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FORMING PROSPECTS FOR THE WORLD BIFUEL MARKET IN THE CONTEXT OF DECARBONIZATION AND SUSTAINABLE DEVELOPMENT

ФОРМУВАННЯ ПЕРСПЕКТИВ СВІТОВОГО РИНКУ БІОПАЛИВА В КОНТЕКСТІ ДЕКАРБОНІЗАЦІЇ ТА СТАЛОГО РОЗВИТКУ

Summary. Large-scale climate change is increasingly leading to rising global temperatures, an increase in the number and scale of natural disasters, catastrophes, floods, droughts in the summer and other negative manifestations. According to authoritative international organizations in the field of climate research, 2024 was the warmest year since 1850, while it is also indicated that the last ten years have been the warmest ten years in the entire history of climate observations. In the context of sustainable development and decarbonization, the most important task for the global economy is the development of renewable energy sources, in particular bioenergy, which already occupies a significant position in the global economy. It is indicated that the total consumption of bioenergy on the planet in 2023 was approximately 60 Ej, while biomass such as wood, coal and other solid bioenergy accounts for about a third of the total, and modern bioenergy occupies the remaining share. In the process of decarbonization, the role of transport biofuels is increasing significantly. Biogas can be converted into biomethane and used as a replacement for natural gas, as well as act as a dispatch source of electricity. It is indicated that such extremely important for the global economy areas of transport as marine ocean shipping and aviation cannot be transferred in the near future to any other type of renewable fuel, except for biodiesel and sustainable aviation fuel, respectively, which makes these two types of biofuels possess a key unique property. It is noted that the role of biofuels as a renewable energy source in the global economy will rapidly increase in the future.

Keywords: bioenergy, biofuels, sustainable development, world economy, decarbonization, biodiesel, sustainable aviation fuels, development, innovation, management, prospects.

Анотація. Масштабні кліматичні зміни з дедалі більшою інтенсивністю призводять до підвищення світових температур, кількості і масштабів стихійних лих, катастроф, повеней, посух та інших негативних проявів. За даними авторитетних міжнародних організацій в галузі вивчення клімату, 2024 став найтеплішим на планеті з 1850 року, при цьому вказується також, що останні десять років були найтеплішими десятьма роками за всю історію спостережень. Показано, що температура 2024 року в Європі була на 1,47°C вище

середнього значення за період 1991–2020 років і на 2,92°С вище за рівень 1850–1900 рр. У контексті сталого розвитку та декарбонізації найважливішим завданням для світової економіки є розвиток відновлюваних джерел енергії, зокрема біоенергетики, яка вже сьогодні займає помітні позиції у світовому господарстві. Вказується, що загальне споживання біоенергії на планеті в 2023 році склало приблизно 60 Едж, при цьому така біомаса, як деревина, вугілля та інша тверда біоенергія, займає приблизно третину загальної кількості, а сучасна біоенергетика – дві третини. У процесі декарбонізації дуже значно зростає роль транспортного біопалива, особливо етанолу та біодизелю, які можуть використовуватись на автомобільному або залізничному транспорті. Властивості біогазу дозволяють припускати його застосування на дуже тривалий час, оскільки він може бути перетворений на біометан для заміни природного газу і виступати в ролі диспетчерського джерела електрики. Вказується, що такі вкрай важливі для світової економіки сфери транспорту як морське океанське судноплавство та авіація не можуть бути переведені в найближчій час на будь-який інший вид відновлюваного палива, крім відповідно біодизеля та стійкого авіаційного палива, що робить останні унікальними. Відзначено, що роль біопалива як поновлюваного джерела енергії у світовій економіці стрімко зростатиме. Розвиток біоенергетики потребує концентрованих зусиль та ефективного інноваційного менеджменту для отримання оптимальних технологій виробництва і використання відновлюваних видів палива в інтересах сталого розвитку світової економіки.

Ключові слова: біоенергетика, біопаливо, сталий розвиток, світова економіка, декарбонізація, біодизель, стійке авіаційне паливо, розвиток, інновації, менеджмент, перспективи.

Problem statement. Comprehensive reviews by international organizations indicate the global climate consequences of human activity, which already lead to destructive natural disasters, hurricanes, droughts and negative economic consequences. Sustainable development of human civilization presupposes harmonious economic growth that does not damage the natural habitat.

Analysis of recent research and publications. The issues of studying the processes of economic growth, numerous factors of sustainable development of the world economy, analysis of destructive manifestations of climate change, progressive development of the most promising renewable energy sources, decarbonization issues arouse the steady interest of scientists, practical experts, specialists in the field of management, innovation, which is accompanied by a large list of scientific articles, reviews, development forecasts. Fatih Birol and Ursula von der Leyen [1; 2] consider the dynamics of providing Europe and the world with various types of energy, including climate-neutral energy. The most important areas of development are outlined, including renewable energy and energy efficiency. It is noted that it is necessary to create large-scale financing mechanisms in order to triple investments in clean energy in developing countries. The authors of the study [3], Borysiak O., Mucha-Kuś K., Brych V., Kinelski G., focused on examining a set of issues of managing climate-neutral innovations and energy security. Researchers Shu Zhang, Yubo Ma, Xinzhu Zheng, Qianting Zhu, Xu Tang, in their work [4], consider the energy security assessment system in the context of the green and low-carbon transition of the economy, which is actively taking place in developed countries of the world. Kuznetsova I. points out in the article [5] that the development of production with low carbon dioxide emissions is a strategically important direction among the promising goals of enterprises. The important benefits of zero-emission policies for the environment, energy security and energy equality in developing countries are analyzed in the work of the authors Gouda K.C., Thirumalai Raja R. [6]. Decarbonization measures of the global economy contribute to the sustainable development of various regions of the planet, including those where such processes have not yet gained high momentum. This is a promising direction for all countries.

Previously unsolved parts of the overall problem. The problem of decarbonization of the global economy attracts the attention of a wide range of researchers. The complexity and diversity of the processes of development of energy, transport and other spheres of the economy determine that their detailed study, taking into account the constant dynamics of such processes, cannot be fully exhausted. Of current scientific and practical interest is the study of modern directions of development of bioenergy, production and use of biofuels within the framework of active efforts to decarbonize the economy in the context of sustainable development of mankind, the definition of innovative priorities and effective management of processes, which determines their compliance with the challenges of the time.

The aim of the article is to formulate a model for the development of bioenergy in the context of decarbonization.

Summary of the main research material. Significant global changes in the planet's climate, as clearly demonstrated by the document "Global Climate Highlights 2024", which is presented by the Copernicus Climate Change Service, have shown the following [7]:

– 2024 was the warmest year on record since 1850;

– the average global temperature was 15.10°C in that year, 0.12°C warmer than the previous highest annual value, which occurred in 2023;

– 2024 was 0.72°C warmer than the 1991–2020 average and 1.60°C warmer than pre-industrial levels;

– the last ten years have also been the warmest ten years on record.

The performance in Europe, according to the Global Climate Highlights 2024, was also quite striking in a negative sense [7]:

– 2024 was the warmest year on record in Europe, with an average temperature of 10.69°C, 0.28°C higher than the previous warmest year for the continent, 2020;

– the temperature in 2024 in Europe was 1.47°C above the 1991–2020 average and, most significantly, 2.92°C above the 1850–1900 level.

Climate change in 2024 was also noticeable for the World Ocean [7]: "the annual average sea surface temperature (SST) over the extra-polar ocean reached a record high of 20.87°C in 2024". Above-average SSTs were recorded in most ocean basins, with record values in the North Atlantic, Western Pacific and Indian Oceans. The total amount of water in the atmosphere was reported to be at a record in 2024, 4.9% above the 1991–2020 average, significantly higher than the second- and third-highest values in 2016 (3.4%) and 2023 (3.3%). Global Climate Highlights 2024 highlights that a large number of extreme events have been recorded around the world, including heat waves, floods, droughts and forest fires [7].

As the review [8] points out: the total bioenergy consumption on the planet in 2023 was approximately 60 EJ. The difference in the use of biomass is noted. Biomass such as wood, coal and other solid bioenergy, which is used in traditional cook stoves, accounts for about a third of the total, and modern bioenergy accounts for the remaining share. It is indicated that in the industrial sector "modern solid biomass is mainly used where process residues are available, such as food or paper production. It can also be employed in the power sector as a dispatchable source of renewable electricity, or in improved cookstoves to replace the traditional use of solid biomass" [8]. In the process of decarbonization, the role of transport biofuels, especially ethanol and biodiesel, is increasing significantly, as these types of fuel can be used not only in, for example, automobile or rail transport, "but can have long-term advantages in areas where electrification is challenging, such as shipping and aviation". The nature of biogas use suggests that it could play a major role in the long term on a global scale, as it can be converted into biomethane for use as a replacement for natural gas and, of significant additional importance, can act as a backup tool for operational power generation.

The review [8] provides the following forecast scenarios for the development of the global economy up to 2050, namely: Stated Policies Scenario (STEPS), Announced Pledges Scenario (APS), Net Zero Emissions (NZE) (Fig. 1).

Solid fractions of biomass (Fig. 1) are used, as a rule, in industries that directly generate waste in one form or another, for example, in the production of paper, food or other similar products. The report notes that biomass can be used in the energy sector, but for auxiliary purposes, when it is necessary to manage energy production relatively quickly during periods of increased energy demand. It is emphasized that, unlike, for example, natural gas, solid biomass is a renewable energy source.

As stated in the document [8]: "Transport biofuels, primarily ethanol and biodiesel, can be used across different transport modes but can have long-term advantages in areas where electrification is challenging, such as shipping and aviation. Biogas is

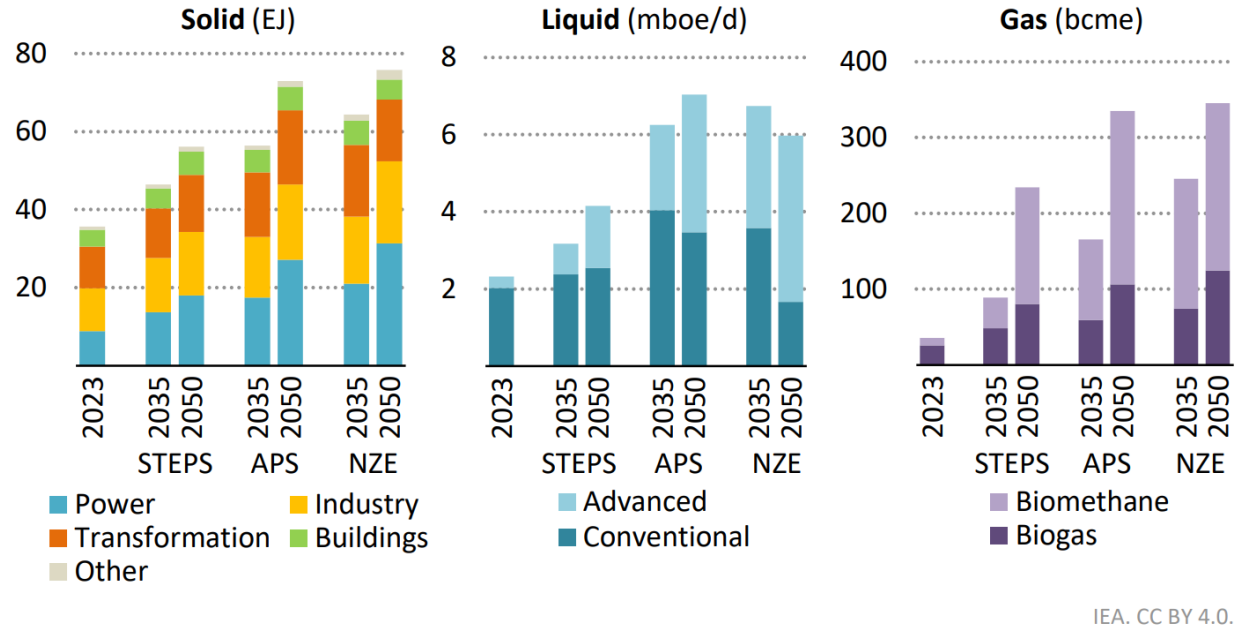

Figure 1 – Modern bioenergy demand by type and scenario, 2023–2050

Source: [8]

used as a local source of dispatchable heat and power, or when upgraded, can be converted to biomethane for use as a drop-in replacement for natural gas". It is particularly pointed out that in such very important for the world economy spheres of transport as highly developed and irreplaceable, at least in terms of transporting large volumes of cargo across the oceans, sea shipping and aviation, passenger and transport, cannot be transferred in the near future, and perhaps even in the more distant future, to electric energy. In this case, the importance of ethanol and biodiesel increases very noticeably. Biogas is already widely used as a local source of heat and electricity when it is urgently needed, but it can also be converted into biomethane and used as a replacement for natural gas.

Solid bioenergy (Fig. 1) accounts for about 85% of total modern bioenergy demand. This share declines in all scenarios to about three-quarters by 2050. In STEPS, modern solid bioenergy demand reaches 45 EJ by 2035 and 55 EJ by 2050, with notable growth in demand from the Chinese power sector and Indian industry. The APS and NZE scenarios project higher growth, to 75 EJ by 2050. The use of solid biomass for electricity generation is the single largest source of bioenergy demand in these two scenarios. This is primarily a result of the large need for dispatchable power in a world in which electricity accounts for about half of total final consumption. The largest source of growth is the power sector in China, where consumption grows from 3 EJ today to 7 EJ in 2050 in the APS.

According to the World Energy Outlook 2024 review, which is presented by the International Energy Agency [8], global demand for liquid biofuels increased by 7% in 2023 and reached 2.3 million barrels of oil equivalent per day (mboe/d). A very important factor of this document is that in the STEPS forecast (Fig. 1), such demand increases to 3.2 mboe/d in 2035 and to 4.1 mboe/d in 2050, mainly due to the increase in demand for sustainable aviation fuel (SAF) from an extremely insignificant figure even on a global scale to more than 0.8 mboe/d. An even more noticeable increase in demand for liquid biofuels is seen in the APS forecast (Fig. 1), where it is expected to grow to 6.3 mboe/d by 2035 and 7 mboe/d by 2050. In this case, the distinguishing feature is that more than 50% of the increase above the STEPS level is due to increased demand for SAF, and most of the remaining increase should come from biodiesel. But the most intense demand for liquid biofuels is expected in the NZE forecast (Fig. 1), namely: 6.5 mboe/d by the early 2030s, with SAF accounting for about 20% of total consumption. The analysis [8] also showed such an important difference in the forecast estimates: the demand for liquid biofuels stabilizes in the NZE after 2035 and will be lower than in the APS forecast by 2040, which is explained by a more significant assessment of the impact of electrification on the entire world economy in the NZE forecast. An interesting feature is the division of countries into groups based on the level of growth in demand for liquid biofuels in the STEPS scenario: such demand will increase by 75% between 2023 and 2035 in emerging market and developing economies, while the forecast estimates that demand will decrease by about 10% in developed economies, which will probably happen due to a qualitatively more intensive use of electric vehicles and electricity in various sectors where liquid biofuels could also be used. Countries such as India, Indonesia, and Brazil, which have a combined population of about two billion people and have the potential to produce large quantities of biofuels from their own feedstock. The review predicts that by 2050 these countries together will provide about 50% of the demand for liquid biofuels, compared to 30% today.

Of interest is the analysis of the global demand for biogas and biomethane in the near and distant future. In this regard, the analysis of document [8] allows us to state the following: according to the STEPS forecast estimates, the global consumption of biogas and biomethane will double by 2035 and amount to 90 billion cubic meters. In all three scenarios (Fig. 1), the share of biomethane in the total demand for biogas will increase by 2050, and, as is especially noted, it is biomethane that is given great importance as an energy source that can be used relatively quickly at times of increased energy demand, i.e., biomethane is an important tool for ensuring dispatchable generation. In addition, biomethane can be considered as a substitute for natural gas in those numerous areas where natural gas is currently used, for example, for household needs of the population. The comparatively higher cost of biomethane in relation to natural gas is currently a negative factor that hinders the development of biomethane production. In this regard, the review [8] states the following: "The cost gap between natural gas and biomethane currently averages around USD 10/MBtu in key gas-consuming regions, but this narrows to USD 4/MBtu in the APS reflecting CO_2 pricing, policy support and economies of scale. In the STEPS, advanced economies see their share of total global demand decline from about 50% today to just 21% in 2050. Demand in China meanwhile rises considerably, reaching nearly 100 bcme by 2050 and accounting for 40% of global demand. In the APS and NZE Scenario, total biomethane demand amounts to around 220 bcme by 2050, compared with about 150 bcme in the STEPS". It is obvious that the development of production and consumption of biomethane has significant prospects and it will occupy an important place in the energy sector in the future.

Decarbonization issues occupy an important place in European politics. The European Union's Renewable Energy Directive is the legal basis for

the development of clean energy in all sectors of the economy. As stated in the document [9]: "since the introduction of the Renewable Energy Directive (2009/28/EC), the share of renewable energy sources in EU energy consumption has increased from 12.5% in 2010 to 24.5% in 2023. Sweden had the highest share of renewables in its consumption (66.4%), ahead of Finland (50.8%) and Denmark (44.9%), as reported to Eurostat". The Renewable Energy Directive aims to increase the share of renewable energy in EU energy consumption to a high level of 42.5% in 2030.

The European Union, through the ReFuelEU Aviation Regulation, is making active efforts to promote the use of sustainable aviation fuels, namely Sustainable Aviation Fuels (SAF), to reduce carbon emissions in the aviation sector. It is stated that the EU intends to achieve carbon neutrality in aviation by 2050 through this innovative regulation [4]. ReFuelEU Aviation promotes the wider use of SAF as the single most powerful tool for reducing CO_2 emissions in aviation. This measure is part of the Fit for 55 package to achieve the target of reducing emissions by 55% by 2030. ReFuelEU Aviation sets requirements for aviation fuel suppliers to gradually increase the share of SAF blended with conventional aviation fuel. The EU plans to increase the share of SAF at EU airports from 2% (as of 2025) to 70% by 2050 [10].

In the United States, much attention is being paid to the development of SAF production and use. The U.S. Department of Energy (DOE) [11] outlines possible routes for the fuel delivery (Fig. 2). SAF must be blended with conventional aviation fuel, Jet A, before it can be used in aircraft. If SAF is co-produced with conventional Jet A at an existing refinery, the fuel would move through the supply chain in the conventional business model by pipeline to terminals and then by pipeline or truck to airports. It may also be possible to produce SAF at biofuel plants, where it would be blended with Jet A at existing fuel terminals and then delivered to airports by pipeline or truck.

According to the US DOE, the dynamics of SAF in the US shows rapid growth (Fig. 3). "This graph shows the estimated quantity of sustainable aviation fuel consumed in the United States, based on the Renewable Identification Numbers (RINs) volume generated as reported to the Environmental Protection Agency (EPA) for the Renewable Fuel Standard" [11]. The rate of SAF use in the US and around the world will increase.

The world's largest airlines pay attention to environmental issues. KLM Royal Dutch Airlines, like a number of other leading airlines in the world, pays great attention to the use of SAF [12]. It is noted that SAF is the best alternative to regular aviation fuel, which has a smaller impact on the environment. At the same time, at present, such fuel is not so widely used and is expensive.

KLM also notes that "SAF stands for 'Sustainable Aviation Fuel,' the term our industry uses to describe

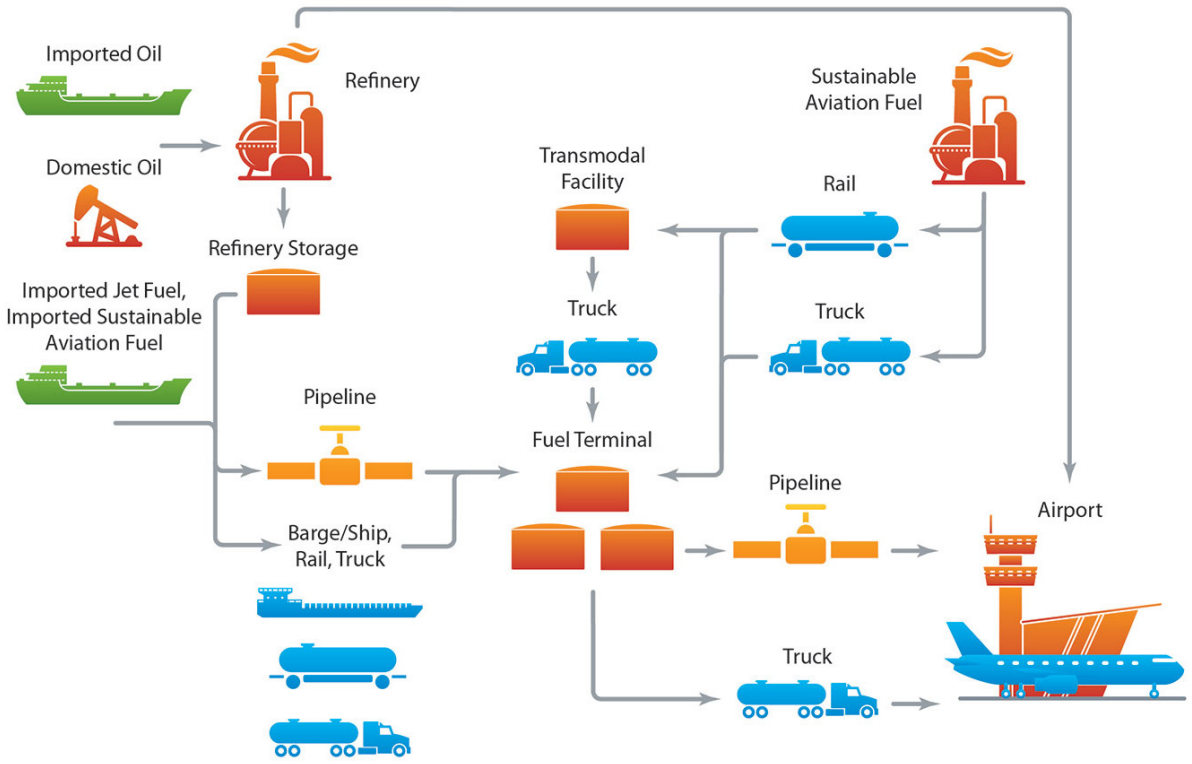

Figure 2 – Various delivery methods SAF

Source: [11]

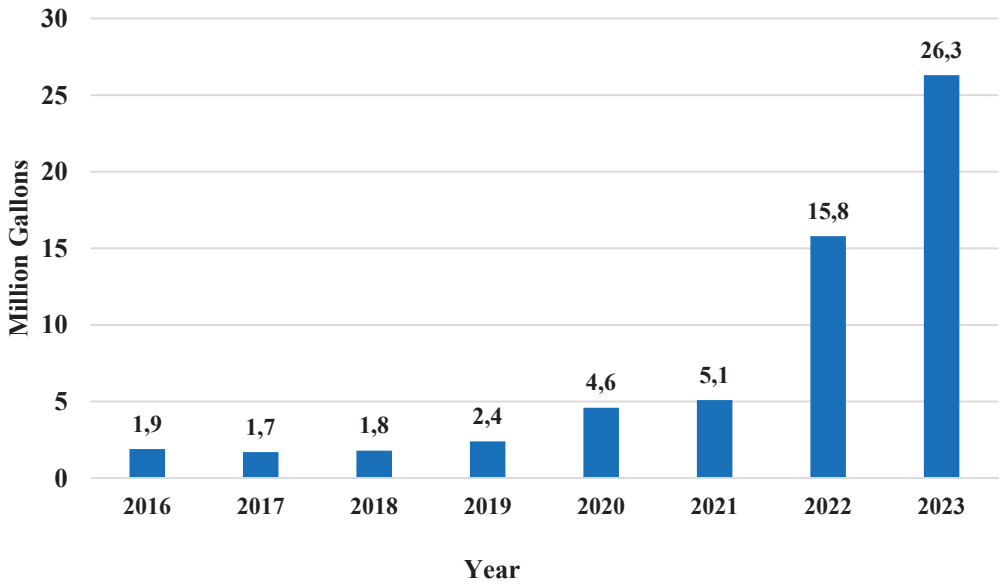

Figure 3 – SAF consumption in the US

Source: [11]

a better alternative to regular aviation fuel. We prefer to call it 'alternative aviation fuel' because SAF still produces harmful emissions and isn't fully sustainable. As of 2025, flights departing from Europe include an average of 2% SAF, as required by EU rules. While this is an increase, the impact of SAF remains limited" [12].

KLM points out the following important advantages of SAF, namely:

– this fuel is produced from non-fossil resources, such as waste cooking oil;

– although SAF emits the same amount of CO_2 during flight as conventional fuel, its overall CO_2 impact is at least 65% lower over the entire life cycle (from production to combustion);

– SAF emits fewer other harmful emissions, such as particulate matter and sulphur, which affect local air quality on the ground

The disadvantage of SAF, as KLM points out, is that it costs 3–4 times more than conventional aviation fuel and its use is currently limited [12].

One of the world's largest oil companies, the American Exxon Mobil Corporation, pays great attention to decarbonization and achieving zero emissions. Darren W. Woods ExxonMobil Chairman & CEO points out: "We'll continue to innovate and provide solutions that meet the growing needs of society, including its net-zero emissions ambitions, by fully leveraging our competitive advantages of scale, integration, technology, functional excellence, and our highly skilled people" [13].

An example of such activity by Exxon Mobil is the production of sustainable aviation fuel (SAF) and other biofuels at the company's refinery in Gravenchon, France. Exxon Mobil отмечает следующее: "Using our existing infrastructure and experience in traditional refining, we're uniquely positioned to produce lower-emission fuels (LEFs) at a scale that can support the European Union's ambitions to reduce CO_2 emissions. Producing SAF in France is part of our ambition to supply approximately 40,000 barrels per day of LEFs by 2025 and 200,000 barrels per day by 2030" [14].

A number of important areas of bioenergy development, their advantages, disadvantages, as well as their significance and prospects are presented in Table 1. The indicated areas fully correspond to the criterion of a key unique property, but, with all the evidence, the importance of sustainable aviation fuel will be preserved and even increased in the future, since for now it is the only alternative to traditional aviation fuel. The prospects for the use of hydrogen fuel in aviation for flights of large aircraft over long distances are potentially of significant interest, however, at present such application is not of any practical nature.

Taking into account the conducted analysis, the following model for the development of bioenergy can be proposed.

Model of bioenergy development in the context of decarbonization

1. Bioenergy should and will play a very important role in the processes of decarbonization of the global economy in the context of sustainable development in the near and, probably, in the distant future.

2. The role of bioenergy in the processes of decarbonization will be of a clearly auxiliary, although very important nature.

3. The main and determining direction of decarbonization of the global economy of the planet in the very long term is the development of wind, solar,

Table 1 – Model of bioenergy development in the context of decarbonization

Direction	Advantages	Flaws	Importance and Prospects
Biogas	A renewable fuel that can be used in areas where natural gas has been used, such as households and dispatchable power generation, using existing infrastructure	Emits CO_2 and some other substances that can harm the climate. Costs more than natural gas. There are some difficulties in production	The development prospects are also important, at least until it is replaced by electrical energy
Biodiesel and bioethanol	Can be used in various types of transport in internal combustion engines. Especially important for marine transport instead of diesel fuel	Emits CO_2 and some other substances that can harm the climate. The cost exceeds the cost of gasoline and diesel fuel. There are some difficulties in providing raw materials and in production	The development prospects are also important, at least until it is replaced by electrical energy
SAF	Currently probably the only fuel that can replace traditional aviation fuel. Can use existing infrastructure	Emits CO_2 and some other substances that can harm the climate. Costs more than traditional aviation fuel. There are certain difficulties in providing raw materials and in production	It has important significance and probably long-term development prospects

Source: developed by the authors

nuclear, hydropower and the production and widest possible use of electricity in the widest possible areas of activity.

4. There are some areas of decarbonization in which, at least at present and in the foreseeable future, bioenergy cannot be replaced by any other types of energy for a number of extremely complex and currently insurmountable technical reasons, at the same time, such a statement is also supported by some economic factors that may lose relevance in the future.

5. The areas of bioenergy development that meet the criterion of key unique areas can be primarily the use of sustainable aviation fuel due to the current technical uncertainty of using hydrogen fuel in aviation and the use of biodiesel in maritime transport, part of automobile and rail transport.

6. An important area of bioenergy development is the use of biogas, which, although it can be replaced by electricity, in many cases it is not economically feasible. The use of biogas in this context can rely on the existing and extensive infrastructure that cannot be replaced in the short term and such use can be associated with the generation of electricity, where biogas will act as a source of dispatchable electricity.

7. The development of bioenergy requires concentrated efforts within the framework of effective innovative management to achieve optimal technologies for the production and use of renewable fuels to ensure sustainable development of the world economy and decarbonization.

Conclusions. Analysis of the dynamics of global use and assessment of the prospects of biofuels allows us to state the following. According to the International Energy Agency, global bioenergy consumption has a steady upward trend, with the dominant trend being the growth in the use of modern bioenergy products. Biogas, liquid biofuel, bioethanol, and biodiesel occupy an important place in the demand for fuel. Unique opportunities and prospects for use relate to sustainable aviation fuel. Leading countries of the world, in particular, the EU, the USA and other countries are pursuing a policy of decarbonization and the use of renewable energy sources. This contributes to global efforts to develop biofuels. At the same time, the widespread use of electricity in all areas of the modern economy, according to estimates, will lead to stabilization of liquid biofuel consumption in the future. The dynamic growth of the planet's economy will correspond to active and comprehensive efforts within the framework of effective innovative management of the development of production and use of modern biofuels within the framework of decarbonization processes.

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