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Current Trends of Biohydrogen Production from Biomass – Green Hydrogen

MONOGRAPH

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The monograph covers current research in the field of using the biohydrogen energy potential as an alternative energy source. The issues of global opportunities for obtaining biohydrogen in Ukraine, the possibility of developing bio-water projects in the domestic and European markets, assessing the risks for investors in biohydrogen, possible environmental and economic aspects, connection with the use of these projects are highlighted. The presented materials are intended for masters, graduate students and scientists involved in the projects related to alternative energy and energy efficiency.

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PREFACE

Mankind invests large sums of money, looking for new ways to obtain energy. He needs to address the urgent needs required to continue a safe and secure life. Safe because oil and gas are causing conflicts and wars, changing governments, enriching and impoverishing individual countries, its impact on the environment is important. Safe because the level of material and spiritual culture directly depends on the amount of energy possessed by a state. The needs of mankind, as well as the population, are growing every year.

Energy security involves achieving a state of technically reliable, stable, cost-effective and environmentally safe provision of energy resources to the economy and social sphere of the state. Energy security of Ukraine should be understood as the ability of the state to ensure the effective use of its own fuel and energy base, to carry out the optimal diversification of sources and ways of supplying energy to Ukraine to ensure the life of the population and the functioning of the national economy in the normal, emergency and martial law, to prevent sharp price fluctuations in fuel and energy resources, or to create conditions for the painless adaptation of the national economy to the new prices for these resources. As defined in the energy policy review of Ukraine by the International Energy Agency (IEA), the most significant threats to Ukraine's energy security at the present stage should be considered:

- low energy efficiency (energy efficiency is defined as a priority for strengthening energy security, which is very important for its economic progress and environmental protection);
- lack of mechanisms to neutralize high energy prices;
- low investment attractiveness of the country's energy sector (in order to attract investment and create incentives for the continuation of market reforms in many areas of the fuel and energy sector it is necessary that prices reflect the real cost of energy resources);
- lack of transparency in the energy sector and unclear definition of market rules.

In recent years, hydrogen energy has shifted from a little-studied direction to the main one with which leading Western countries associate the prospects of their national economies. The reasons are the unprecedented pace of development of hydrogen technologies. It turned out that they are able to provide significant reductions in greenhouse gas emissions, and thus bring closer the solution to the problem of global climate change.

The first and foremost purpose of our investigation is to reveal that our country has ample opportunities to become the main supplier of hydrogen to the EU market. At the heart of the innovation is the so-called green hydrogen; it is produced using renewable energy sources that have great potential for development in Ukraine. According to the Concept of "green" energy transition of Ukraine, the state "is quite capable and economically feasible to reach 70% of the share of RES in electricity production by 2050".

In contrast, hydrogen is a sector of the future for Ukraine that can create additional jobs, create new capacity for energy production, balancing and accumulating, actualize the role of our gas transmission system, generate export earnings and bring us energy independence and help make the energy transition to "green" future. As a conclusion, the path of the hydrogen industry development in Ukraine will allow us to receive additional investments in the Ukrainian economy for the creation of new capacities for the production of "green" hydrogen. In return, Europe will receive research and evolution of the bioenergy component of the economy, which will permit the safe transition of Europeans to an affordable, competitive and stable energy system.

The purpose of this monograph is to promote the use of biohydrogen for energy purposes. The materials presented in this scientific paper are intended to provide answers to the questions most often arising in the planning and implementation of projects for alternative energy use, in this case – biohydrogen, in the field of energy and heat supply; highlight a number of technical, economic and environmental issues regarding their development and implementation; raise the general level of public awareness of biohydrogen energy use.

The following issues that are currently relevant in Ukraine and the world are considered in the monograph:

- Conceptual bases for the development of biohydrogen;
- World experience of the system of production of biohydrogen;
- Conceptually – strategic framework for the development of the biohydrogen product market;
- Methodological basis of estimation of biohydrogen production;

- Research on the market for biofuels and biomass in the EU and Ukraine – potential for biohydrogen;
- Analysis and evaluation of resources for biohydrogen sources in EU and Ukraine;
- Optimization of the process of production for biohydrogen;
- Ecological and economic substantiation of the development of production of hydrogen.

The methodological support of the study was based on a systematic approach, which allowed to reflect the state of research on hydrogen technology, to justify the need to develop energy from hydrogen, taking into account the environmental approach, to calculate and analyze the economic components of hydrogen development, proportional dependences of indicators – in the study and identification of dependencies between the studied indicators in conditions of the limitation of the researchs. Authors also used analytical method, which allowed to summarize and visualize the studied processes.

Of the special research methods used in the work are:

- abstract-logical – in the study and research of the development of the problem of implementation and development of bioenergy;
- generalization – in assessing the current state of development and use of alternative energy sources from biohydrogen;
- computational and constructive, graphical, proportional dependences of indicators – in the study and identification of dependencies between the studied indicators.

The performed studies also are based on simulation modeling of projects dedicated to the production of biohydrogen from biomass.

It provides high-quality forecasting of investments in biohydrogen production, taking into account the existing global trends in terms of cost and volume used.

The stochastic market value of biohydrogen and natural gas is estimated based on statistical and forecasted data of countries where large biohydrogen production projects are implemented.

The monograph shows the results of the research performed within the framework of the topic "Formation of Organizational and Economic Mechanism for Development Production Biohydrogen From Biomass – Green Hydrogen", which was performed with support International Visegrad Fund and implemented by scientific and pedagogical staff of the educational and scientific laboratory "DAK GPS" Institute of Energy of State Agrarian and Engineering University in Podilya, drying laboratory Faculty of Production Engineering Warsaw University of Life Sciences – SGGW, National University of Life and Environmental Sciences of Ukraine, Lviv National Agrarian University and Zhytomyr National Agroecological University.

Acknowledgments: We express our gratitude **International Visegrad Fund** (www.visegradfund.org) and reviewers for a constructive review, which made it possible to improve the monograph.

With best regards, Editors

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CHAPTER 1

OBTAINING BIOHYDROGEN FROM BIOMASS IN UKRAINE

Introduction

The country's energy security is an important condition for Ukraine's sustainable development. The energy consumption of the economy, inefficient use of energy resources, market monopolization and total dependence on energy imports (oil, gas, fuel for nuclear power plants and even coal) make the domestic energy sector vulnerable to sustainable operation and rapid response to technological, economic and social challenges both internal and external.

Solving these problems will allow to move to a new level of technological development of the energy sector, increase its competitiveness and make the sector transparent for both service providers and consumers, which in general will increase the level of energy security of Ukraine (Energy Security Center of Ukraine, 2020).

Energy reform aims to bring national legislation in line with EU law, norms and standards, as provided for in the Association Agreement between Ukraine and the European Union. Completion of the implementation of European legislation, implementation of European standards will not only accelerate positive transformations in the energy sector. This will help unleash the country's significant potential in emerging energy segments, such as renewable energy. Together, all these steps will help strengthen Ukraine's energy independence and improve the quality of services for household consumers.

The Government's efforts to reform the energy sector aim to bring the energy sector to a fundamentally new, high-quality level of development, bring it in line with EU norms and standards, liberalize and form full-fledged natural gas and electricity markets with transparent and competitive pricing and adequate consumer protection.

The goal of the Government's reform is to increase energy efficiency, which has thefollowing components:

- increasing energy efficiency in the chain from production to energy consumption;
- promotion of energy efficiency measures;
- attracting investments for the introduction of energy efficient and innovative technologies;
- development of renewable and low-carbon energy sources, alternative fuels, ensuring reliability, environmental friendliness and availability of energy for all consumers.

As well as a comprehensive approach to the formation of energy and environmental policies, which in turn involves harmonizing the vectors of development of Ukraine's energy sector with the needs of combating climate change in accordance with current EU legislation and practices of EU member states, including the principles of the European Green Agreement.

Achieving this goal will form a strategic vision of greening and decarbonization of the energy sector (Government portal, 2020).

Theoretical background

On December, 2019, the European Commission adopted the European Green Deal. The European Green Course is a set of measures that determines the EU policy for the coming years in such areas as climate, energy, biodiversity, industrial policy, trade, etc. The main goal of this course is a sustainable green transition of Europe to a climate-neutral continent by 2050.

The European Green Deal is just being formed, it is a dynamic tool. Strategies, plans, legislation for the implementation of the European Green Deal will be developed and approved, mainly during 2020-2021. So far, the pace of the European Green Deal implementation has slowed slightly, given the priority of responding to COVID-19. However, the European Commission stressed that the recovery must focus on a more sustainable, green and digital Europe, solutions that are not only good for the economy but also for the environment. This means a constant "green" course and adherence to the implementation schedule of important components of the European Green Deal. This approach has been supported by a number of EU Member States, including Germany and France.

The Government of Ukraine has announced the intention of our state to join the European Green Dea. Such aspirations of the government are important given the need to develop in Ukraine a policy in various areas that would take into account today's environmental and climatic challenges. At the same time, we should take into account the full range of consequences of the European Green Deal for Ukraine in the context of opportunities and threats that it creates for us. The formation of the main conclusions and recommendations on the impact of the European Green Deal is important at this stage, when Ukraine has not yet finalized its intentions, and the European Green Deal is also in the process of forming and filling with content.

The European Green Deal is a European Commission action program centered on an ambitious plan to move to a climate-neutral Europe by 2050.

Politically, it is a response to the challenges of global climate change, pollution, biodiversity loss and, consequently, the EU's position as a global leader. Together with other key institutions, the European Commission develops the EU's overall strategy and policy.

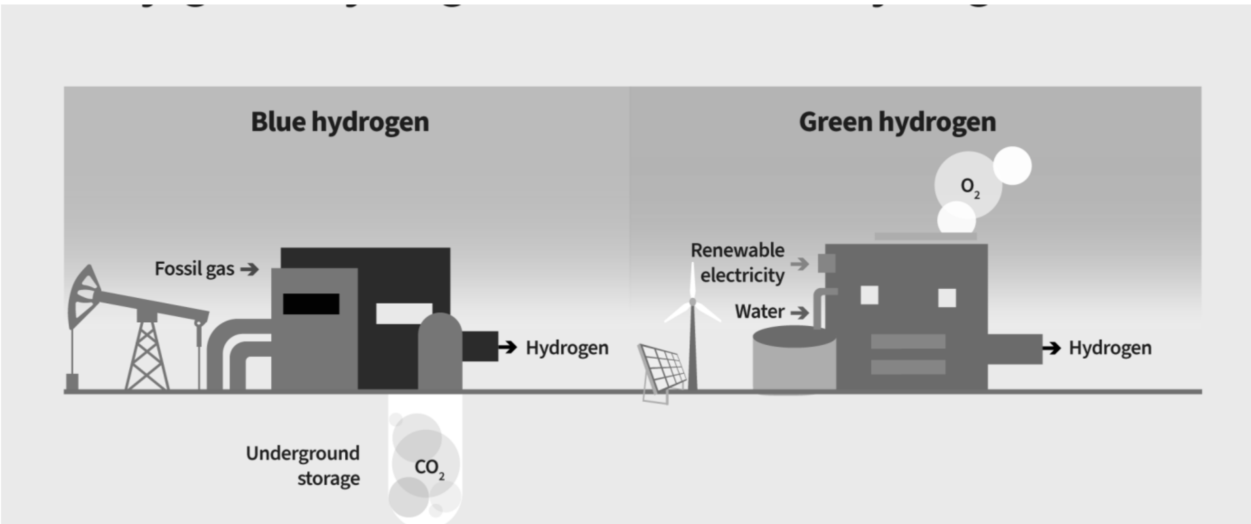

Fig. 1. Blue and green hydrogen (Banon, 2020)

Every 5 years, at the beginning of the new Commission, the President of the Commission also sets political priorities for the duration of his activities. The Commission translates these priorities into concrete actions on the basis of an annual program setting out an action plan for the next 12 months. In fact, the The European Green Deal is one of the six priority areas of the European Commission's action program under the leadership of Ursula von der Leyen, on the basis of which activities will be carried out during 2019-2024.

The inclusion of climate ambitions in the EU agenda is a response to the request of EU citizens who have recently expressed their climate position.

On December 11, 2019, the Communication of the European Commission "European Green Course" (Kayfeci, 2019; Gołębiewski, Kucher, 2020) was adopted. The communiqué includes a Roadmap, which contains the main measures in the areas covered by the European Green Course, as well as the timeframe for their implementation. The European Parliament as a whole supported this program with its resolution of January 15, 2020 (Kucher, 2018).

Thus, the communiqué and the roadmap are the main documents that will define the content and directions of EU action for the transition to a climate-neutral Europe. However, the European Green Course is just being formed, it is a dynamic tool. Strategies, plans, legislation for the implementation of the European Green Course will be developed and approved, mainly during 2020-2021.

The European Green Course is part of the European Commission's Strategy for the Implementation of the UN Agenda 2030 and the Sustainable Development Goals.

The European Green Course is not just about energy and the environment. It sets priorities in virtually all areas of EU activity.

Ukraine, as a Party to the Kyoto Protocol and the Paris Agreement, has committed itself, in particular, to taking measures to limit greenhouse gas emissions and adapt to climate change.

The main current legislation on public policy and governance in the field of climate change is the Basic Principles (Strategy) of State Environmental Policy of Ukraine for the period up to 2030 (Kucher, 2020; European Green Deal, 2019; European Parliament, 2020), The concept of implementation of state policy in the field of climate change for the period up to 2030 (The Law of Ukraine, 2019; CMU, 2016) and the corresponding action plan (CMU, 2017) to it. At the same time, the Strategy of Low Carbon Development of Ukraine until 2050 was developed (Ministry of Environmental Protection, 2020).

The low-carbon development strategy identifies three key objectives:

- transition to an energy system that provides for the use of low-carbon energy sources, development of clean electricity and heat sources, energy efficiency and energy saving in all sectors of the economy and housing and communal infrastructure, promotion of alternative fuels to motor products, in particular for freight and passenger transportation due to cleaner modes of transport;
- increasing carbon sequestration and retention through the application of best practices in agriculture and forestry adapted to climate change;
- reducing emissions of greenhouse gases such as methane and nitrous oxide, mainly related to fossil fuel production, agriculture and waste. The strategy states that Ukraine will make efforts to achieve the

level of greenhouse gas emissions in 2050 at the level of 31-34% of the 1990 level.

The draft Concept of Green Energy Transition of Ukraine until 2050, presented on January, 2020, is structurally and substantively the closest to the European Green Course document, given the dynamism, intersectoral approach and ambition (the goal is a climate-neutral economy by 2070).

As the development of renewable energy sources (RES) is relied on as the basis for decarbonisation of the energy system, new RES trends can become a starting point for intensifying cooperation between Ukraine and the EU. This is primarily about cooperation in the field of hydrogen energy, which is of interest to the EU and has a high potential in Ukraine (especially given the need to replace the transit of natural gas and ensure the congestion of the Ukrainian gas transmission system).

Reducing natural gas consumption in the EU or replacing it with, say, "green" hydrogen (which is an obvious positive trend in the context of decarbonisation) could leave Ukraine without transit revenues. This risk can be offset by the development of its own hydrogen energy, preventive adaptation to changes in the global natural gas market and the integration of the Ukrainian gas market into the EU market.

Today, the share of all renewable energy sources is approximately 2.72% of the total energy balance of Ukraine. However, by 2035 this figure is planned to increase to 25% at the state level. Traditional fuels – coal, gas, oil and oil products, will be replaced by renewable sources, and in the transport sector Ukraine must abandon internal combustion engines and switch to environmentally friendly transport (European

Green Deal, 2019; European Parliament, 2020; The Law of Ukraine, 2019).

According to expert assessments from the Institute of Renewable Energy of the National Academy of Sciences of Ukraine, Ukraine has a significant technically achievable potential for renewable energy production. This energy will be enough to replace the use of about 69 million tons of oil per year. That is, in six years the share of renewable energy sources and alternative fuels will be able to replace more than 22 million tons of oil equivalent (Golub, 2020).

Materials and Methods

The purpose of the study is to substantiate practical recommendations on the feasibility of the development of hydrogen technologies, namely the production of biohydrogen in Ukraine.

The following methods were used in the research process: method of systematization of materials, method of analysis and logical generalization for studying the preconditions of biohydrogen production, method of logical conclusions when formulating conclusions and proposals.

Research results and discussion

Hydrogen production technology is a basic issue today. The most effective and environmentally friendly method is water electrolysis. Modern electrolysis plants are easy to maintain and have high technical characteristics. Excess electricity from renewable sources or peak energy from traditional stations can be used as the primary source of electricity.

Another important point is the storage of hydrogen. The creation of energy storage systems based on renewable energy sources is promising, in particular in areas that are difficult to supply for electricity, which have the greatest potential for renewable energy sources. Hydrogen can be stored in compressed or liquid state, as well as in metal hydrides. The most advantageous option is the storage and transportation of hydrogen as an additive to natural gas through existing pipeline systems. This method can provide the filling of the Ukrainian gas transportation system, while improving the quality and environmental friendliness of gas fuel.

Hydrogen and hydrogen technologies are already being discussed about at the state level. The National Academy of Sciences of Ukraine recently allocated three million hryvnias to support hydrogen projects. The next step should be the development of Ukrainian legislation on hydrogen energy. The Ukrainian Hydrogen Council together with the Institute of Renewable Energy of the National Academy of Sciences of Ukraine develop and co-finance a practical program for sectoral integration of hydrogen into the economy of Ukraine. In particular, the development of a roadmap for the introduction of hydrogen technologies in the main sectors of the Ukrainian economy is nearing completion.

Work is underway on the concept of hydrogen development in Ukraine until 2035 and the national action plan for renewable energy 2020-2030.

Fig. 2. Hydrogen storage (Kudria, 2019)

Them an in directions of development of hydrogen energy for the construction of a new economic model on the energy hydrogen model of Ukraine are:

- development and implementation of efficient energy systems based on renewable energy sources, equipped with systems of accumulation, storage, transportation and use of hydrogen of different types and capacities (so-called "green" hydrogen);
- development and implementation of systems for accumulation, storage, transportation and use of hydrogen of various types and capacities in traditional energy for the accumulation of peak electricity (industrial hydrogen);
- development and implementation of systems for the accumulation and use of hydrogen of various types and capacities in the transport industry (road transport, railway transport);

- development and implementation of hydrogen pipeline transportation systems, including as additives to natural gas;
- achieving a 25 percent share of hydrogen in Ukraine's gas transportation companies;
- development and implementation of mechanisms of public administration and regulation in the field of hydrogen energy;
- development of legislative and normative-legal acts aimed at the development of hydrogen energy;
- increasing the level of competitiveness of renewable energy facilities;
- development of safety requirements and measures in the process of production, storage, transportation and consumption of hydrogen;
- creation of systems of analytical and information support of scientific and technical development of hydrogen energy;
- creation of a system of metrological and certification support.

In such way, the use of the potential of renewable energy in combination with hydrogen technologies will allow Ukraine not only to abandon the import of natural gas and be an energy independent state, but also to export the latest energy to EU countries.

Energy potential of Ukraine. According to Ukrenergo, the share of renewable energy sources (RES) has doubled in just one year (from 2.9 GWton June, 2019 to 5.8 GWton June, 2020), and at the end of November, 2020 exceeded 6.3 GW.

In order to accelerate and implement innovative developments in the field of hydrogen energy and fuel cells in Europe, the Hydrogen

Europe Association was established, which unites more than 100 industrial companies, about 68 research organizations and 11 national hydrogen associations. In the field of research, Hydrogen Europe works closely with the EU Horizon 2020 Framework Program, with the Joint PC and Hydrogen Initiative, with a total budget of €1.33 billion.

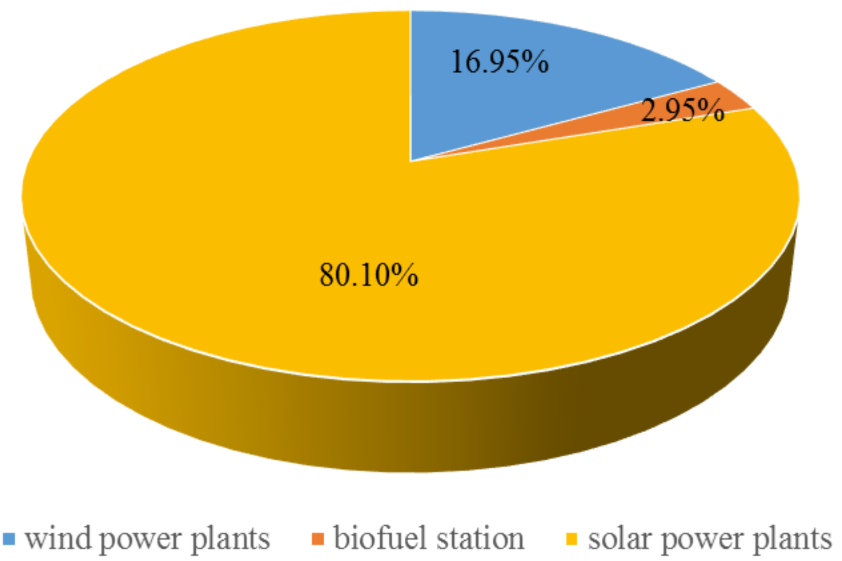

Fig. 3. Renewable energy equipment capacity (National Power Company "Ukrenergo")

In Ukraine, the construction and development of a new hydrogen economy and the country's involvement in the European hydrogen energy space is carried out by the Energy Association "Ukrainian Hydrogen Council", which in 2018 became the first in Ukraine and non-EU countries to become a member of the European Commission of the organization "Hydrogen Europe" (Economictruth, 2020).

For many countries around the world, research on hydrogen energy is becoming a priority for science. They are provided with funding from both the state and business structures.

It is clear that the main purpose of the development of hydrogen technologies is to reduce dependence on traditional energy sources, and most importantly – to reduce toxic emissions from the combustion of hydrocarbons (Tryhuba, 2021).

There are two industrial sources of hydrogen today: electrolysis of water (it has long been the most optimistic hope) and chemical conversion of organic matter (combustible minerals, biomass or biomass processing products – alcohols) to synthesis gas (a mixture of CO and H_2).

The greatest environmental effect is to be expected if all the transport of large cities is converted to hydrogen. After all, this is where massive environmental pollution occurs. So, let's assess the situation when all motor fuels consumed in the world could be replaced by hydrogen. Due to its energy consumption and higher efficiency of hydrogen drives, compared to internal combustion engines, hydrogen in this case will require approximately 3.2 times less.But in order to obtain with the help of the latest electrolysis technologies the hydrogen needed to replace all motor fuels, it is necessary to increase electricity production at least three times. We will have to triple the power capacity because at least the existing consumers will remain. Of course, this is not yet a real task (Tryhuba, 2021).

Another way to produce hydrogen is biohydrogen, it is a type of biofuel.The raw material for its production is biomass. The use of biohydrogen gives three times the amount of energy released when using traditional fuels. Given the current problems with the environment, the use of biohydrogen is completely environmentally friendly, because its combustion does not produce harmful substances.

Due to favorable soil and climatic conditions and land structure, Ukraine has significant opportunities and real reserves for the development of plant bioenergy, ie obtaining energy from biomass, especially that generated from waste. Biomass can be of plant and animal origin, ie it is a renewable source for energy (Pustova, 2004).

Despite certain difficulties in the energy use of agricultural biomass, it remains one of the cheapest types of biomass, which has the greatest potential in Ukraine.

There are two main methods of biohydrogen production:

1. Thermochemical method is based on the fact that biomass is subjected to heat treatment at a temperature of 500-800°C. Heating occurs in the absence of oxygen. The temperature of the process is below the temperature of coal gasification. As a result of this process, hydrogen and other gaseous products are released. It is planned to improve this process and, consequently, reduce the cost of production.

2. The biochemical method is the production of biohydrogen from biomass using special bacteria. If the biomass is rich in starch or it contains a significant amount of cellulose, it is advisable to use special enzymes that accelerate the process of biomass processing. Stable parameters (temperature 30°C and normal pressure) must be maintained for efficient process.

However, the development of an ideal method of biohydrogen production does not stop, and gradually gaining popularity production of this type of fuel from algae.

Both autotrophic and heterotrophic microorganisms are able to produce biohydrogen. The biochemical path of hydrogen molecule formation, efficiency and necessary process conditions primarily depend on the microorganisms-producers.

According to the energy sources used by organisms during the production of biohydrogen, microbiological processes can be divided into the following (Mohammad, 2020; Diachuk, 2017):

- dark anaerobic release of biohydrogen, in the process of which the energy of chemical bonds of substrate molecules is converted into the energy of chemical bonds of hydrogen;
- light-dependent release of hydrogen, in which microorganisms convert light energy into the energy of chemical bonds of hydrogen molecules;
- bioelectrochemical production of hydrogen using modified microbial fuel cells, in which electrical energy, as well as the energy of chemical bonds of the organic substrate is accumulated in hydrogen molecules.

Dark hydrogen evolution is common in anoxic or anaerobic conditions (ie in the absence of oxygen – electron acceptor). Many bacteria use the process of reducing protons to hydrogen molecules in order to accumulate reduced equivalents, which are the result of primary metabolism. In other words, when bacteria grow on organic substrates (heterotrophic growth), these substrates decompose and, as a result of oxidation, provide the cell with “building blocks” and metabolic energy for growth. In this oxidation process, electrons are generated, which must be neutralized. Under aerobic conditions, oxygen is restored and water is formed. Under anoxic or anaerobic conditions, other compounds, such as protons, which combine with electrons to form molecular hydrogen (H_2) act as electron acceptors.

At the same time, a maximum of 4 mol of H_2 per mol of glucose can be formed with an energy production of 206 kJ/mol of glucose, which is enough to support the growth of microorganisms. The yield of hydrogen during dark fermentation largely depends on the partial pressure of the product.

Both aerobic and anaerobic bacteria and their mixtures can be used to produce hydrogen in this way. Strict anaerobes are represented by a number of bacteria (*Clostridia*, *Ruminococcus* (cattle rumen bacteria), *Anaerocellum*, *Caldicellulosiruptor*, *Clostridium*, *Dictyoglomus*, *Fervidobacterium*, *Spirocheta*, *Thermotoga*, *Thermoanaerobacter*), *Pyrococcus* (thermophilic)).

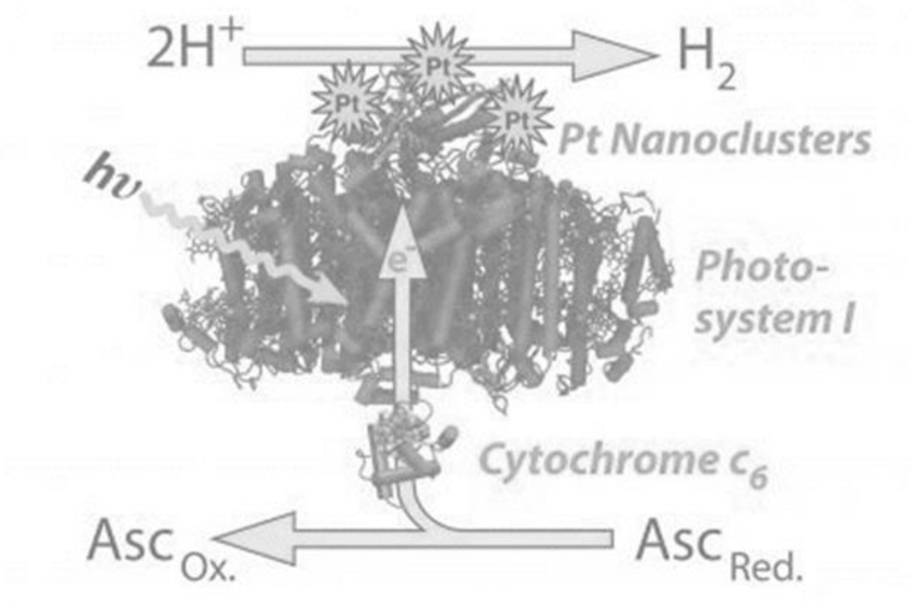

Fig. 4. The process of obtaining hydrogen from algae (Hydrogen Production Using Algae, 2019)

Light-dependent hydrogen production can be carried out by photoautotrophic and photoheterotrophic microorganisms.

In the process of photoautotrophic hydrogen production, solar energy is captured by photosystems and used to produce hydrogen and oxygen from water (water biophotolysis). This process takes place in a special bioreactor. The main disadvantage of this process is that hydrogen and oxygen are produced simultaneously, which leads to oxygen inhibition of hydrogen production enzymes.

The efficiency of the process can be increased by 3-10% with immediate removal of oxygen. For today, such developments are aimed at minimizing oxygen inhibition by temporal or spatial separation of hydrogen and oxygen flows. In photoheterotrophic hydrogen production, solar energy and organic compounds are used as a substrate. Microalgae and cyanobacteria are photoautotrophic organisms because they can use light as a source of energy and carbon dioxide as the only source of carbon.

Bacteria is called photoheterotrophic microorganisms, despite their ability to use light as a source of energy, need organic carbon as a source of carbon. Microalgae and cyanobacteria are able to use sunlight to metabolically convert carbon dioxide into energy-rich organic compounds [Cn (H2O) N] with water as an additional substrate.

Another no less interesting way to obtain this fuel is to reform biogas. Reforming is well studied and widely used. The process of biohydrogen production by steam reforming is well established and is a good alternative in regions where there is a shortage of traditional fuels.

The whole process consists of several stages (Nikolaidis, 2017; Ishaq, 2021).

Today, the biochemical method of biohydrogen production is the most popular and widespread. Given that the raw materials may be agricultural waste (husks, meal, etc.), household organic waste, wastewater and sewage, its amount is inexhaustible (Shchurska, 2011; Huber, 2006).

Also in the production of hydrogen by this method does not require any special conditions and special equipment. For efficient production, microorganisms of different evolutionary groups can be used, which belong to the following families: *Geobacteraceae*, *Desulfuromonaceae*, *Alteromonadaceae*, *Entero-bacteriaceae*, *Pasteurellaceae*, Clostridiaceae, *Aeromo-nadaceae*, and *Comamonadaceae*, *Gammaproteo-bacteriaceae*, *Betaproteobacteriaceae*, *Rhizobiaceae* and thermophilic *Thermincola carboxydophila*, *Deferribacter ferribacter*, *Coprothermobacter* sp. (Zhou, 2011). Bacteria can be reused after each production cycle. Therefore, this method depends entirely on the activity of bactria and it is less energy-intensive and cheapest.

By 2050, most regions of the world can produce hydrogen from solar and wind power at a price of $0.8 to $1.6 per kilogram (Bloomberg NEF, 2020). The cost of "green" hydrogen roughly corresponds to current prices for natural gas in energy equivalent ($6-12 per million British thermal unit). The cost may be even lower in countries with significant potential for renewable energy.

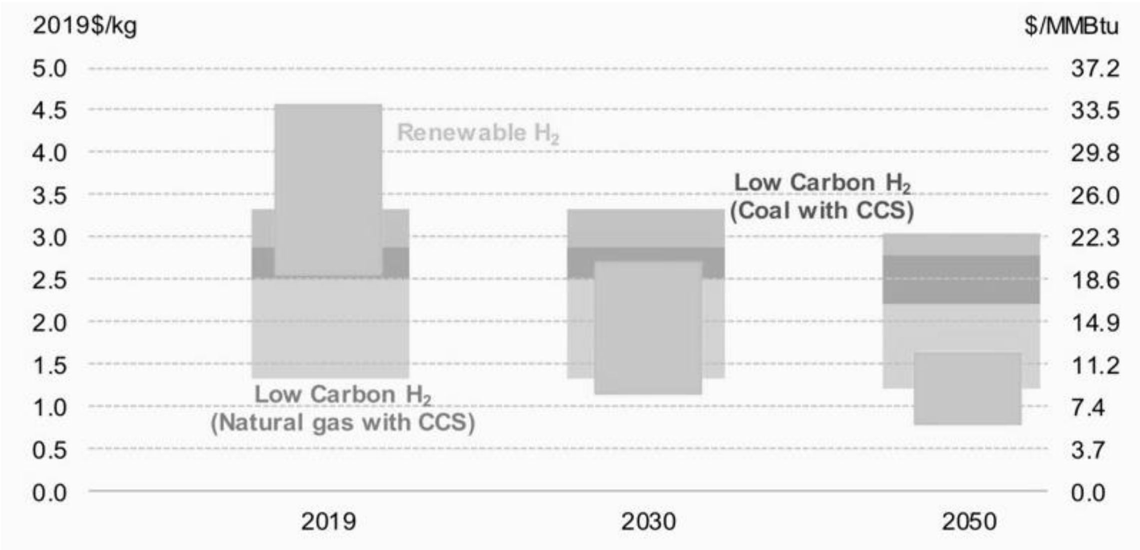

Fig. 5. Forecast global range of levelized cost of hydrogen production from large projects (Bloomberg NEF, 2020)

According to Bloomberg NEF, falling prices will allow “green” hydrogen to meet 24% of global energy needs by 2050, and reduce global emissions from fossil fuels in industry by a third.

Conclusion

In the system of sustainable development, energy is an important factor that has a direct impact on industrial relations, social development of society, the state of the environment. Limited energy resources require their assessment as a factor of economic security and consideration in the formation of national and business strategies. Due to favorable soil and climatic conditions and the structure of land, Ukraine has significant opportunities and real reserves for the development of plant bioenergy, ie obtaining energy from biomass. Ukraine will make efforts to achieve greenhouse gas emissions in 2050 at 31-34% of 1990 levels.

In Ukraine, the development of hydrogen technologies is at an early stage, despite the presence of a significant number of scientific institutions that deal with this problem. Hydrogen has a very wide use – in metallurgy, the most – in the chemical industry, in the production of nitrogen fertilizers. Hydrogen is also used in energy, but in a different form – to cool turbines. Therefore, in general, hydrogen technology has long been known. At the same time, with the successful development of hydrogen production technologies, Ukraine could rationally use its rich (including unconventional) energy resource base, diversify energy sources, reduce energy dependence and, as a result, improve the energy and environmental situation in the country. Biohydrogen is seen as a good replacement for traditional fuels. Biohydrogen is an environmentally friendly fuel that is several times more efficient than oil and gas.

Fuel production is easy and simple, and no less important is the fact that it is still financially profitable. Ambitious, focused and short-term action is needed to further overcome barriers and reduce costs.

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CHAPTER 2

PROSPECTS FOR THE DEVELOPMENT OF UKRAINIAN BIOHYDROGEN PROJECTS IN EUROPE

Introduction

It is a well-known fact that the world's reserves of traditional fuels are declining and the world's production of energy from alternative sources is constantly growing. Every year the number of countries that show interest in the development and use of renewable energy increases. The use of alternative energy sources has a global perspective for the further successful development of civilization. In the world there are phenomena that disrupt the stability of civilized development of society: depletion of traditional energy sources, increasing the cost of their extraction, intensively polluting the environment, destroying the biosphere, generating excessive amounts of organic waste of industrial, agricultural and domestic origin. All these problems must be eliminated at an accelerated pace.

According to FAO calculations, there are 10 million square kilometers of agricultural land on the globe, 40 million square kilometers are forested, deserts and semi-deserts cover about 49 million square kilometers. Every year, photosynthesis in the world produces about 220 billion tons of biomass (dry matter), of which 80% is accounted for by forests, which is 170 billion tons. As we noted earlier, two tons of biomass is energetically equal to about one ton of oil. This means that the annual growth of forests is 25 times higher than the energy equivalent of annual oil production of 3.3 billion tons. In other words, biomass produced per 2 million square kilometers of forest under sustainable management could cover the annual global oil demand (Kuzmenko, 2016; Kovalenko, 2020).

Today, the production of electricity from renewable sources reaches more than 30%, namely 86,841 thousand tons of oil equivalent.

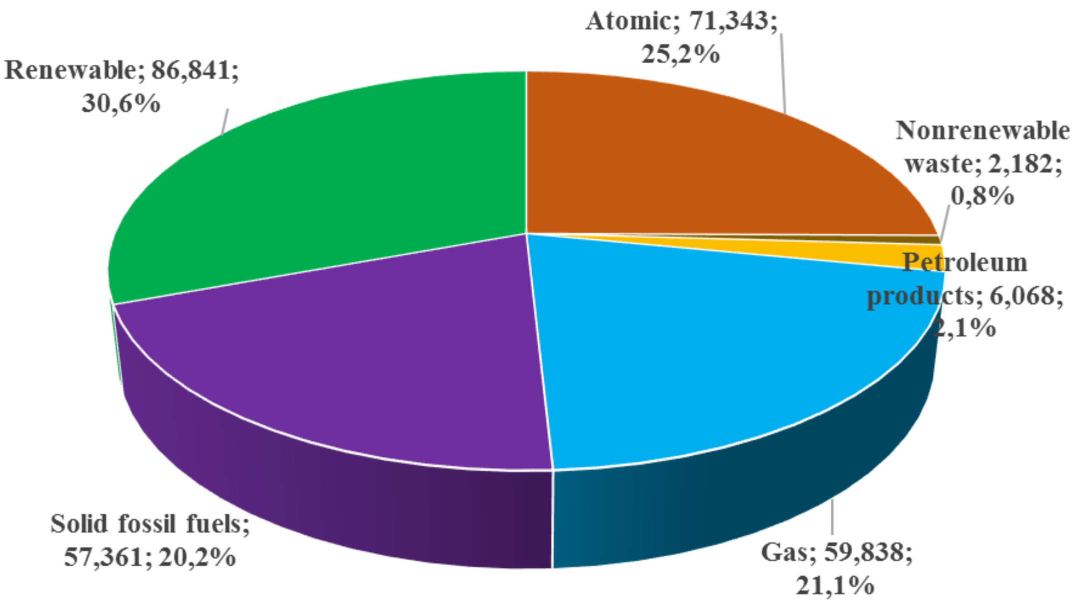


Fig. 1. Gross electricity production by type of source in the EU-28 in 2017 (thousand tons oil equivalent) (Sustainable Agribusiness Forum materials)

Biomass as a by-product or production waste (crop straw, sawdust, wood waste, biogas) is an alternative fuel that can replace traditional, expensive fossils in energy production. The importance of its use is also that you can take into account the specifics and personal potential of each EU country.

The European Bioenergy Association has published a report on the development of the renewable electricity sector in Europe. A separate section of the report is devoted to the production of electricity from biomass and biofuels. The share of electricity from biomass in the gross electricity production in the EU-28 is 5.6% (15,929 thousand tons oil equivalent), ranking 3rd among all RES after Hydro and Wind (Epstein, 2020; Savchuk, 2020; Repkin, 2020).

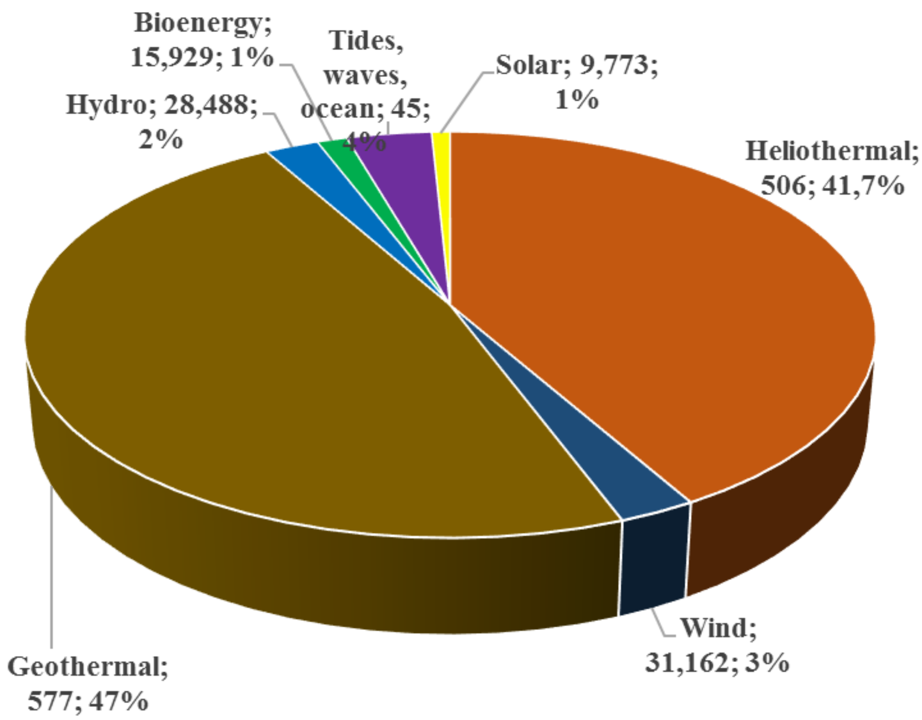


Fig. 2. Electricity production from renewable energy sources in the EU-28 in 2017 (thousand tons oil equivalent) (Sustainable Agribusiness Forum materials)

Bioenergy should be considered one of the most promising components of renewable energy in Ukraine.

It is based on the use of biomass – carbon-containing organic substances of plant and animal origin – wood, straw, crop residues of agricultural production and so on. Biomass is a renewable, environmentally friendly fuel, the use of which does not increase the global greenhouse effect.

The experience of the EU countries shows that there are many factors that influence the extent and prospects for the development and use of renewable energy sources.

At the same time, a large role in this process is played by the systems of economic incentives operating in these countries, which Ukraine lacks (Tryhuba, 2021; Kubon, 2010; Kozina, 2019; Dziedzic, 2018):

- tax exemption of a part of the profit that is invested in the development of unconventional energy;
- compensation to tariffs for energy received from renewable energy sources;
- exemption of consumers of “clean” energy from economic taxes; tenders and quotas (“green certificates”) in support of various types of renewable energy sources from the general special fund.

An important component of any development program implemented in Ukraine should be its consideration in terms of sustainable development. The development of bioenergy issues is no exception. Sustainable development must become the organizing principle of all democratic societies, while supporting all other goals, policies and processes.

Thus, it provides a basis for integrating economic, social and environmental issues over time, not just through trade itself, but by achieving and enhancing the public good. Sustainable development contributes to the organization of good governance, healthy living conditions, innovation, lifelong learning and all forms of economic growth that guarantee the preservation of natural capital, on which we depend (Kasprzak, 2018; Kayfeci, 2019; Nikolaidis, 2017). This contributes to the improvement of social harmony and provides ways to protect the prospects of each individual to lead a full life.

The European Commission believes that thanks to the hydrogen technologies development, Ukraine is able not only to approach European standards, but also to become a significant international player in the energy market. They are ready to help us, but on condition that Ukraine also makes a lot of efforts (Ishaq, 2021; Golub, 2020; Ni, 2006; Diachuk, 2017; Azizan, 2020).

Therefore, Ukraine as a state, as well as the Ukrainian producers, must fit into the environmental strategy of the European Union through actions and projects, and not just theoretical plans. Only in this case we will have access to funds from financial funds within the framework of cross-border cooperation with the EU. They expect from Ukraine initiatives that will expand cooperation with the EU and will contribute to the decarbonization of the economy. This means that our country and business will have to pass the certification of production, the implementation of European climate standards and the transformation of the economy, the substitution of fossil fuels with renewable resources should be taken into account. If we express the potential of such a partnership as a percentage, then Brussels is ready to finance about 75% of all funds necessary for the integration of hydrogen technologies into the Ukrainian economy, and the remaining 25% are our domestic investments (Repkin, 2020).

In December 2019, the European Commission adopted the European Green Deal. The European Green Deal is a set of measures that determines the EU's policy for the coming years in such areas as climate, energy, biodiversity, industrial policy, trade. The main goal of this course is Europe's sustainable green transition to a climate-neutral continent by 2050.

The European Green Deal is just being formed and is a dynamic instrument. Strategies, plans, legislation for the implementation of the European Green Deal in life will be developed and approved mainly during 2020-2021.

Currently, the pace of implementation of the European Green Deal has slowed slightly, despite the priority of responding to COVID-19. However, the European Commission emphasized that recovery should focus on a more resilient, greener and digital Europe, solutions that not only benefit the economy but also the environment. This means that the Green Deal remains unchanged and that important components of the European Green Deal are on schedule. This approach was also supported by a number of EU member states, including Germany and France.

The Ukrainian government announced the intention of our state to join the European Green Deal. Such aspirations of the government are important given the need to formulate policies in Ukraine in various fields that would take into account environmental and climatic challenges. At the same time, the full range of consequences of the European Green Deal for Ukraine should be taken into account in the context of the opportunities and threats that this creates for us. Formation of the main conclusions and recommendations regarding the impact of the European Green Deal is important at this stage, when

Ukraine has not yet finally formulated its intentions, and the European Green Deal is also in the process of being formed and filled with content.

Ukraine as a Party to the Kyoto Protocol and the Paris Agreement has undertaken obligations, in particular, to take measures to limit greenhouse gas emissions and adapt to climate change.

The draft Concept of Ukraine's "green" energy transition by 2050, presented in January 2020, is structurally and substantively the most similar document to the European Green Deal, taking into account the dynamism, intersectoral approach and ambition (the goal is climate-neutral economy by 2070).

Reducing the consumption of natural gas in the EU or replacing it with, say, "green" hydrogen (which is obviously a positive trend in the context of decarbonization) could leave Ukraine without transit revenues. This risk can be mitigated through the development of our own hydrogen energy, preventive adaptation to changes in the global natural gas market and the integration of the Ukrainian gas market into the EU market.

Materials and Methods

For our analytical study on the prospects for the development of biohydrogen projects in Ukraine, we used materials from existing bioenergy foundations in Ukraine and Europe. Among the domestic organizations are the Bioenergy Association of Ukraine (UAIBO) which includes the well-known Scientific and Technical Center "Biomass" and the public association "Agency for Renewable Energy", IRENA (International Renewable Energy Agency). Our research and conclusions are based on the study of the objectives of the following programs and agreements: “European Green Deal”, “Green Hydrogen Investment and Support Report”, “FCH JU Hydrogen Roadmap Europe”, “Green Hydrogen of Europe”.

We have considered the goals of the European funds in the direction of the development of energy production from biohydrogen, studied the potential for the implementation of hydrogen projects, the possibilities of financing them and the potential ability of Ukraine to form internal and external markets for hydrogen energy.

Of the special research methods used in the work are:

- abstract-logical – in the study and research of the development of the problem of implementation and development of bioenergy;
- generalization – in assessing the current state of development and use of alternative energy sources from biohydrogen;
- computational and constructive, graphical, proportional dependences of indicators – in the study and identification of dependencies between the studied indicators.

Research results and discussion

Ukraine is a country that is heavily dependent on imports of fossil fuels. Given the underdeveloped energy situation with its own natural resources, Ukraine faces the problem of reducing natural gas consumption. The cost of natural gas is a great economic and political risk, which has caused problems in recent decades. As a result, a number of sectors of the national economy were on the verge of viability. In this regard, Ukraine must urgently look for alternative energy sources and implement energy-saving technologies. Widespread use of renewable energy technologies, especially biomass, can be one way to reduce natural gas consumption (Kuzmenko, 2016).

Despite the fact that most of the electricity and heat in Ukraine is produced from traditional sources that pollute the environment, the situation should change in the coming years. Thus, Ukraine's commitments under the Protocol on Accession to the Energy Community include an action plan for the implementation of Directive 2009/28/EU on the promotion of the use of energy from renewable sources.

We are talking about the adaptation of Ukrainian legislation in the field of renewable energy to EU legislation, in particular:

- development of technical requirements for the production and use of biofuels and bioliquids with reduction of greenhouse gas emissions;
- development of sustainability criteria for liquid and gaseous fuels produced from biomass, etc.

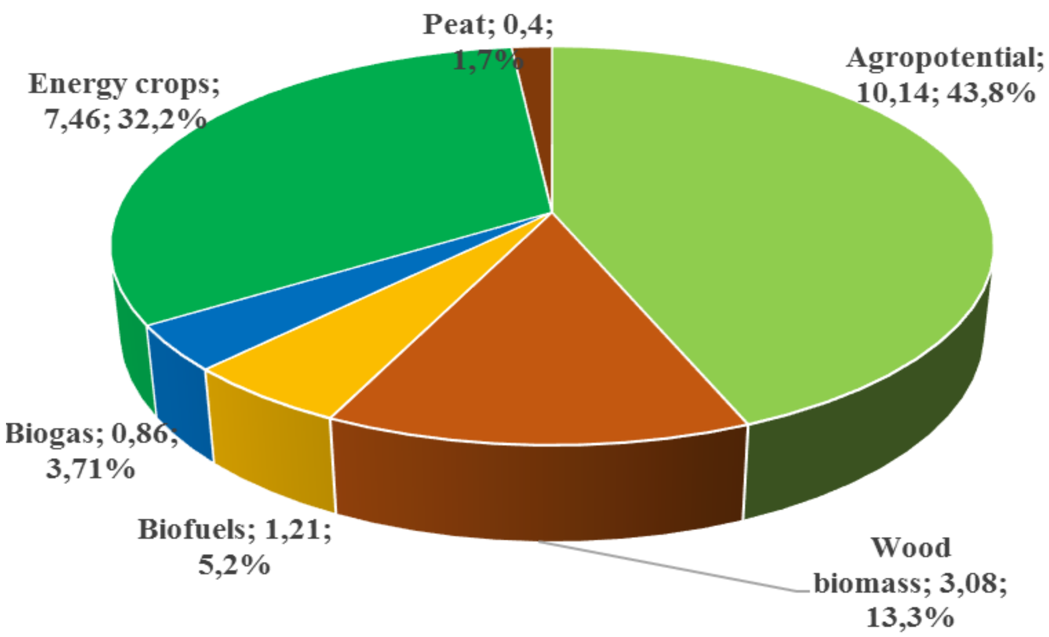


Fig. 3. Bioenergy potential of Ukraine, 2018 (million tons oil equivalent) (according to Bioenergy Association of Ukraine)

The development of bioenergy is very important for Ukraine as it has a significant potential of biomass, which is available for energy production. Biomass in Ukraine is enough to replace imports of gas, gasoline and coal (about 23 million tons oil equivalent).

Hydrogen as an energy raw material. The European Renewable Energy Council has proposed introducing the concept of "green or renewable" hydrogen as one of the renewable energy sources.

Hydrogen is a gas that can be obtained from water. It is the simplest and lightest of all chemical elements, which is an ideal fuel. When hydrogen is burned, water is formed, which can be decomposed again into hydrogen and oxygen, without any pollution of the environment.

Carbon dioxide, carbon monoxide (CO), hydrocarbons, soot, organic peroxides and others are not released during combustion (as when burning other types of fuel). Hydrogen has a very high thermal capacity: when burning 1 g of hydrogen, 120 J of thermal energy is released, and when burning 1 g of gasoline – only 47 J.

Hydrogen is a type of biofuel. The raw material for its production is biomass. The use of biohydrogen gives three times more energy than is released when using traditional fuels. Given the current problems with the environment, the use of biohydrogen is completely environmentally friendly, because its combustion does not produce harmful substances.

Today, in present economy, hydrogen is used as a chemical rather than an energy raw material. It is used about 20 million tons per year: 50% goes to the production of ammonia and fertilizers, the rest –

to remove sulfur from gaseous fuels in metallurgy, for the hydrogenation of coal and other fuels.

Currently, hydrogen is largely produced from fossil fuels, such as natural gas, and is therefore contaminated with CO_2. Only the electrolysis of water with electricity from renewable sources creates green hydrogen – without CO_2 emissions.

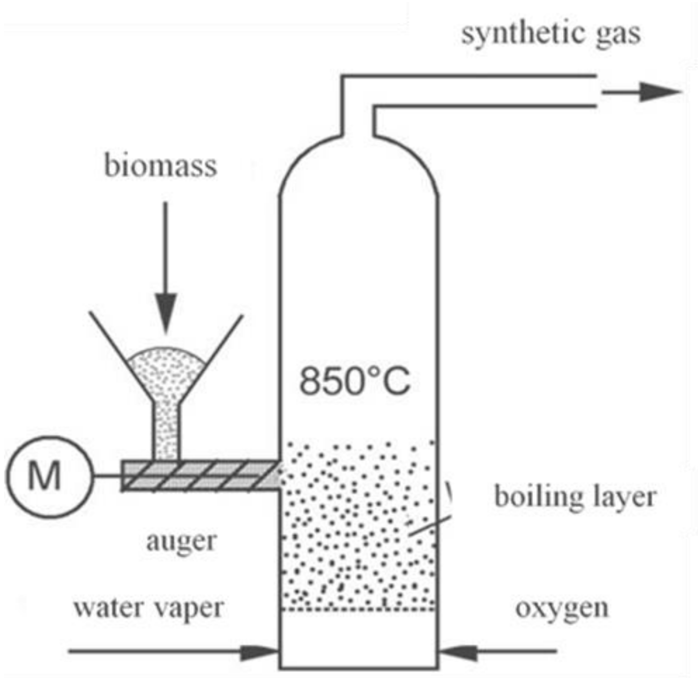
Proponents of the industrial use of green hydrogen believe that its use is a necessity for the development of the energy industry and the creation of a reliable and stable energy system of the future. The European Council for Renewable Energy does not share such positions and points out that the large-scale introduction of renewable energy sources is a necessary condition for the use of hydrogen and its "promised" impact on the environment.

According to Lins H. the production of hydrogen in industrial conditions requires a complex multi-stage conversion process, which requires both significant investment and significant electricity costs. First you need electricity, which would ideally be generated from renewable energy sources. Then it is necessary to ensure the electrolytic separation of the water molecule into oxygen and hydrogen atoms.

Finally, for further transportation, the hydrogen is cooled, followed by liquefaction. This third stage is associated with the highest energy consumption. The last stage involves the direct production of heat or electricity from hydrogen in fuel cells. It should be emphasized that the compliance of each individual energy source with the criteria of economy, efficiency and environmental friendliness depends on the extent to which production technologies used in energy processing allow to avoid transport costs and electricity losses due to complex multi-stage conversion processes.

Therefore, hydrogen is considered as a possible alternative for renewable energy, but in no case as a factor in the development of the latter.

Figure 4 shows a diagram of a standard reactor for hydrogen production in energy and chemical production.



$H_2 + CO + CO_2 + H_2O$

Conversion in the reactor:
$CO + H_2O \Rightarrow CO_2 + H_2$

Fig. 4. Hydrogen production in an industrial reactor

Chemical and electrochemical methods of obtaining H2 are uneconomical. Biohydrogen (biohydrogen) is obtained:

- biochemically with biobutanol butyl or acetone-butyl fermentation of industrial plant biomass;
- by thermolysis of wood biomass;
- by biogas reforming;
- by photolysis with algal biomass.

Biohydrogen is mainly produced by two main methods:

1. Thermochemical method – based on the fact that biomass is subjected to heat treatment at a temperature of 500-800°. Heating occurs in the absence of oxygen. The temperature of the process is below the temperature of coal gasification.

As a result of this process, hydrogen and other gaseous products are released. It is planned to improve this process and, consequently, reduce the cost of production.

2. The biochemical method is the production of biohydrogen from biomass using special bacteria. If the biomass is rich in starch or it contains a significant amount of cellulose, it is advisable to use special enzymes that accelerate the process of biomass processing. Stable parameters (temperature 30° and normal pressure) must be maintained for efficient process.

However, the developments of an ideal method of biohydrogen production does not stop. And production of this type of fuel from algae is gradually gaining popularity.

This method is called photolysis. Since it has been found that algae produce biohydrogen under certain conditions, this process takes place in a special bioreactor. In the presence of a small amount of sulfur in the environment in algae, the process of photosynthesis is suspended, and then stops completely. In this case, the algae switch to the production of hydrogen instead of oxygen.

Another no less interesting way to obtain this fuel is to reform biogas. Reforming is well studied and widely used. The process of biohydrogen production by steam reforming is well established and is a good alternative in regions where there is a shortage of traditional fuels.

Table 1 shows the characteristics of the main technologies for the production of hydrogen from biomass.

Table 1. Characteristics of the main technologies of biohydrogen production (Epstein, 2020)

Characteristics	Electrolysis of water	Plasma gasification	Steam reforming
Raw materials	biomass	solid household waste	biomass
Technological process	biochemical + electrochemical	thermochemical	biochemical + thermochemical
Stage of readiness	industrial production	industrial production	industrial production
Temperature range, °C	50-800	3500-5000	700-1000
The cost of production ($/kg)	4-5	5-6	2-3
Yield of hydrogen from 1 ton of raw material (m^3)	120	500	300
Impact on ecology	+	+	+

Analyzing the presented table, it can be noted that the above methods of biohydrogen are quite expensive, have a fairly high yield of hydrogen from 1 ton of raw material and are environmentally friendly.

Today, the biochemical method of biohydrogen production is the most popular and widespread. Given that the raw materials may be agricultural waste (husks, meal, etc.), household organic waste, wastewater and sewage, the amount is inexhaustible. Also the production of hydrogen by this method does not require any special conditions and special equipment. Good bacteria are needed for efficient production.

The most suitable for this work are purple bacteria, which are found in alpine springs. Bacteria can be reused after each production cycle. Therefore, this method depends entirely on the activity of bacteria and it is less energy-intensive and cheapest.

In his works, the famous scientist Podgorny A. stressed the possibility of transporting and distributing hydrogen through pipelines as well as natural gas. Advantages of this method: pipelines are laid underground (does not disturb the landscape), occupy less land area (unlike power lines). And, compared with the transmission of electrical energy in the form of alternating current, the advantage is given to the transmission of energy in the form of hydrogen gas through the pipeline. This is economically proven – transmission via a pipeline with a diameter of 750 mm over a distance of 80 km is cheaper than the transmission of the same amount of energy in the form of alternating current by underground cable. At a distance of more than 450 km, hydrogen pipeline transportation is cheaper than using a 40 kV DC overhead power line, and at a distance of more than 900 km, it is cheaper than an 500 kV AC overhead power line. The author claims that when hydrogen becomes a really available fuel, like natural gas today, it will completely and successfully replace it: it can be used in water heaters, heating stoves, kitchen stoves, etc. And since it does not emit harmful substances during combustion, there will be no need in a system for their removal for heating devices. In addition, the steam released during the combustion of hydrogen also moisturizes the air, which in apartments with central heating is too dry. And the absence of flues during construction (saving construction costs) increases the efficiency of heating by 30 percent.

Inaction of Ukraine on climate issues can lead to many issues. For example, the "green course" provides for the introduction of a carbon tax on imports in the EU that worries the Ukrainian exporters. The calculation method has not yet been precisely defined, but theoretically its size will depend on the amount of emissions from the production of a particular product. The carbon tax on imports should level the playing field for the European and foreign producers. In theory, it should stimulate foreign companies to reduce CO_2 emissions, without which the cost of their goods will additionally increase when crossing the European border. The Ukrainian producers will be able to avoid the new collection if they introduce climatic standards similar to the European ones.

Transport. Cars with hydrogen fuel cells are launched by Honda, Toyota, Hyundai and a number of Chinese companies.

The only disadvantage of hydrogen cars is their cost. In hydrogen fuel cells as a catalyst a rare and expensive metal is used – platinum. Because of this, the cost of hydrogen cars starts from 70 thousand dollars.

In 2018, Germany launched the world's first train running on hydrogen fuel cells. The train can travel about 800 km at one gas station and carry 300 passengers.

Hydrogen transport faces many challenges: infrastructure, cheaper hydrogen and hydrogen transport, and security.

Also, a number of experts emphasize that hydrogen is explosive. Hydrogen leakage cannot be traced, so there is a risk of formation of explosive mixtures.

Pure hydrogen cannot be transported by ordinary uncoated metal pipes, it makes the metal brittle, so the gas transmission system and consumer devices need to be upgraded.

Based on the above views, it can be argued that hydrogen is one of the most promising sources of renewable energy and Ukraine has broad prospects in this area of cooperation with the EU, where today there are serious intentions to develop cooperation with Ukraine in the spread of hydrogen technologies.

Ukraine's partnership as a major supplier of "green" hydrogen with the European Union, where hydrogen is gradually displacing fossil fuels and becoming a key energy resource, is a win-win strategy for both parties. Our country is able to become the main market for hydrogen production in Europe.

In order to successfully implement such intentions, which will strengthen Ukraine's European integration, a new structural unit for the introduction of hydrogen technologies is being created within the Ministry of Energy. A working group will also be set up with the involvement of experts from Ukraine and the European Union.

After the EU has made it a priority to replace coal generation, the gas sector has become an important part of achieving this goal. But the European Commission's ambitious plans to decarbonize the economy also mean the need to introduce green technologies in the gas sector to keep pace with the times and stay one step ahead of all market transformations that are important for tackling climate change.

One such innovative solution is the use of “green” (or “pure”) hydrogen produced from water using electricity from renewable sources in gas supplies.

This technology (Power-to-Gas) involves the addition of “green” hydrogen to existing gas pipelines during the transportation of natural gas (up to 20%). It is the most modern, simple, fast, and least expensive way to create a new hydrogen market, because it does not require investment in new infrastructure.

The addition of hydrogen to natural gas significantly improves its properties and reduces CO_2 emissions during the operation of the gas transmission system.

As a result, consumers have the opportunity to use not only safer and climate-neutral fuel, but also save on its purchase. After all, a mixture of natural gas and hydrogen gives more heat than ordinary natural gas, and therefore it is needed less, for example, for use in everyday life or industry (in metallurgical and chemical plants, in heat-generating boilers).

Ukraine has certain achievements in research on adding hydrogen to the gas transportation system. The first large-scale experiment began to be prepared by the Regional Gas Company (RGC) at the end of February 2019. The RGC for the first time in Ukraine began to test transportation of a mixture of hydrogen and natural gas in closed sections of the gas distribution system. This experiment is needed in order to understand how the existing gas delivery system will behave when using hydrogen. At first, it was planned to use a mixture of natural gas with hydrogen from cylinders in the networks in concentrations from

2% to 100%. In the future it is lined up to build a hydrogen production unit.

It is noted that the case is a drop in the cost of electricity produced on the basis of renewable energy sources (RES). For example, within the framework of "best-in-class" American RES projects, "green" hydrogen can be obtained even today at $1.53 per kg, which makes it competitive with "blue" hydrogen, which is obtained from fossil fuels (mainly natural gas) with CO_2 capture, according to an analytical note by Morgan Stanley. The analytical note states that this would make green hydrogen produced by wind power competitive with new gray projects "much faster than previously thought", at a cost of about $1 per kg.

Experts also note that the price of "green" H_2 is "very sensitive" to the cost of electricity. Reducing it by $2 per MWh reduces the cost of hydrogen by $0.10/kg.

According to the forecast of Bloomberg New Energy Finance (BNEF) "Prospects for the hydrogen economy", by 2050, "green" hydrogen could meet up to 24% of global energy needs and reduce global greenhouse gas emissions from fossil fuels and industry by a third. And the price of "green" hydrogen will be equal to the cost of natural gas in energy equivalent in most regions of the world. However, such a scenario can only be realized if policies are implemented to scale up technology and reduce costs.

There is the following situation with the assessment of the cost of hydrogen.

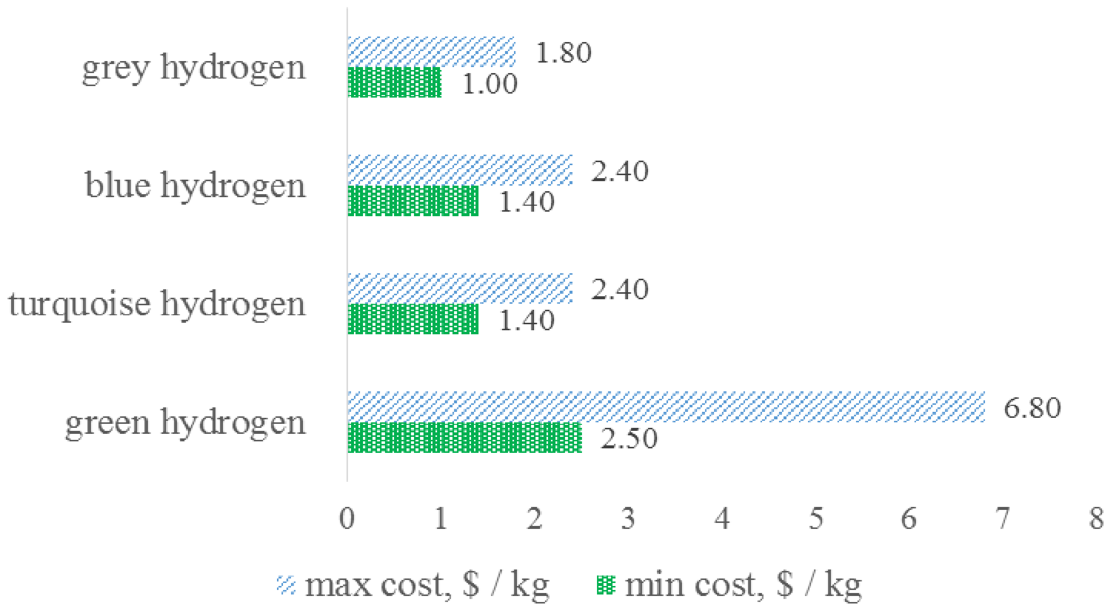


Fig. 5. Cost of Hydrogen (Hydrogen in a low-carbon economy, 2018)

As of 2020 green hydrogen costs between $2.50-6.80 per kilogram and turquoise hydrogen $1.40-2.40/kg or blue hydrogen $1.40-2.40/kg compared with high-carbon grey hydrogen at $1–1.80/kg.

The bet on Ukraine as a priority partner made by the EU states to implement the Green Agreement on the introduction of the latest environmentally friendly technologies to reform key sectors of the European economy is well calculated.

Ukrainian scientists have revolutionary scientific and technical developments in hydrogen technologies for generating electricity. They were highly appreciated in the world 20 years ago. In particular, the first wind power plant in Europe was created by the Institute of Renewable Energy of the National Academy of Sciences of Ukraine together with the Danish company "Volkecenter". Today the Europeans are ready to buy electricity at 18 eurocents per kWh. However, according to the technologies of the Ukrainian researchers, it turns out about

23 euro cents, which is of an order of magnitude a more expensive indicator. According to all calculations, economic and technological, in 2023 the kilowatt-hour obtained from the system wind – electrolyzer – transportation – fuel cell will cost 8 euro cents. This is already a business project that has the right to exist. Therefore, focusing on renewable energy and hydrogen, you can meet the needs of not only your own country, but also earn enormous amount of money for Ukraine.

Based on the research, it is established that the forecasted increase in the biohydrogen production projects, and the related technologies, will reduce the total biohydrogen production costs. Starting in 2030, 80% of biohydrogen production from agricultural raw materials (Tryhuba, 2021).

Now in Ukraine it is economically profitable to use "green" hydrogen. But due to climate change, the time is not far off when countries will pay much more for carbon emissions from fossil energy sources.

Projects in hydrogen energy in Ukraine are based on the demand for hydrogen consumption and research on the volume of its production until 2030 in Europe. The total volume of European investments until 2030 is estimated at 430 billion euros, and support for the development of this area is needed – 145 billion euros. Thus, by 2030, the total investment in the hydrogen industry will amount to 575 billion euros.

The European Green New Deal provides Ukraine an opportunity to quickly restore production of bioenergy potential and create and develop an industry that could potentially make Ukraine energy independent with an export-oriented economy.

Conclusion

Thus, hydrogen energy technologies have not yet gained the quality and efficiency in the world when they could replace traditional energy and existing oil technologies in transport. However, the potential of hydrogen technologies allows us to predict their widespread use in the future, which will contribute to these advantages of hydrogen over fossil fuels.

Hydrogen is gradually becoming one of the main directions that should contribute to achieving energy independence in Ukraine and the world. Governments have begun to create the conditions for investment in the development of hydrogen projects, which include finding ways to reduce the cost of production, technologies for use in various fields and building infrastructure. Thus, hydrogen has a new chance to become the main source of energy for the “green” future.

The development of the hydrogen industry in Ukraine will allow us to receive 20 billion euros of investment in the Ukrainian economy to create 10 GW of new capacities for the production of “green” hydrogen.

It will also allow the formation of an internal market for hydrogen with various sources of energy origin and the formation of demand for this energy. Also, in the future, the possible use of the gas transmission system of Ukraine for the transportation of produced green hydrogen to European countries is being considered.

In return, Europe will receive research and development of the bioenergy component of the economy, which will allow the safe transition of Europeans to an affordable, competitive and stable energy system.

In future studies on the hydrogen energy development in Ukraine, we will consider the ecological and economic component of hydrogen domestic production. In the future, it is planned to consider the transport infrastructure in Ukraine, which is not yet ready to accept hydrogen cars, as is already practiced in the world due to the high cost of fuel cells for cars. Also, one of the most interesting applications for hydrogen is heating residential buildings. Despite the high cost of hydrogen fuel, similar experiments are already being carried out in developed countries and we reflect on to calculate not only its environmental friendliness, but also its economic component.

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CHAPTER 3

CONCEPT OF BIOHYDROGEN PRODUCTION BY AGRICULTURAL ENTERPRISES

Introduction

Agricultural production is first of all focused on providing the population with foodstuffs (Golub, 2017). However, agricultural production can also effectively arrange for the production of biofuel from biomass, in particular biogas, diesel biofuel, bioethanol, baled straw, fuel pellets, briquettes and generator gas. (Kukharets, 2016; Rzeznik and Mielcarek, 2018; Ovcharuk, 2020).

Such a production has become traditional, though the production of renewable energy from biomass causes some fear in researchers as to reducing the level of core product production – foodstuffs, as well as to reducing the amount of plant food in soil caused by using some cultivated areas for growing bioenergy crops as well as by using straw as fuel. (Verdade, Piña and Rosalino, 2015; Gomiero, 2018; Tryhuba, 2021).

For this reason it is necessary to coordinate the main criterion of functioning of the agricultural production:

- ecological safety;
- power supply;
- economic effectiveness.

Such research was conducted and it was found that agricultural production can provide itself with energy resources (Yarosh, 2020; Golub, Skydan, 2020). But this research was based only on biomass utilization, thus the effects on biological safety and economic effectiveness of using hydrogen technologies was not determined.

Material and Methods

Though, as the research testifies, (Gas Decarbonisation Methods, 2020) the EU is planning to produce more than 1700 TWh using hydrogen technologies by 2050. That is why it is appropriate to use hydrogen technologies for producing energy in agricultural production.

Two methods of biofuel production are appropriate for producing hydrogen in agricultural production – thermochemical (Fig. 1) and biofermentation (Fig. 2).

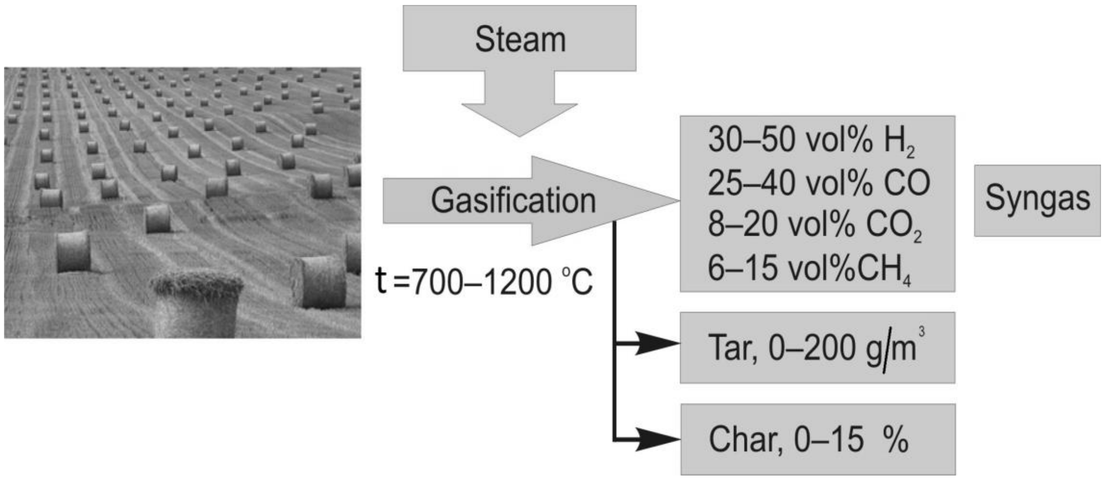


Fig. 1. Thermochemical method (Bhoopendra et al, 2019)

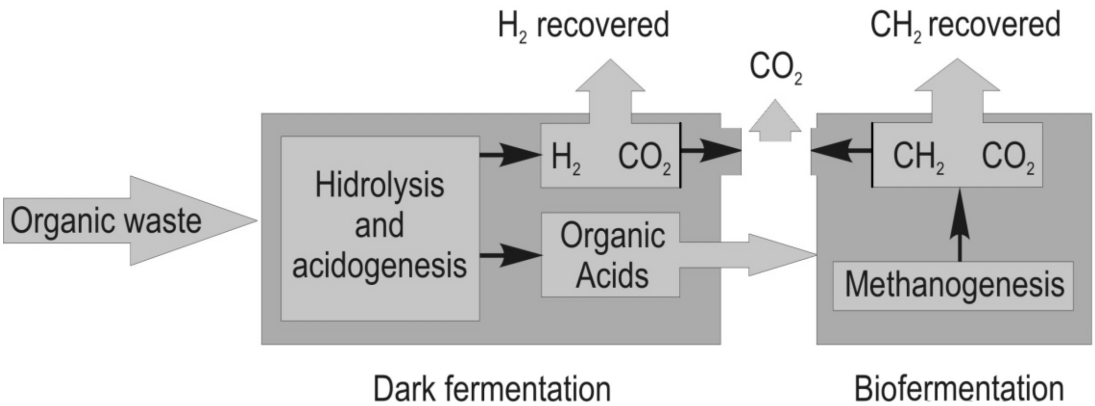


Fig. 2. Fermentation method (Baeyens, 2020)

When using thermochemical method, hydrogen is produced owing to decay of plant origin biomass (Bhoopendra, 2019). To produce hydrogen from biomass by thermochemical method it is appropriate to use gasifiers of a new type (Fig. 3) designed by the authors of the paper.

The main obstacle for producing generator gas from plant biomass is the formation of solid agglomerates (particles, residues) in the process of generator gas producing. To avoid the formation of agglomerates, the authors of the paper have designed the gasifier construction which does not have a fire grate, and gas withdrawal occurs through joints on the side surface of a recovery zone (Golub, Kukharets, 2020).

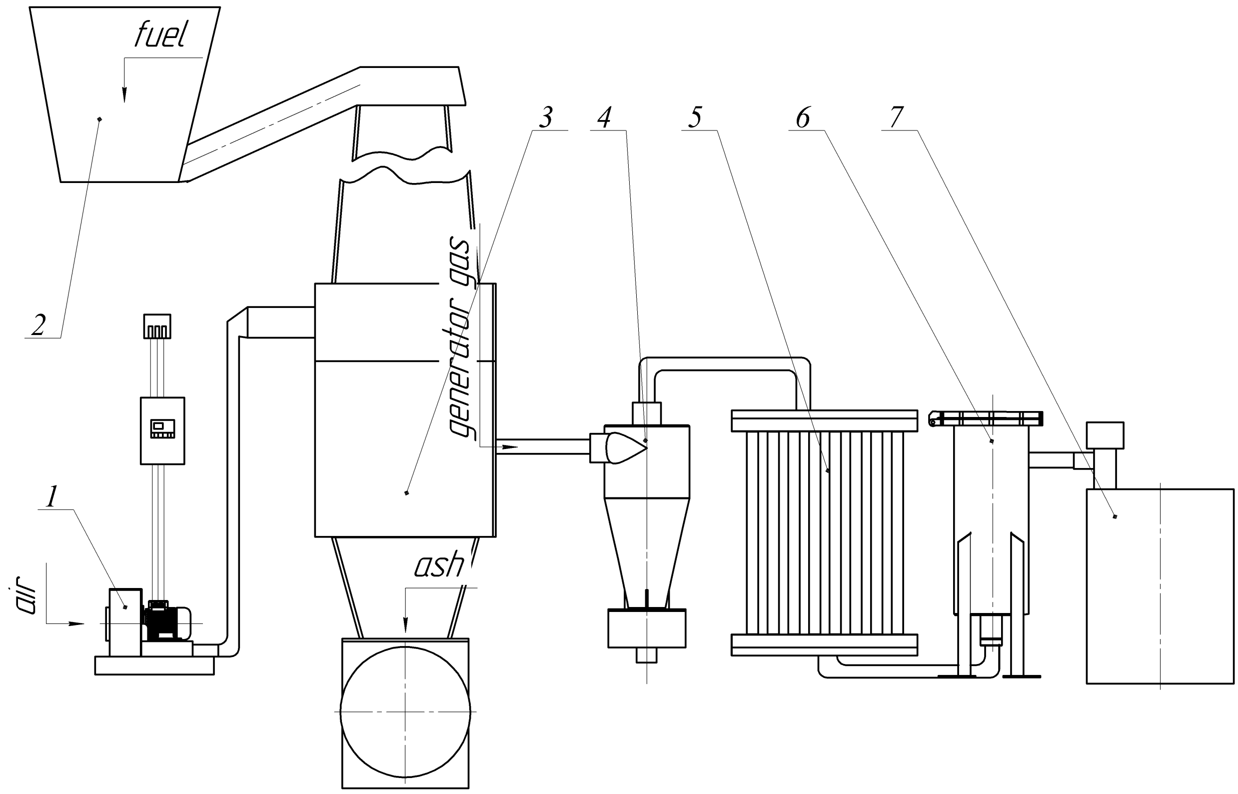
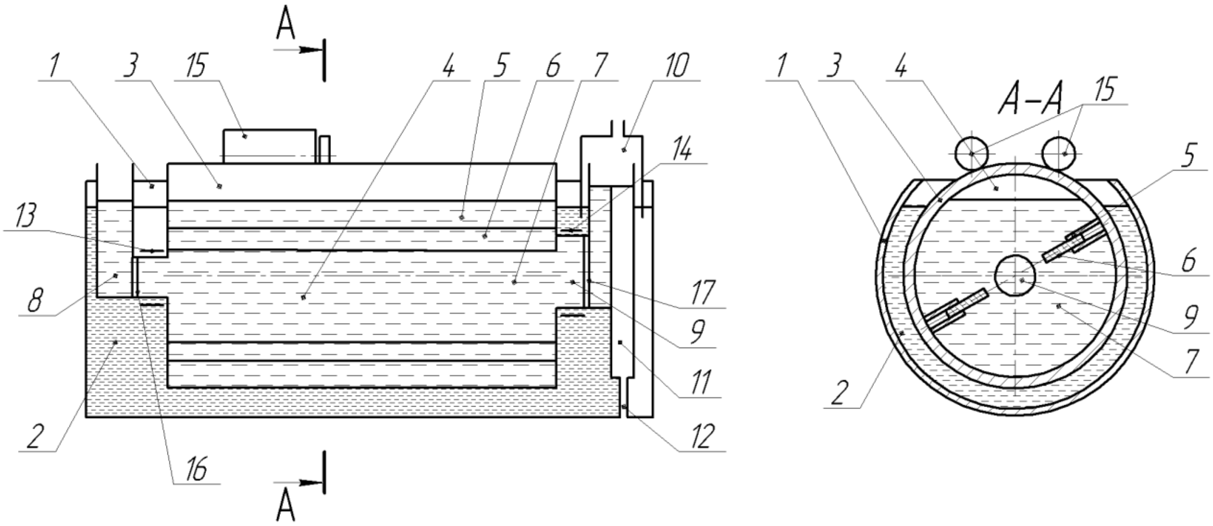


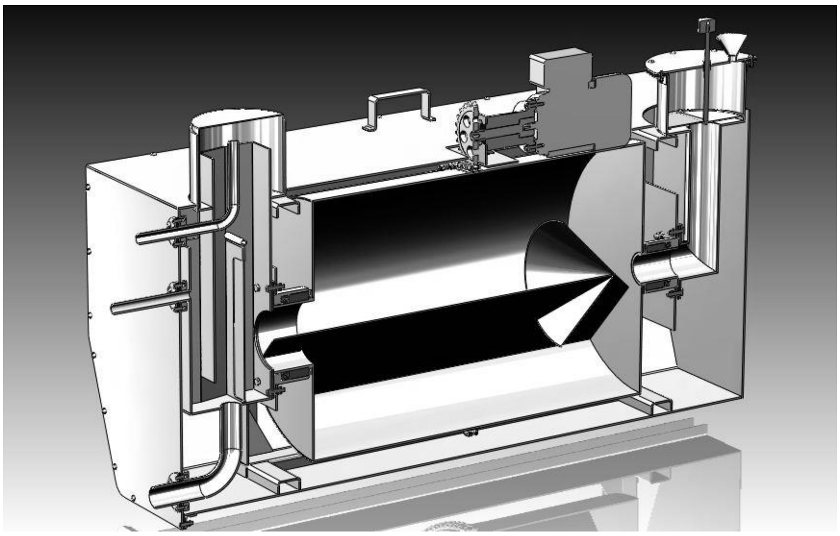
Fig. 3. Thermochemical plant scheme: 1 – a fan for supplying air to the gasifier; 2 – bunker for fuel; 3 – gasifier; 4 – prime filter; 5 – cooler; 6 – fine filter; 7 – gas upgrading

In the process of fermentation hydrogen is received by biomass processing with special bacteria (Baeyens, 2020).

To provide efficient production of hydrogen by fermentation under conditions of agricultural enterprises we suggest using bioreactors designed by us (Fig. 4).



a



b

Fig. 4. Biohydrogen plant, a – scheme, b – model: 1 – horizontal outer housing; 2 – liquid; 3 – cylindrical bioreactor; 4 – fermentation chamber; 5 – partition; 6 – movable plates; 7 – organic mass; 8, 9, 12 – sockets; 10 – gas collector; 11 – the discharge chamber; 13, 14 –bearing joints; 15 – external drive; 16, 17 – interpolator

The authors of the paper (Golub, 2019) suggest new engineering solutions in the system of substrate motion in bioreactor. They insist on using direction change of gravity forces, that influence the movement of organic and mineral fractions of biomass. The bioreactor case is cylinder-shaped which spins around a horizontal axis. Bioreactor rotates in liquid which is in an outside case. Such a construction induces the lift for a rotary bioreactor while discharging the supporting bearings. The friction force reduces and the energy which is used for bioreactor rotation and substrate motion, reduces as well. The bioreactor construction contributes to a steady motion of a substrate and prevents the formation of floating organic particles as well as of immersed sediments.

The use of a suggested equipment for hydrogen production requires further economic and technological research.

The utilization of plant-origin biomass for hydrogen production requires bulk-yield monitoring of grain-crops by-products (straw) as well as giving consideration to coefficient of its utilization for energy requirements.

While determining the theoretical potential of biohydrogen it should be taken into account that some amount of straw is required for using in cattle breeding and for fields fertilizing. Thus, while determining the potential, it the necessary to use the factor for reducing to by-products (Avcıoğlu, 2019). It is also necessary to use the factor for reducing to a hydrogen equivalent with heat value 119.83 mJ/kg (Mortensen, 2020; Cao, 2020) and the lose factor when producing hydrogen.

Research results and discussion

With due regard to feasibility of hydrogen production, an advanced method of biofuel production at the agricultural enterprises has been suggested (Fig. 5).

Diesel biofuel, bioethanol (in the amount necessary for providing the mobile machinery operation), biogas, biohydrogen, generator gas, solid fuel (rolls, pellets (granules), straw briquettes) are produced according to this method.

A part of plant biomass (straw) is used for the production of pellets (granules). Generator gas is made from granules. Generator gas is used for biohydrogen production. Biohydrogen and biogas are made from animal residues by means of fermentation.

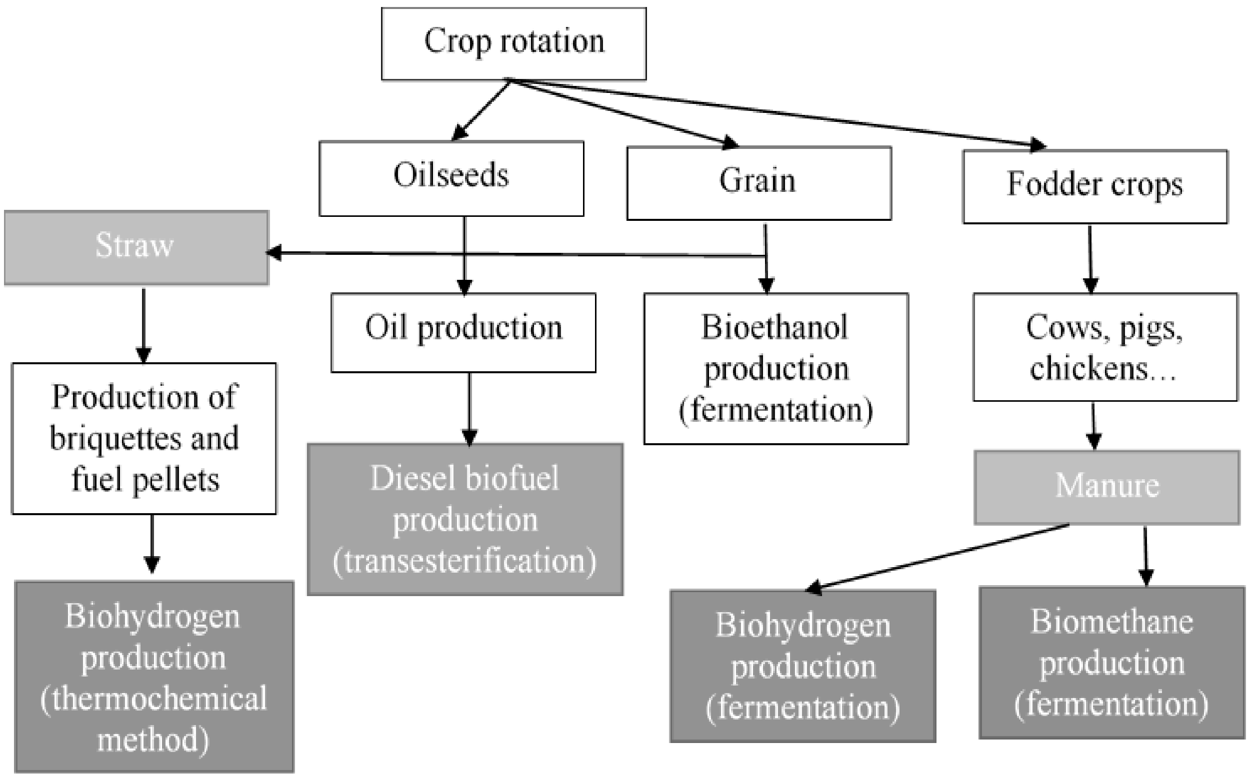


Fig. 5. Scheme of biofuel production at agricultural enterprises

The aim of the research was to assess the quality of delivery as exemplified by a selected company. The main criterion for selecting suppliers for the evaluation was the number of product lines delivered to the company.

They were selected from five assortment groups with the largest number of product lines delivered to the selected company. The thus selected criterion for supplier assessment also limits the impact of exceptional situations, both incidental and individual, on the overall picture of suppliers' activities in the course of cooperation with a selected production company. The scope of work covered the deliveries of fifty suppliers from five assortment groups in 2018.

Gross yield of grain crops which are grown on all types of farms in Ukraine is given in Table 1 (without oil plants).

Table 1. Gross yield of grain crops whose products are suitable for energetic needs in Ukraine, thous. t

Crop	2016	2017	2018	In aggregate, in the course of 3 years
Winter wheat	25320.7	25398.5	23906.6	74625.8
Spring wheat	722.7	759.5	699.2	2181.4
Winter rye	389.2	505.4	393	1287.6
Spring rye	2.4	2.5	0.8	5.7
Winter barley	3637.5	3041	2923.2	9601.7
Spring barley	5798.2	5243.9	4425.9	15468
Oats	499.9	471.4	418.5	1389.8
Millet	189.7	84.4	80.5	354.6
Buckwheat	176.4	180.4	137	493.8
Rice	64.7	63.9	69.2	197.8
Grain maize	28074.6	24668.8	35801.1	88544.5
Sorgo	273.7	198.5	194	666.2

Sources: calculated according to the data of State Statistics Service of Ukraine.

The theoretical potential of biohydrogen (Table 2) and (Fig. 6) was determined with due regards to indices mentioned above.

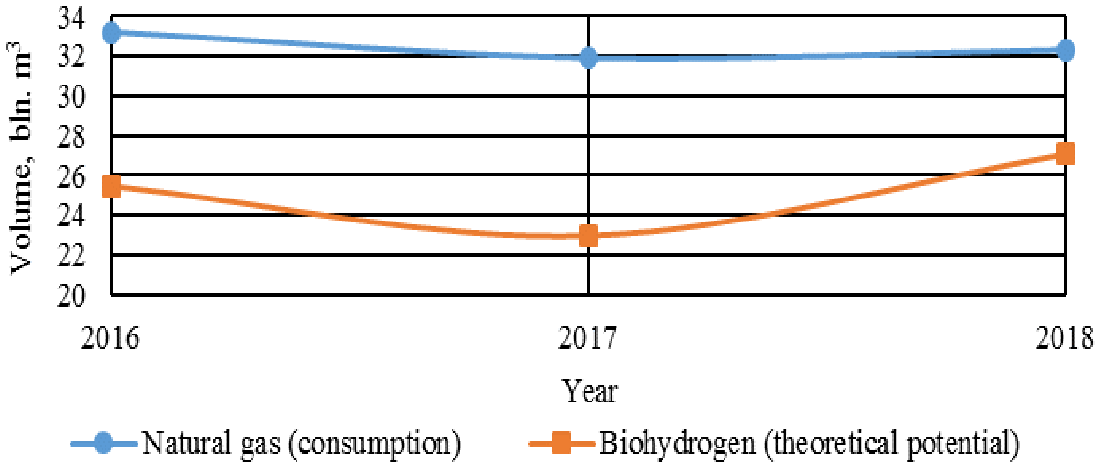


Fig. 6. Biohydrogen potential on the basis of biomass of plant origin in the agricultural production of Ukraine

Table 2. Monitoring of theoretical potential of biohydrogen production from biomass of plant origin during 2016-2018 in Ukraine, mln. m^3

Crop	2016	2017	2018	In aggregate, in the course of 3 years
Winter wheat	11431	11466	10793	33690
Spring wheat	326	343	316	985
Winter rye	119	154	120	393
Winter barley	1093	913	878	2884
Spring barley	1742	1575	1329	4646
Oats	98	93	82	273
Grain maize	10721	9420	13671	33812
In aggregate	25529	23964	27189	76682

Thus, theoretical potential of biohydrogen from biomass of plant origin in Ukraine is 77 bln. m^3, during 3 years (25.6 bln. m^3 on the average).

Conclusions

It is expedient for the agricultural production to produce biohydrogen by thermochemical method from biomass of plant origin and by fermentive method from biomass of animal origin.

It is appropriate to use the improved gasifiers without a fire-grate for biohydrogen production by thermochemical method. And it is expedient to use bioreactors for biohydrogen production by fermentive method.

Theoretical potential of biohydrogen from biomass of plant origin in Ukraine is 77 bln. m^3, during 3 years and 25.6 bln. m^3, on the average.

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CHAPTER 4

FORECASTING QUANTITATIVE RISK INDICATORS OF INVESTORS IN PROJECTS OF BIOHYDROGEN PRODUCTION FROM AGRICULTURAL RAW MATERIALS

Introduction

By 2050, the "New Green Deal" document will cover all definitions of CO_2 reduction in Europe for the so-called ETS sector, which is obliged to purchase CO_2 emission rights, as well as the so-called non-ETS sectors, e.g., transport and agriculture.

They are not part of the system but are also required by law to reduce CO_2 emissions. The main aim of EU Green Deal is decarbonization, i.e., reducing the use of coal and coal products, as well as natural gas and crude oil (International Energy Agency, 2020; Hydrogen Europe, 2020; National Energy and Climate Plans, 2020; European Biogas Association, 2020; Gas Decarbonisation Pathways, 2020).

For this purpose, new activities, financial instruments, and legal acts are being introduced. In transport and industry, the most profitable solutions include the use of biomethane, i.e., purified biogas, and biohydrogen, i.e., hydrogen derived from biomass or other renewable energy sources (Szelag-Sikora, 2019; Sikora, 2017; Gródek-Szostak, 2019; Kargbo, 2021; Yermakov, 2019; Krzysztof, 2018; Kubon, 2018).

Currently, the industry uses hydrogen derived from coal or natural gas. However, the use of biohydrogen should soon become a priority for the national goals of the EU Member States (Hydrogen Economy Outlook, 2020). On 14 March 2020, the European Commission announced the Clean Hydrogen Alliance – a code of conduct that requires the largest companies in Europe, such as refineries or gas operators, to implement the largest projects in the field of decarbonization in the gas or industrial products market. The second area of work is the development of hydrogen technologies in transport, primarily in public transport. Currently, Sweden and Norway operate the largest number of hydrogen filling stations.

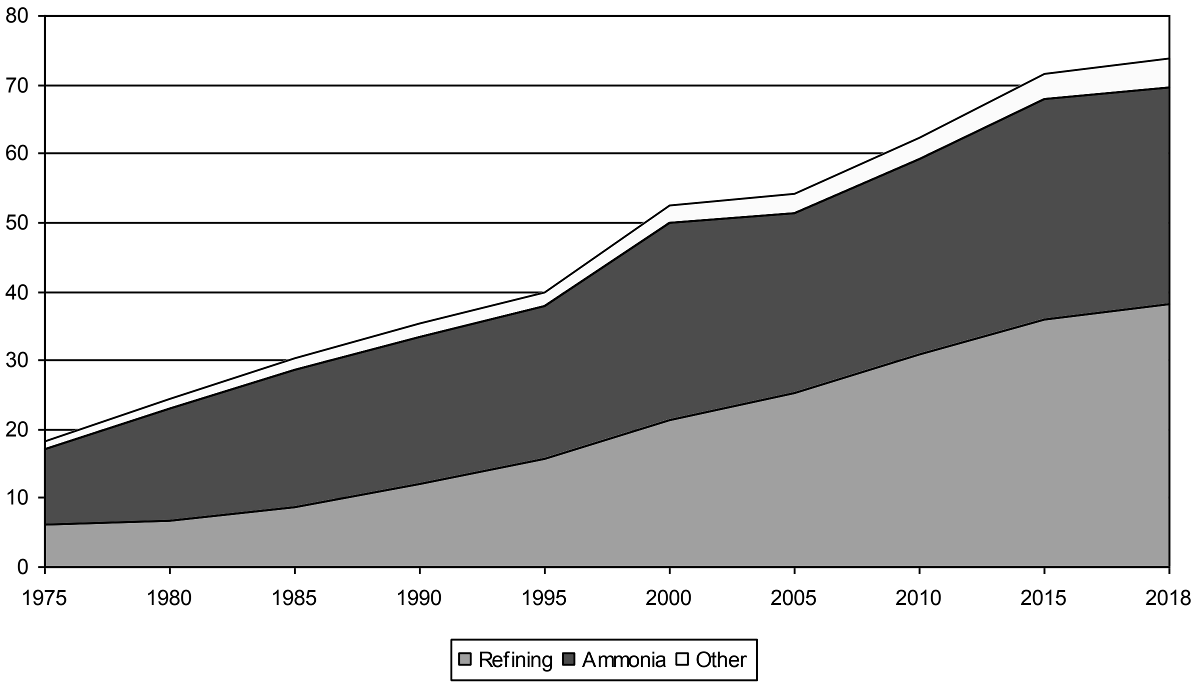

Fig. 1. Global demand for pure hydrogen, 1975–2018 (International Energy Agency, 2018)

In 2019, Germany has also adopted the Hydrogen Strategy to create a hydrogen refueling infrastructure for cars or technical vehicles, but above all, to use the current gas infrastructure for mixing natural gas with hydrogen. This trend is the most cost-effective due to the technical simplicity of mixing both gases (Fig. 1).

The preliminary analysis allows identifying at least four areas that demonstrate the greatest potential for the use of hydrogen, and where it can contribute to the successful decarbonization and global energy transformation in Europe: power and heat production, transport, and industry (Fig. 2).

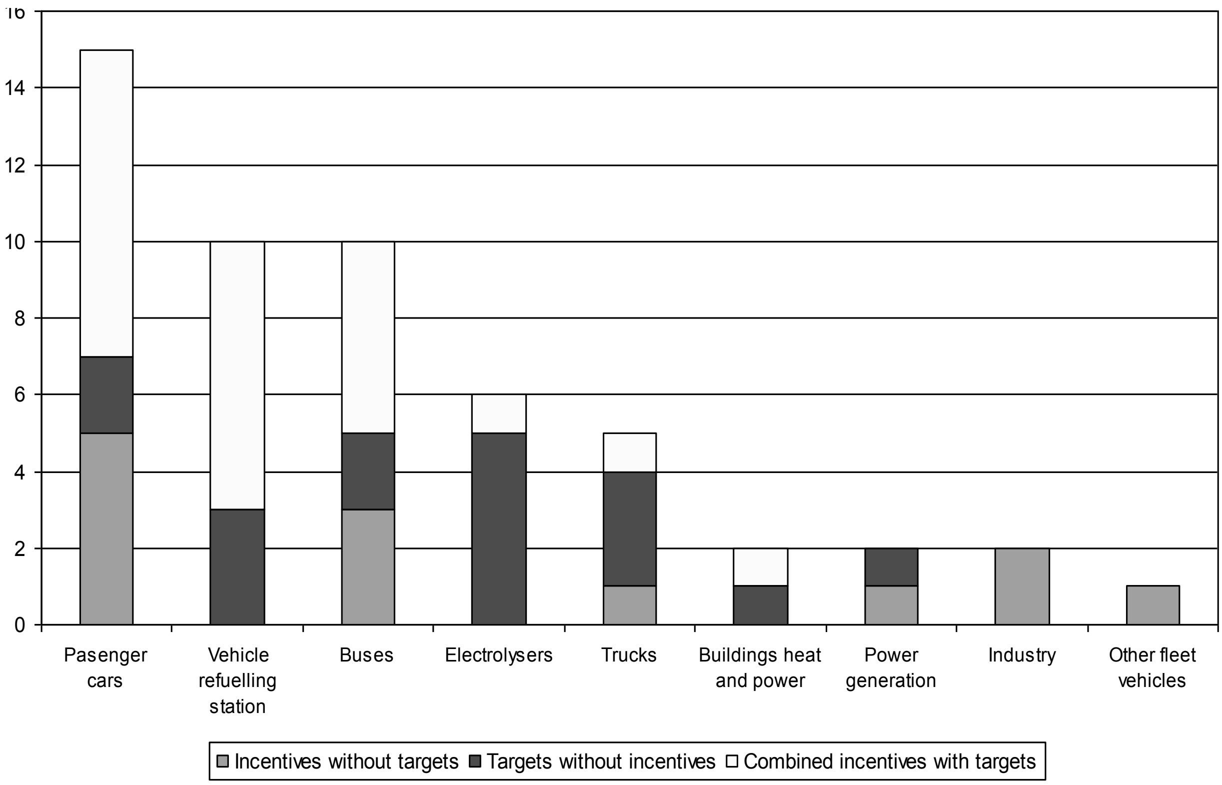

Fig. 2. Current policy support for hydrogen deployment, 2018 (International Energy Agency, 2018)

According to Hydrogen Europe (Hydrogen Europe, 2020), the largest industry organization that unites the largest producers of biohydrogen for the industrial and transport sectors, the key document, Hydrogen in the EU Green Deal COM (2019), includes the most important postulates on hydrogen that will allow EU governments and sectors to effectively implement new policies on this key technology towards decarbonization of the economy (National Energy and Climate Plans, 2020; European Biogas Association, 2020; Gas Decarbonisation Pathways, 2020).

Materials and methods

The performed studies are based on simulation modeling of projects dedicated to the production of biohydrogen from agricultural waste (Tryhuba, 2020; Nikolaidis, 2017; Ishaq, 2021).

It provides high-quality forecasting of investments in biohydrogen production, taking into account the existing global trends in terms of cost and volume used. The stochastic market value of biohydrogen and natural gas is estimated based on statistical and forecasted data of countries where large biohydrogen production projects are implemented.

Models of the variable market value of biohydrogen and natural gas are substantiated according to the known methods of probability theory and mathematical statistics (Tryhuba, 2019; Golub, 2020).

A set of studies in this area was conducted in the educational and scientific laboratory "DAK GPS" at the Institute of Energy of State Agrarian and Engineering University in Podilya (Yermakov, 2019; Krzysztof, 2018; Hutsol, 2018). For high-quality and accelerated risk assessment of biohydrogen production profits, the software written in "Python" technology, developed at the Department of Information Systems and Technologies of Lviv National Agrarian University was used (Tryhuba, 2019).

Research results and discussion

Based on the statistical data analysis (Tryhuba, 2019) and relevant calculations, the authors estimated the stochastic characteristics of the market value of biohydrogen and natural gas (Table 1). It was adopted that the biohydrogen will be produced from agricultural waste.

The biomass gasification based on the hydrogen production system has the energy and exergy efficiency of 53.6% and 49.8%, respectively, at the hydrogen production rate of 106.9 g/s (Mohammad, 2020; Ni, 2006). Thus far, it is one of the most prospective methods of obtaining biohydrogen available in Ukraine (Diachuk, 2017).

Considering the results of research (Szelag-Sikora, 2019; Hutsol, 2018) which state that the global market value of energy resources is described by the normal law distribution, we have constructed the market value distributions for biohydrogen from agricultural waste and natural gas.

Table 1. Characteristics of the market value of biohydrogen from agricultural waste and natural gas, $\$\cdot kg^{-1}$

Indicator	Period		
	2019	2030	2050
Mathematical expectation of the market value of biohydrogen	3.55	1.95	1.15
The standard deviation of the market value of biohydrogen	1.05	0.75	0.45
Mathematical expectation of the market value of natural gas	2.4	2.4	2.15
The standard deviation of the market value of natural gas	1	1	0.85

In particular, based on the analysis of the obtained data (Table 1) and their visualization in the Python 3.8 (Corporation for National Research Initiatives, Reston, Virginia, USA) programming language using Matplotlib, Numpy, and Scipy libraries, the market value distributions of biohydrogen and natural gas for the previous year (2019), as well as forecasts for the years 2030 and 2050 are constructed (Fig. 3).

The obtained densities and functions of the market value distributions of biohydrogen from agricultural waste and natural gas are the foundations for assessing the profit risk in biohydrogen production projects. For high-quality and accelerated profit risk assessment in biohydrogen production projects, the application software written in Python, developed at the Department of Information Systems and Technologies of Lviv National Agrarian University, was used (Tryhuba, 2020).

The initial data for calculation of the investors' profit in biohydrogen production from agricultural raw materials include market value distribution of biohydrogen and natural gas. Based on the obtained data, presented in Table 1, distributions of investor profit from the individual projects for the previous year (2019) and the forecasted years 2030 and 2050 are calculated (Fig. 4).

Based on the obtained distributions of profits in biohydrogen production from agricultural raw materials (Fig. 3), integrated with profit (P_r) and loss curves (P_l) under the set investor requirements – the minimum profit P_s, are constructed in Figure 5.

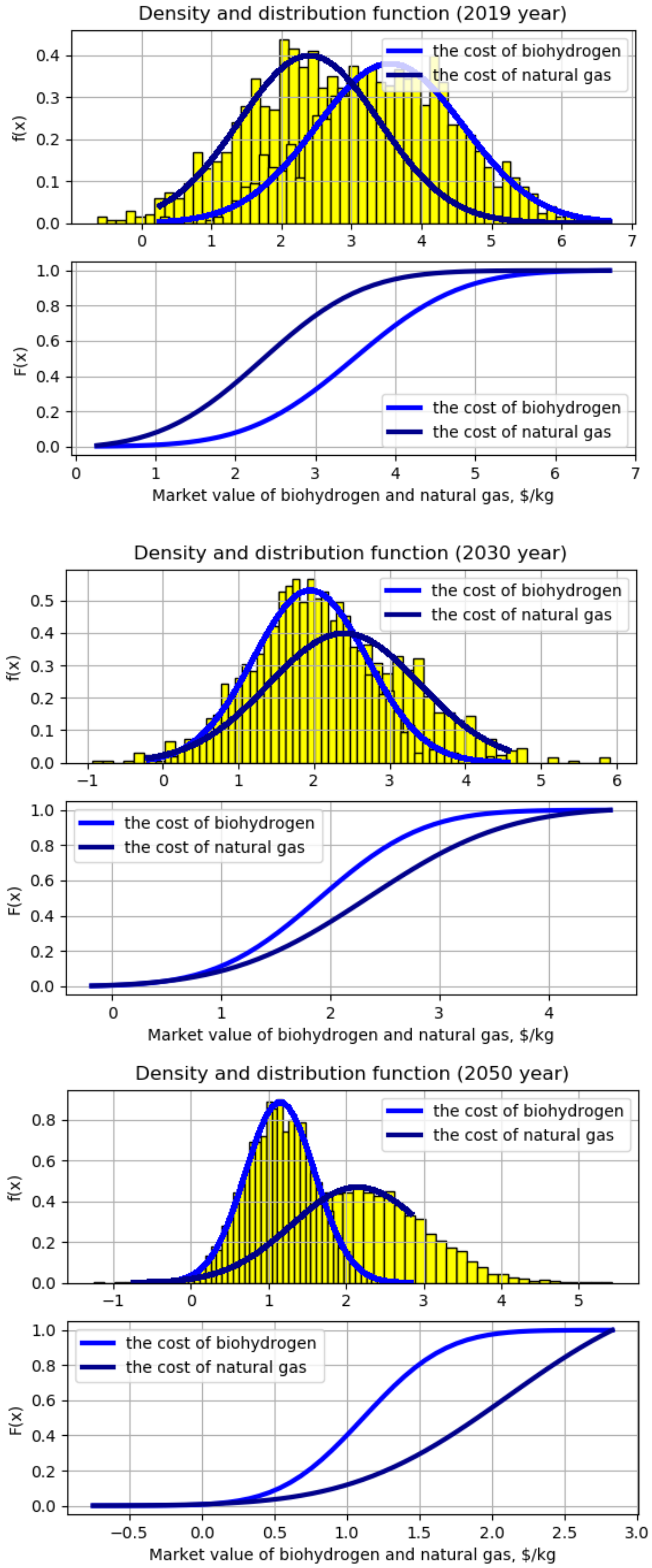

Fig. 3. Density and function of market value distributions of biohydrogen from agricultural waste and natural gas

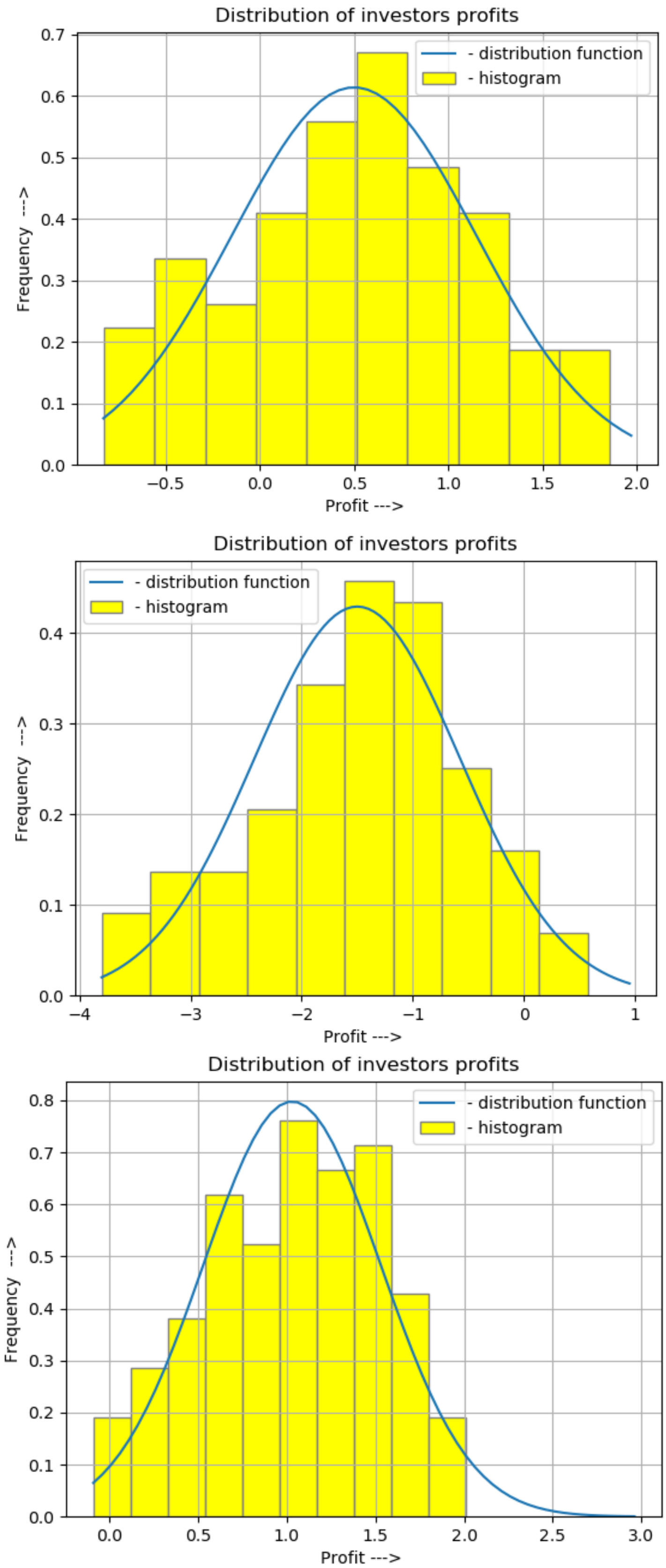

Fig. 4. Histogram and theoretical curve of investors' profit distribution in projects dedicated to the production of biohydrogen from agricultural raw materials

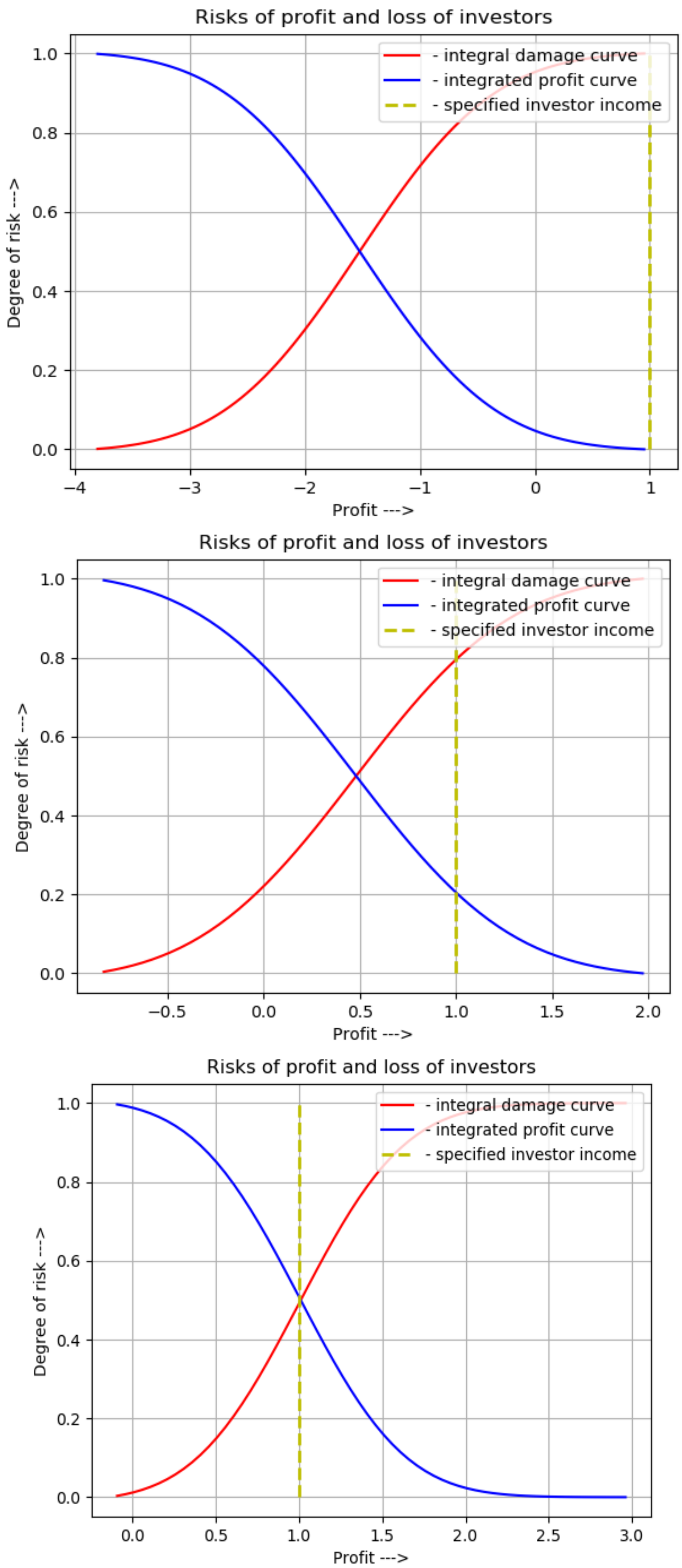

Fig. 5. The integrated curves of profit (P_r) and loss (P_l) for investors in biohydrogen production projects from agricultural raw materials, taking into account their requirements (the minimum profit of investors—P_s = 1 $/kg)

The conducted computer experiments allowed forecasting the quantitative indicators of the profit risk in global projects dedicated to the production of biohydrogen from agricultural raw materials (Table 2).

Based on the obtained results of forecasting the quantitative indicators of the profit risk $R(P_s)$ in the projects dedicated to biohydrogen production from agricultural raw materials, it is established that the profit risk is critical in 2019 for all project options at the minimal profit requirement of 0.1–1.0 $/kg of obtained biohydrogen.

At the same time, the forecasted increase in the scale of biohydrogen production projects, and the level of technologies used, will reduce its production cost and increase the investor profits.

It is predicted, that in 2030, at the requested minimal profit of 0.1-0.2 $/kg of obtained biohydrogen, the production risk will be admissible within 0.3-0.5 $/kg — average, within 0.6-0.8 $/kg — high, and more 0.9 $/kg – critical. At the same time, it is established that in 2050 for changes in the minimal profit within 0.1-1.0 $/kg of obtained biohydrogen, the forecasted profit risk will change from minimal to average.

The results of the research indicate that in 2019, the projects of biohydrogen production from agricultural raw materials were mostly unprofitable and had no value for their investors.

At the same time, starting from 2030, the forecasted profit risk indicators in projects dedicated to the production of biohydrogen and agricultural raw materials indicate that such projects will be valuable for investors and their number will significantly increase globally.

Table 2. The results of forecasting the quantitative profit risk indicators $R(P_s)$ in projects dedicated to the production of biohydrogen from agricultural raw materials[1]

Indicator	Options for the Implementation of the Biohydrogen Production Project									
	1	2	3	4	5	6	7	8	9	10
Minimum profit from biohydrogen production, $/kg	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
2019										
Probability of profit in a biohydrogen production project	0.1	0.09	0.08	0.07	0.05	0.03	0.0	0.0	0.0	0.0
Probability of loss in a biohydrogen production project	0.9	0.91	0.92	0.93	0.95	0.97	1.0	1.0	1.0	1.0
Profit risk in a biohydrogen production project	critical	critical	critical	critical	critical	critical	critical	critical	critical	critical
2030										
Probability of profit in a biohydrogen production project	0.78	0.73	0.57	0.53	0.51	0.44	0.4	0.3	0.26	0.23
Probability of loss in a biohydrogen production project	0.22	0.27	0.43	0.47	0.49	0.56	0.6	0.7	0.74	0.77
Profit risk in a biohydrogen production project	admissible	admissible	average	average	average	high	high	high	critical	critical
2050										
Probability of profit in a biohydrogen production project	0.97	0.93	0.89	0.85	0.8	0.78	0.7	0.64	0.62	0.57
Probability of loss in a biohydrogen production project	0.03	0.07	0.11	0.15	0.2	0.22	0.3	0.36	0.38	0.43
Profit risk in a biohydrogen production project	minimal	minimal	admissible	admissible	admissible	admissible	admissible	average	average	average

[1]Options for the implementation of projects dedicated to the production of biohydrogen differ in the minimum set profit of their investors, $/kg.

Further research should be conducted to substantiate the planning and implementation of projects dedicated to the production of biohydrogen from agricultural raw materials, taking into account the characteristics of production conditions in individual regions and the risk change tendencies in the investment value of the individual projects.

Conclusions

Based on the analysis of the state of the art and practice of biohydrogen production from agricultural raw materials, the relevance and feasibility of the relevant projects have been established. However, the tasks of qualitatively forecasting the value of investors in biohydrogen production projects from agricultural raw materials remain unsolved.

The proposed approach, and the applied forecasting software, are based on simulation modeling. They take into account the stochastic market, and the production conditions of these projects, allowing for high-quality and accelerated risk assessment in biohydrogen production projects.

Based on the research, it is established that the forecasted increase in the biohydrogen production projects, and the related technologies, will reduce the total biohydrogen production costs. Starting in 2030, 80% of biohydrogen production from agricultural raw materials.

The profitability change tendencies in the projects dedicated to the production of biohydrogen from agricultural raw materials were established, taking into account the project requirements. In particular, in 2030, at the minimum return request of 0.1-0.2 $/kg, the risk of obtaining biohydrogen from agricultural materials will be “acceptable”, at 0.3-0.5 $/kg – "average", at 0.6-0.8 $/kg – "high", and at over 0.9 $/kg – "critical". At the same time, in 2050, these indicators will significantly improve.

Along with the changes in the minimum return on investment in biohydrogen production at 0.1-1.0 $/kg, the projected profit risk will change from "minimum" to "average". This indicates that the biohydrogen production from agricultural raw materials will be more relevant and more attractive for investors with every year.

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CHAPTER 5

ECOLOGICAL AND ECONOMICAL SUBSTATIATION OF PRODUCTION OF HYDROGEN

Introduction

The Integration of Ukraine's economy into the European and world economy and the high level of its dependence on the external supply of traditional energy sources (oil and gas) due to the deficit of its own, necessitates the introduction of strategic directions of the domestic bioenergy market. Adoption of legislation aimed at creating favorable conditions for increasing the use of renewable energy sources while identifying strategic priorities in the development program of domestic bioenergy, will achieve the goals of sustainable development of society through the system "man-economy-nature". Ultimately, such an approach will not only allow not to violate the principles of ensuring the energy balance of Ukraine, but also help to preserve the environment and solve social problems.

The development of hydrogen technology is gaining popularity around the world. Currently, the main direction of biomass energy production in Ukraine is the production of thermal energy for district heating of enterprises and private households by burning biomass of wood and agricultural origin.

The hydrogen economy remains a matter of the future, but hydrogen technologies for energy, such as hydrogen storage of renewable energy, hydrogen storage for autonomous and distributed generation, refueling for ever-increasing quantitative and qualitative hydrogen transport, are actively introduced into the economies of developed countries (Dudnikov, 2017; Kuzmenko, 2016).

Hydrogen energy includes a set of technologies for the production, transportation, accumulation and use of a universal secondary energy source – hydrogen. In the concept of hydrogen energy, hydrogen complements the most important secondary energy source – electricity, energy use of hydrogen is determined by the possibility of environmentally friendly electricity generation and long-term storage without losses, including large-scale. The problem of using hydrogen as a promising environmentally friendly and universal energy source and energy accumulator in various sectors of the economy was formulated in the early 70s of last century after the first oil fuel crisis. It became clear that it is necessary to develop new environmentally friendly energy technologies based on the use of renewable energy sources, nuclear energy, coal and universal environmentally friendly energy sources that can replace non-renewable energy resources as they become depleted and more expensive (Kovalenko, 2020; Malyshenko, 2012).

From an ecological point of view, the concept of "green hydrogen" is not always environmentally friendly. Technological processes associated with the manufacture of equipment for hydrogen production are completely non-ecological. This is still an ecologically dirty chain of processes, starting from the stage of extraction of rare earth metals. Thus, the "dirty" part of the technological processes that ensure the production of "clean" electricity from renewable energy sources, simply taken (with all their negative environmental and climatic effects) far beyond the EU – mainly in Asian countries. But the global climate problem is not regional but global.

According to the new “Green Course” of the European Commission (Green New Deal), the main bet is made on the use of renewable energy sources and decarbonized gases, primarily hydrogen.

In this case, hydrogen is considered both as an energy source and as a means of accumulating excess electricity from renewable energy sources during periods of active sun and wind, when their production exceeds consumer demand and can be preserved.

According to the nomenclature used by the research firm Wood Mackenzie, most of the gas, which is already widely used as an industrial chemical, or brown, if it is produced by gasification of coal or lignite; or gray, if it is carried out by steam conversion of methane, which usually uses natural gas as a raw material. None of these processes are completely safe in terms of carbon emissions. Presumably a cleaner option is known as blue hydrogen, where the gas is produced by steam conversion of methane, and emissions are reduced by capturing and storing carbon.

This process can halve carbon emissions, but it is still a long way from carbon-free production. On the other hand, green hydrogen can almost completely eliminate harmful emissions by using renewable energy – fast-growing and often generated in less favorable periods of time – to power water electrolysis (Energy club, 2021).

Materials and methods

For our analytical study on the prospects for the development of biohydrogen projects in Ukraine, we used materials from existing bioenergy foundations in Ukraine and Europe. Among the domestic organizations – the Bioenergy Association of Ukraine (UAIBO) which includes the well-known Scientific and Technical Center "Biomass", Accord Ltd and the public association "Agency for Renewable Energy".

The methodological support of the study was based on a systematic approach, which allowed to reflect the state of research on hydrogen technology, to justify the need to develop energy from hydrogen, taking into account the environmental approach, to calculate and analyse the economic components of hydrogen development.

They also used a graphical and analytical method, which allowed to summarize and visualize the studied processes.

Research results and discussion

One of the main issues of Ukraine's possible participation in Europe's hydrogen energy as a supplier and producer of renewable hydrogen is the possibility of cost-effective production and technically safe transportation to EU countries. At the moment, it makes no sense to approach hydrogen production only from an economic point of view. Traditional types of energy production are certainly much cheaper and proven. But traditional fuels are non-renewable and often environmentally polluting, which is why humanity has turned to renewable sources.

Environmental component of hydrogen production

Negative environmental consequences of the use of petroleum fuels are already visible in large industrial centers, primarily due to transport (The Hydrogen Economy, 2004). Thus, in a city with a population of about 1 million inhabitants, the share of vehicles accounts for almost 70% of the total amount (several hundred tons per day) of environmentally harmful, including toxic emissions. Common forecasts say that by 2030 the number of cars on the planet will double to 1.6 billion. Whether hydrogen production is environmentally friendly depends on the presence or absence of CO_2 emissions at the end of the process.

Today, the vast majority of hydrogen in the world is from the gray category. It is extracted from fossil fuels such as natural gas or coal. And such hydrogen is harmful to the environment, because the process of its production causes huge emissions of CO_2.

Natural gas is a fossil fuel whose entire life cycle is accompanied by greenhouse gas emissions, and renewable energy sources produced from renewable raw materials are biomass. By replacing natural gas with biohydrogen, we reduce greenhouse gas emissions and thus prevent environmental catastrophe.

Therefore, the transition to the use of hydrogen as a motor fuel in transport is a promising task. The undeniable advantages of the new fuel, firstly, are that with any release of energy using hydrogen (fuel cell, conventional heating, internal combustion engine) we have a favorable energy / mass ratio.

That is, hydrogen is an extremely energy-intensive fuel. Thus, when it is burned per unit mass, almost 3.5 times more heat is released than when burning hydrocarbon oils or coal. It is especially important that in the case of hydrogen use there will be almost no emissions of harmful substances, especially carbon dioxide. After all, when hydrogen is burned, only water is formed.

Hydrogen fuel also has its drawbacks: the probability of explosion of the system when the normalized pressure in it is exceeded; it is not always possible to find hydrogen cylinders within walking distance (it is not natural propane gas). The technology has not been fully tested, it takes time to refine and experiment.

Economic component of hydrogen production

During the swift development of solar and wind energy among experts and politicians is growing awareness of the need to use a new gaseous carrier of renewable energy, which would allow not only to compensate for seasonal unevenness and poor predictability of solar and wind generation, but also to completely decarbonize other sectors of the economy – heat, transport, metallurgy, chemical industry and others.

"Green" hydrogen produced without any use of fossil fuels was almost unanimously recognized as such an energy carrier.

Green hydrogen production requires large-scale production of a wide range of new related equipment and infrastructure elements. Electrolyzes and fuel cells, hydrogen engines and specialized vehicles, gas stations and means of transportation and storage.

A direct competitor to hydrogen, natural gas today costs around $220 per 1000 m^3, containing 40,000 MJ of energy. The equivalent volume of hydrogen is ~ 3700 m^3.

That is, to be competitive in the domestic market with natural gas, 1000 m3 of hydrogen must cost ~ $60, which corresponds to $0.67/kg. To begin with, biohydrogen needs to be produced by investing considerable funds in the construction of biohydrogen complexes.

At the same time, as mentioned earlier, the approximate cost of biohydrogen production will be, on average (according to Akkord Ltd), $600 per 1000 m3, which is 10 times more expensive than gas and will be $6.7/kg.

Let's see what is happening with the price of natural gas in the markets in recent years and what are the forecasts for the future.

According to experts in the longer term, the EU GDP growth is projected to slow down to 1.7% per year between 2020 and 2030.

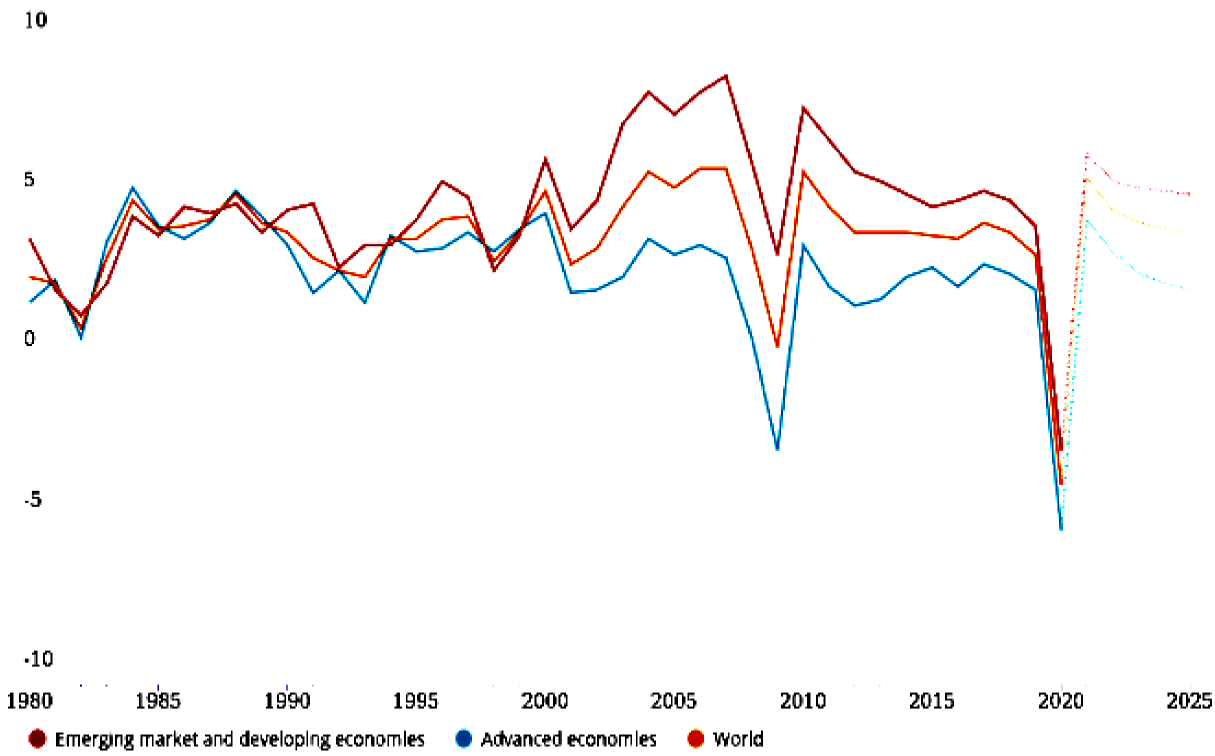

Fig. 1. Real GDP growth (annual percent change) (International Monetary Fund, 2020)

Thus, to produce hydrogen to replace natural gas – it is possible, but economically – it's impractical now and the situation will change little in future, if we consider only the economic approach.

In Europe and the United States, it's predicted that the cost of hydrogen is projected to decline when considering several technology development scenarios and increased production. According to the forecast of the first scenario, it is assumed that the cells are connected to the grid and can produce hydrogen with a power factor of 100%.

The minimum price in Europe is expected to fall from \$4.83/kg now to \$3.21/kg by 2050. In the US, the lowest price of hydrogen production in 2050 is expected to be almost a dollar higher – \$4.15/kg (at \$6.06/kg at present).

According to the forecast of the second scenario, it is assumed that the cells are not connected to the grid, but instead are connected directly to power plants that generate electricity from renewable energy sources. In this scenario, the average price of hydrogen production in the United States will fall from the current \$10.61/kg to \$5.97/kg, and the minimum price will fall from \$4.56/kg to \$2.44/kg. It is expected that in Europe the minimum price will be even lower – \$2.23/kg (at \$4.06/kg at present), and the average price will decrease from \$19.23/kg – to \$10.02/kg in 2050.

In terms of electricity substitution, hydrogen may also be attractive in Ukraine to participate in European hydrogen technology projects.

1 m^3 of hydrogen weighs 89.8 g (44.9 mol), so to obtain 1 m^3 of hydrogen will be used 12832.4 kJ of energy. 1 kWh = 3600 kJ, so we get 3.56 kWh of electricity. The feasibility of switching to hydrogen fuel can

be assessed by comparing the existing tariff per 1 kWh of electricity and, for example, the cost of 1 m^3 of gas or the cost of another energy source.

As we received earlier, the cost of hydrogen is currently $6.7/kg, but experts aim to reduce it to the European ~ 4.83/kg ($430 per 1000 m^3), $0.43 per 1 m^3 (which will be 3.56 kWh of electricity). Therefore, the cost of 1 kWh of electricity will cost $0.15 or 0.13 euros. Compared to the current tariff in Ukraine – 0.05 euros, the calculations are not profitable. But 0.13 euros is the cost of hydrogen that Europe is counting on in its hydrogen strategy and with which it can start synergies.

Regarding the attractiveness of using hydrogen for transport 1 kg of natural gas (55.6 mJ) is 1.39 m^3, currently it costs $0.37/kg in Ukraine. Per 100 km requires 10-12 kg of gas, which will average $4.07.

A hydrogen supply of 5-7 kg is enough for a mileage of about 500 km – on average, the developers promise to achieve hydrogen consumption, which will be about 1 liter per 100 km, but in reality the flow is 1.1-1.3 kg per 100 km (E-move Project, 2017). We have such a high efficiency of hydrogen use due to the efficiency of internal combustion engines: the efficiency of gas combustion – 10-42%, the efficiency of hydrogen combustion – 75-85%.

1 kg of hydrogen – 11.1 m^3 (142.43 mJ), take the minimum projected cost of $2.23-4.3/kg or it will be $2.7-5.5 per 100 km. Even in a more expensive scenario, the cost of 100 km is economically comparable and, of course, environmentally efficient.

What then hinders the development of this technology. Fuel cells and volumetric hydrogen cylinders are the "heart" of the entire hydrogen car system. With cylinders, everything is simple and clear:

- multilayer composite materials;
- today they already have a relatively low cost;
- good resistance to destruction;
- they take the place of the fuel tank and the trunk pallet.

But with fuel cells, everything is much more complicated: they are expensive to produce (used platinum coating) and can be easily destroyed. The cost of such an engine will be many times more expensive than those we have today and there aren't many consumers who are willing to buy a car more expensive just to save the environment.

But we believe that this technology is very promising for large industries in transport, such as aircraft, large water transport, trains.

Conclusion

After conducting preliminary calculations, we came to the following conclusions. Projects to replace natural gas with hydrogen, today, from an economic point of view are not profitable. The process of adding hydrogen to the gas system of Ukraine requires additional research, in terms of a safe maximum ratio of gas and hydrogen. Some scientists talk about the limit range of 5-10%, others push it to 20%. All in one – the inevitability of hydrogen corrosion and increased brittleness of the metal when using traditional carbon steels, due to the penetration of very small hydrogen molecules into their crystal lattice. Each individual situation requires painstaking research and largely depends on the condition and wear of the system.

For this reason, in many countries around the world are building special separate water pipelines, which transport pure hydrogen, suitable for further use in fuel cells. According to average estimates, the cost is approximately 60-70% higher than the cost of construction of standard gas pipeline systems. The necessary infrastructure is also undergoing the necessary changes in this case.

Regarding the production of electricity from hydrogen, while achieving a reduction in the cost of hydrogen production to $4.83, we will get a result that is currently attractive for Europe and will attract potential investors.

The most attractive are the calculations for the use of hydrogen in the transport system, which is perhaps the largest polluter of the ecosystem.

An obstacle to development is the increase in the cost of cars if they switch to hydrogen technology, but this does not diminish the importance of technology for major transport.

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CONCLUSION

Ukraine is a strategic player in energy transit as well as one of the largest producers of hydrocarbons in Central and Eastern Europe. Theenergy sector is undergoing a major transformation in the fields of power generation and oil and gas.

Hydrogen production from biomass may become one of the leading areas of bioenergy in Ukraine soon. Currently, the main direction of biomass energy production in Ukraine is the production of thermal energy for distributed heat supply of enterprises and private households by burning biomass of wood and agricultural origin. Nowadays in Ukraine, there is a technology for the production of biohydrogen.

The theoretical potential of biohydrogen was established with due regard to the amount of biomass which is necessary for utilization in livestock agriculture, for fields fertilizing as well as with the consideration of the coefficients of concordance with hydrogen equivalent and loss factor under biohydrogen production. Theoretical potential of biohydrogen from biomass of plant origin in Ukraine amounts to 77 billion m^3, during the period of three years (on average 25.6 billion m^3).

We calculated the environmental and economic effects of hydrogen production as a source of energy. We have come up with the following conclusion that if there is a demand for the final product, hydrogen production will be attractive from economic standpoint and will not require a green tariff or other support from the government. The market price of biohydrogen will be $4-5 per kg and will be comparable to that which the European Union aims to achieve.

We assume that hydrogen may be a cleaner source of energy for end users, especially in the transport sector in the future.

One of the main issues of Ukraine's possible participation in Europe's hydrogen energy program as a supplier and producer of renewable hydrogen is the possibility of its technically safe and cost-effective transportation to EU countries.

As the main hypothesis considered transportation of hydrogen using the gas transmission system of Ukraine as part of a mixture with natural gas. Calculations show that, of course, obtaining energy from hydrogen, even in mass production, will be more expensive than alternative traditional and non-traditional methods. The development of this technology, in any case, is promising in terms of the development of energy independence and environmental development of states. The effect of scale in mass production of hydrogen energy should also work, which will significantly reduce the cost of this technology.

Biohydrogen production at the agrarian enterprises is the matter to be treated as urgent. It is appropriate to utilize two methods of biohydrogen production: thermochemical method – from biomass of plant origin and fermentive method – from biomass of animal origin. It is appropriate to use gasifiers for thermochemical method and bioreactors for fermentive method.

As a conclusion, the path of the hydrogen industry development in Ukraine will allow us to receive additional investments in the Ukrainian economy for the creation of new capacities for the production of "green" hydrogen.

In return, Europe will receive research and evolution of the bioenergy component of the economy, which will permit the safe transition of Europeans to an affordable, competitive and stable energy system.

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