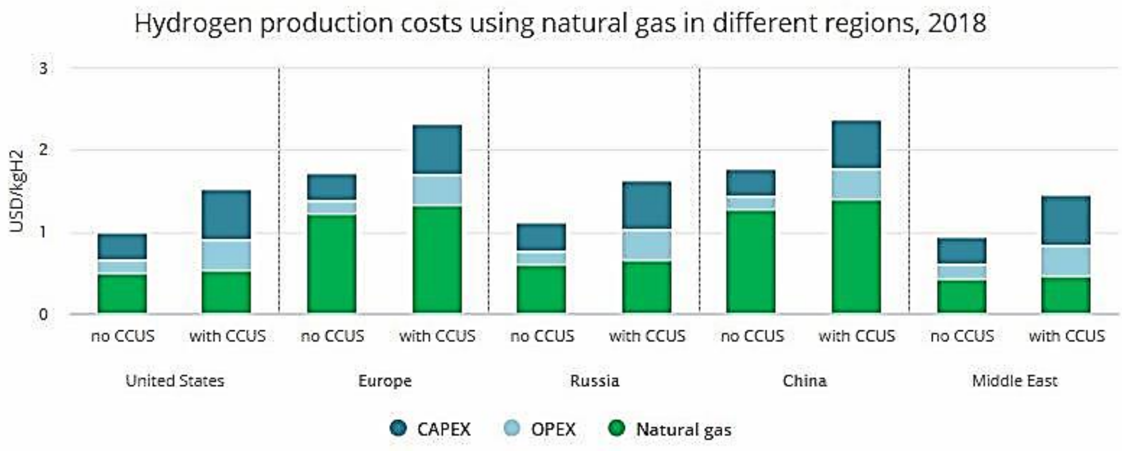

Fig. 2. Costs of hydrogen production using natural gas in different regions.

The modern chemical industry offers several thermochemical methods for obtaining hydrogen, which are based on the transformation of organic or fossil materials under the influence of high temperatures and pressures. The main ones include:

Steam reforming of methane - This method involves the use of natural gas, the main component of which is methane. During steam conversion, methane interacts with water vapor under a pressure of 3–25 bar in the presence of a catalyst. As a result, hydrogen, carbon monoxide and a small amount of carbon dioxide are formed. The method is widely used due to the relatively low cost of raw materials and well-established technologies.

Coal gasification is used to produce hydrogen by reacting coal with oxygen and steam at high temperatures and pressures. This process generates a mixture of carbon monoxide and hydrogen, which can be separated to release pure hydrogen. This method also allows obtaining other valuable products, such as liquid fuel, chemicals and electricity [6].

Biomass gasification - In this method, organic or fossil carbonaceous materials are heated to temperatures above 700°C under controlled conditions (limited oxygen or steam). As a result, carbon monoxide, carbon dioxide and hydrogen are formed. Biomass gasification is promising for sustainable hydrogen production, but requires large volumes of biological raw materials.

Solar thermochemical hydrogen - This technology is based on the use of high temperatures obtained from concentrated solar energy or excess heat from nuclear reactions. High temperatures ensure the splitting of water into hydrogen and oxygen through chemical reactions.

Liquids obtained from biomass (for example, bio-oil , ethanol) can be converted into hydrogen by analogy with the reforming of natural gas. This opens up possibilities for the use of biological resources in the production of hydrogen.

Electrolysis of water is one of the simplest and most affordable methods of obtaining hydrogen. In the process of electrolysis, water is split into hydrogen and oxygen under the influence of an electric current. The main types of electrolyzers include:

Alkaline electrolyzers - Use an alkaline solution to reduce electrical resistance, which increases the efficiency of the process.

Polymer membrane electrolyzers - Based on polymer electrolytes that provide high performance and reliability.

Solid oxide electrolyzers - Work at high temperatures, which increases efficiency, but requires special materials.

Electrolysis also makes it possible to obtain oxygen as a valuable by-product, which increases the economic feasibility of the method.

One of the most promising areas is the technology of artificial photosynthesis, where sunlight is used to split water into hydrogen and oxygen. In Japan, a hybrid system has been created that combines photovoltaic elements and water splitting processes. This approach allows efficient use of solar energy, reducing dependence on traditional energy sources.

Thus, the variety of methods for obtaining hydrogen creates a wide range of technologies for its production, storage and use. The choice of the optimal method depends on the availability of resources, environmental requirements and economic factors.

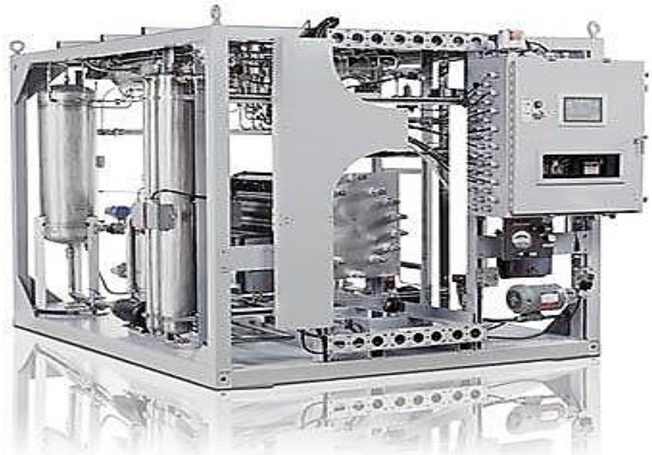

Fig. 3. Industrial hydrogen generator

The development of direct solar water splitting technologies is a promising direction in the field of hydrogen production. These processes are based on the use of solar energy to dissociate water molecules into oxygen and hydrogen, which ensures ecological purity of production and reduces or completely eliminates greenhouse gas emissions. One of the most innovative approaches is photolysis, which allows the use of solar energy to directly split water.

Photolysis can be implemented using biological or chemical methods. In the photobiological approach, microorganisms, particularly bacteria and algae, use sunlight for natural biochemical reactions that produce hydrogen. These organisms have the ability to process biomass or organic matter, releasing hydrogen as a byproduct. However, such processes are currently limited in duration and productivity, as they stop in the presence of oxygen, which is formed during water splitting [7].

Another approach to photolysis involves the use of photoelectrochemical materials. These specialized semiconductors are used to absorb sunlight and transfer the received energy to water molecules, which leads to their dissociation. This approach is characterized by a high potential for reducing greenhouse gas emissions and gradual introduction into industrial processes. Although these technologies are still in the early stages of development, researchers are working to improve their efficiency and reduce costs.

At the same time, there is growing interest in the world to create "hydrogen houses" that can simultaneously reduce carbon dioxide emissions and use it to produce hydrogen through artificial photosynthesis. The basis of such systems is solar energy, which provides chemical reactions. The hydrogen produced in the process can be used as a fuel to meet the energy needs of these homes. This approach contributes to the ecological integration of hydrogen technologies into everyday life, as well as to the expansion of their use in the future.

Japanese researchers from the National Institute of Materials Science, the University of Tokyo, and the University of Hiroshima have conducted a joint feasibility study of hydrogen production using photovoltaic energy and a battery-powered electrolyzer. The purpose of this study was to determine the efficiency and economic feasibility of using solar energy to produce hydrogen.

The analysis results showed that the cost of hydrogen production can range from 17 to 27 yen per cubic meter (0.16 to 0.25 dollars) (Fig. 4). These indicators give reason to consider hydrogen technologies quite promising, especially in conditions of growing demand for environmentally friendly energy. The developed integrated system is able to dynamically adapt to changes in the amount of solar energy produced, regulating the amount of battery discharge and charge , as well as the amount of hydrogen produced by electrolysis.

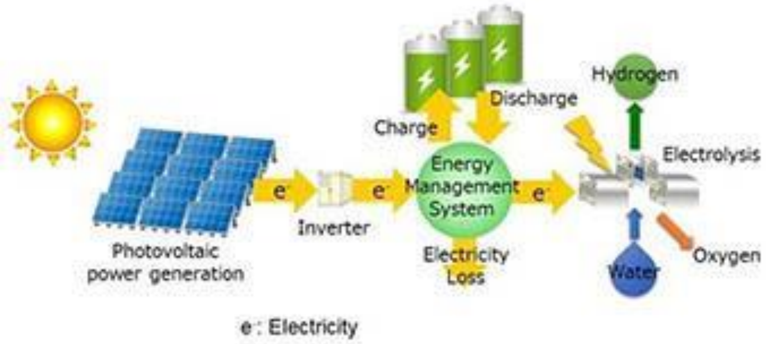

Fig. 4. The system is able to regulate the amount of charge/discharge of the battery and the amount of hydrogen produced by electrolysis depending on the amount of solar energy produced

The researchers also assessed the economic feasibility of such a system, taking into account different usage scenarios. The results of the study demonstrate the potential for the commercialization of these technologies, especially in countries with developed infrastructure for the use of renewable energy sources. Integrated systems combining photovoltaic panels, electrolyzers and batteries can play a key role in ensuring sustainable hydrogen production and reducing dependence on fossil fuels.

As the cost of producing renewable electricity, especially from solar photovoltaic panels and wind turbines, has fallen, interest in the production of hydrogen by electrolysis has increased significantly. Electrolytic hydrogen is considered one of the most promising technologies capable of providing sustainable energy supply with minimal impact on the environment. In this regard, several demonstration projects were implemented in recent years , which confirmed the feasibility of using hydrogen technologies in combination with renewable energy sources.

However, producing all of today's hydrogen needs with electricity poses significant challenges. To ensure the required volume of hydrogen electrolysis, about 3,600 TWh of electricity is required per year. This value exceeds the annual volume of electricity production in the European Union, which indicates the scale of the task and the need to modernize the energy infrastructure.

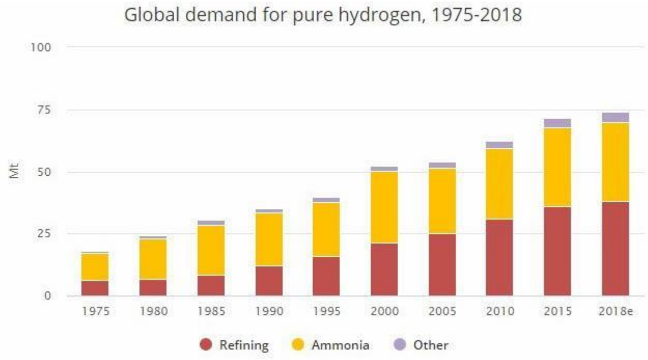

Fig. 5. Demand for hydrogen

Such indicators emphasize the importance of optimizing energy consumption and integrating new technologies into hydrogen production processes. In addition, it contributes to the development of energy policy aimed at increasing the share of renewable sources and creating conditions for an economically efficient transition to hydrogen energy. The successful implementation of such initiatives depends on an interdisciplinary approach that combines scientific research, engineering solutions and management practices [8].

As the costs of wind and solar photovoltaic production decrease, as well as the cost of building electrolyzers decreases, a new opportunity arises for efficient hydrogen supply. This becomes possible even in places where the conditions for the use of renewable energy sources (RES) are the best, but they are far from the final consumers. In such regions, water electrolysis for hydrogen production may be a more cost-effective option compared to other methods, even considering the costs of hydrogen transmission and distribution.

The peculiarity of this approach is that in view of the reduction in the cost of RES technologies, the construction of hydrogen production facilities in regions with high potential for wind or solar energy becomes profitable. This makes it possible to reduce the overall costs of hydrogen, since the production itself is economically profitable, and the costs of transporting hydrogen from distant sources to the final point of consumption are offset by low costs of energy generation. Therefore, even considering the infrastructural costs of hydrogen transportation, this supply option becomes competitive and profitable against the background of growing demands for sustainable energy supply.

Thus, the development and cost reduction of renewable energy sources opens up new opportunities for the use of hydrogen as an energy source, which provides an alternative to traditional energy supply methods.

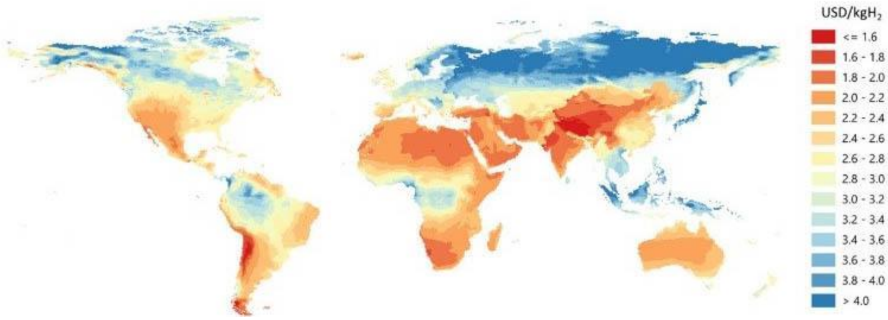

Fig. 6. Hydrogen costs from hybrid solar PV and onshore wind systems in the long run

Hydrogen is already widely used in some industries such as petrochemicals, metallurgy and food, but its potential as an energy resource to support the clean energy transition has not yet been fully realized. In order to overcome the existing barriers and reduce the costs of hydrogen production, targeted, ambitious and short-term actions aimed at the development of new technologies, infrastructure and market mechanisms are necessary.

One of the areas that is gaining popularity is the search for new ways of obtaining hydrogen from organic waste. For example, a known patent describes a method of treating organic materials, such as garbage or sewage sludge, by anaerobic decomposition with subsequent release of hydrogen. In this process, electric potential is used to optimize gas components, in particular, increasing the hydrogen content and reducing the amount of methane compared to the natural process of decomposition of organic materials. The use of this technology makes it possible to reduce energy costs and reduce the time required for waste processing, thereby increasing the efficiency of hydrogen production.

However, a significant problem remains on the way to the spread of hydrogen energy: the lack of proper infrastructure. The oldest hydrogen pipeline in the world, located in the Ruhr area of Germany, is only 50 years old, and the longest hydrogen pipeline in the world is only 400 km. However, many countries already have prepared gas pipelines that can be used to transport the methane -hydrogen mixture. This mixture can be transferred through pipelines, and at the stage of consumption it can be separated into hydrogen and methane, which greatly facilitates infrastructure provision.

At the same time, hydrogen filling stations are already operating in Japan, the USA, China and several European Union countries. Leading European companies such as Air are engaged in the development of hydrogen refueling infrastructure Liquide , H2 Logic , Linde , Hydrogen Link and others. They are actively developing a network of gas stations and working on creating more efficient and cheaper technologies for storing and transporting hydrogen. This contributes to the further growth of the popularity of hydrogen as a fuel for transport and industry, as well as the formation of a hydrogen economy on a global scale.

For the effective implementation of hydrogen energy, it is necessary to focus on investing in infrastructure, developing new technologies for obtaining hydrogen, as well as improving existing market mechanisms to stimulate demand for hydrogen. Only in this case, it is possible to achieve sustainable growth in the use of hydrogen as the main source of clean energy in the future.

In a conservative development scenario, the growth of industrial hydrogen consumption by 2050 is expected from 70 million to 230 million tons per year. At the same time, the share of commercial hydrogen produced using the technologies of hydrogen thermochemical generators (HTGR) will increase from 4 million to 140 million tons per year. This growth will require a significant expansion of the capacity of VTGR reactors for hydrogen production, since to ensure the production of 140 million tons of hydrogen per year by 2050, it is necessary to create power units with VTGR with a total thermal capacity of 400 GW . Such ecologically clean production of hydrogen will be the basis for the transition to a hydrogen economy, which will ensure the reduction of CO2 emissions and the achievement of climate goals.

In parallel with this, companies such as Toyota are actively working on the development of hydrogen technologies and infrastructure. Thus, together with partners, including Toshiba and Iwatani , as well as several Japanese prefectures, Toyota launched a test project to create a local energy system in which hydrogen is the main energy carrier. This system, whose name is " End-to-End Hydrogen Supply Chain ", includes the production of hydrogen, its transportation and direct use in transport and at places of consumption. The task of the project is to demonstrate the environmental and economic advantages of hydrogen fuel, as well as to identify possible technical and logistical difficulties associated with its introduction into wide circulation.

At the first stage of the project, it is planned to use hydrogen forklifts that will run on fuel cells manufactured by Toyota Industries . The hydrogen for these vehicles will be produced at a wind farm in Yokohama using its energy and electrolyzers manufactured by Toshiba . Hydrogen will be delivered to places of consumption by a special hydrogen truck.

Japan's strategy envisages the construction of a "hydrogen society", where hydrogen technologies will be used not only in automobile transport, but also to meet the energy needs of homes, offices and other facilities. In the future, this will make it possible to significantly reduce dependence on traditional energy sources, ensure energy security and reduce greenhouse gas emissions.

Thus, the development of hydrogen technologies and the corresponding infrastructure, as well as the integration of hydrogen into the economy at all stages — from production to consumption — will be an important step towards the realization of global environmental and energy goals. In this context, the study of various aspects of the hydrogen economy and its implementation becomes particularly relevant.

The Israeli company H2Pro has developed an innovative water splitting technology that will allow the production of green hydrogen at a price of less than $1 per kilogram by 2030. This will mean a significant reduction in the cost of green hydrogen production, by 60-80%, making it economically competitive with other energy resources. In particular, the price of hydrogen will be lower than the current retail prices of gasoline per unit of energy, which opens up new prospects for the transition to renewable energy sources.

The company has already introduced a lab bench that generates small amounts of hydrogen, but even at this stage the technology shows a significant leap in efficiency. Its efficiency is expected to reach 95%, which makes this technology one of the most promising in the field of hydrogen energy.

The technology used for hydrogen production is an improvement of classical electrolysis. In this process, an electric current is passed through water that is enriched with alkali or acid, which allows the water to be split into hydrogen and oxygen. Oxygen is attracted to the anode and hydrogen to the cathode, after which these gases are collected separately thanks to a special membrane that separates the chamber.

One of the main aspects of the new technology is the E-TAC (Electrochemical Thermally Activated Chemical Water Splitting) process, which consists of two stages. The first stage is a cold electrochemical stage that generates hydrogen and oxidizes the anode, while the second stage is thermally activated, where the anode is regenerated and oxygen is released without the need for electricity.

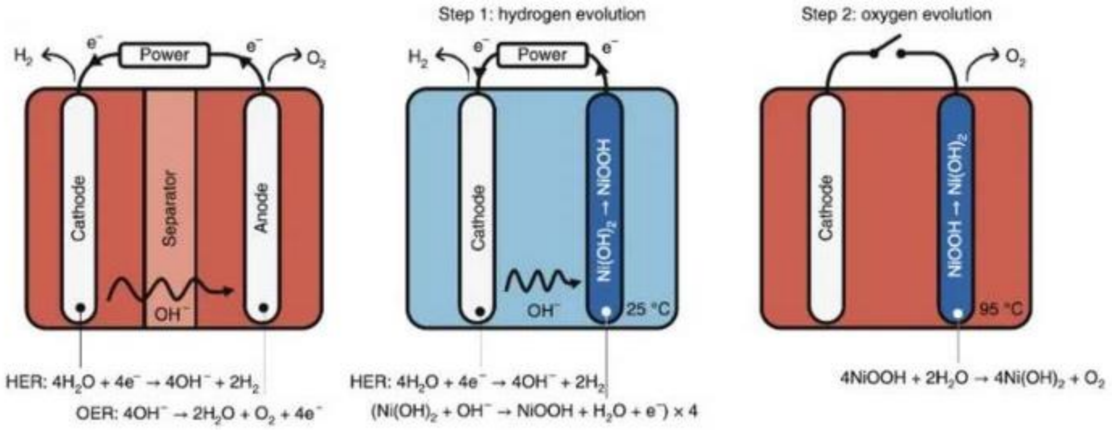

Fig. 7. Typical design of a single-stage electrolyzer with a membrane separating hydrogen and oxygen gases (a) two-stage E-TAC process. The first, cold, electrochemical stage generates hydrogen and oxidizes the anode. The second, thermally activated stage regenerates the anode, releasing oxygen, and does not require current (b)

This technology, developed at the Israel Institute of Technology, is a significant step forward in the development of hydrogen energy. It promises to significantly reduce the cost of hydrogen production, which is important for the economic feasibility of the widespread use of hydrogen as a clean energy carrier in the future. Thus, E-TAC can become a key technology for the mass introduction of hydrogen energy into the global energy landscape.

5. Conclusions

Hydrogen energy as the key to decarbonization of energy systems Hydrogen has the potential to become an important element in the global transformation of energy systems, contributing to the reduction of carbon dioxide emissions and ensuring sustainable development. In particular, hydrogen can become a universal source of energy, providing both energy storage and its use in various sectors of the economy. With the development of hydrogen energy infrastructure, hydrogen will be able to become a significant player in the energy market, which will reduce dependence on traditional carbon sources of energy.

Reducing the cost of hydrogen production An important factor for the large-scale implementation of hydrogen energy is the reduction of the cost of hydrogen production, in particular due to the development of technologies such as hydrogen electrolysis technology (E-TAC) and other innovative methods. It is expected that by 2030, the cost of "green" hydrogen may decrease by 60-80%, which will significantly increase its competitiveness with respect to traditional energy carriers. This will make it possible to create a sustainable hydrogen market at the global level.

Infrastructure and development of the hydrogen economy Although hydrogen energy is already starting to develop in a number of countries, one of the main barriers remains the lack of the necessary infrastructure. The development of hydrogen pipelines, fueling stations and logistics is critical to ensuring the efficient use of hydrogen as an energy carrier. This includes not only the transportation of hydrogen, but also its integration into existing energy networks and connections with producers, consumers and other market participants.

Projects are important , such as the initiatives of the Toyota company and other experimental projects in Japan, the USA and the EU. These projects demonstrate the potential of hydrogen as an ecologically clean energy resource and its ability to be implemented in various areas of the economy, including transport, industry and everyday life. In addition, international cooperation in the field of hydrogen energy helps to create uniform standards, which contributes to the further development of infrastructure and technology.

The potential of using hydrogen in various fields Hydrogen has a huge potential for application in various fields. The prospects for its use in transport, in particular in hydrogen cars, buses and trains, as well as in industry, where hydrogen can replace carbon energy carriers in processes such as the production of steel, chemical products, as well as in the production of electricity, are important. Hydrogen can also be used for energy storage, which is an important aspect for the integration of renewable energy sources into power systems.

Prospects for the development of technologies and reduction of energy costs With the development of new technologies for hydrogen production, such as the use of waste and organic materials for hydrogen synthesis, as well as further improvement of electrolysis processes, energy costs for obtaining hydrogen will decrease. Innovations such as high-efficiency electrolysers are capable of increasing hydrogen production and reducing environmental impact, leading to significant economic and environmental benefits in the long term.

Risks and Challenges for Hydrogen Energy Development Along with great opportunities for growth, hydrogen energy faces certain challenges, including high initial investment in infrastructure, technical difficulties, and the need for significant resources to produce hydrogen. Significant efforts are needed to overcome these barriers and ensure the efficient integration of hydrogen technologies into existing energy networks.

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ПЕРСПЕКТИВИ РОЗВИТКУ ВОДНЕВОЇ ЕНЕРГЕТИКИ: ІННОВАЦІЙНІ ТЕХНОЛОГІЇ ЯК КЛЮЧ ДО ЗДЕШЕВЛЕННЯ «ЗЕЛЕНОГО» ВОДНЮ

У статті розглядаються перспективи розвитку водневої енергетики, зокрема, застосування технології виробництва водню, що базується на розщепленні води за допомогою новітніх електролізерних технологій. Окрему увагу приділено інноваційній методиці, запропонованій ізраїльською компанією H2Pro, яка обіцяє значне зниження вартості «зеленого» водню до 2030 року до рівня менш ніж $1 за кілограм. Це зниження цін на водень на 60-80% дозволить зробити його більш конкурентоспроможним на ринку енергоносіїв, що може призвести до широкого впровадження водневих технологій у різних галузях економіки.

Технологія, яку розробляє H2Pro, використовує метод E-TAC (електрохімічне термічно активоване хімічне розщеплення води), що полягає в двоетапному процесі виробництва водню і кисню. Перший етап передбачає холодне електрохімічне розщеплення води, яке генерує водень та окислює анод, а другий етап — термічно активований — регенерує анод, виділяючи кисень, без необхідності додаткового споживання електричного струму. Ця технологія дозволяє знизити енерговитрати та підвищити ефективність процесу, досягаючи коефіцієнта корисної дії 95%, що є значним досягненням у галузі водневої енергетики.

Автор статті також звертає увагу на важливість цього досягнення для глобального переходу до відновлювальних джерел енергії. Зокрема, зниження витрат на виробництво водню за допомогою *таких технологій може забезпечити дешевше виробництво енергії, ніж традиційні енергоносії, такі як бензин і дизель, а також стати ключовим фактором у реалізації амбітних екологічних ініціатив, спрямованих на скорочення викидів вуглекислого газу.*

Окрім технологічних інновацій, в статті також обговорюється необхідність розвитку інфраструктури для зберігання, транспортування та використання водню, що залишається одним із головних бар'єрів на шляху до його широкомасштабного використання. Проте, завдяки зусиллям таких компаній, як H2Pro, які активно працюють над удосконаленням процесів виробництва та зниженням витрат, воднева енергетика має великі шанси стати невід'ємною частиною енергетичної системи майбутнього.

Таким чином, розвиток технологій водневої енергетики, таких як E-TAC, є важливим кроком на шляху до забезпечення чистої та сталого енергопостачання, що сприятиме зниженню екологічного впливу та забезпеченню сталого розвитку світової економіки в умовах глобальних змін клімату.

Ключові слова: *водень, воднева енергетика, зелений водень, електроліз, технологія E-TAC, термічно активоване хімічне розщеплення води, енергоефективність, зниження вартості водню, екологічні технології, відновлювальні джерела енергії, водневі технології.*

Рис. 7. Літ. 8.

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