CHAPTER 3
PROSPECTS FOR THE DEVELOPMENT OF BIOENERGY POTENTIAL OF RURAL AREAS: METHODOLOGICAL, LEGAL AND STRATEGIC SUPPORT

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3.1 Theoretical and Methodological Aspects of Bioenergy Potential

The current stage of development of the energy sector is characterized by the need to transition to renewable energy sources, which is due to the depletion of traditional fuel and energy resources, the instability of global energy markets and the aggravation of environmental problems. In this context, bioenergy occupies a leading place among the areas of sustainable development, as it combines energy production with the utilization of organic waste and the reduction of anthropogenic load on the environment.

Rural areas of Ukraine have significant bioenergy potential, due to the high share of agricultural production, the presence of significant volumes of agricultural by-products (straw, manure, livestock waste, industrial crop residues, etc.) and bioresources of forest and municipal origin. The use of this potential can not only reduce the country's energy dependence and reduce pollutant emissions, but also provide additional sources of income for local communities, create new jobs, contribute to the diversification of the energy balance and the development of a circular economy in rural areas.

At the same time, the level of practical implementation of bioenergy projects in rural regions remains low due to the imperfect regulatory framework, insufficient investment, lack of effective incentive mechanisms, and underdeveloped infrastructure for biomass collection and processing. Therefore, scientific substantiation of the assessment of the bioenergy potential of rural areas is an urgent task that requires a comprehensive approach that includes an analysis of the natural resource base, technological capabilities, socio-economic factors, and environmental consequences.

All energy flows from renewable sources (RES) can generally be grouped into two large categories: direct solar radiation and its secondary forms,

in particular wind energy, water mass energy (hydropower), ambient heat and biomass energy. RES include: solar energy, wind, energy of currents, waves and tides, as well as thermal energy of the atmosphere, waters of the World Ocean and the Earth's surface. This also includes the muscular energy of humans and animals. A special place among RES is occupied by biomass – all vegetation, which, thanks to photosynthesis, constantly accumulates solar energy in the form of organic substances, primarily hydrocarbons [1].

Geothermal energy, although formally referred to as a renewable resource, is actually of limited nature. It is formed as a result of chemical processes and the decay of radioactive elements in the bowels of the Earth, the reserves of which are exhaustible. Therefore, by origin it is close to non-renewable sources. Bioenergy focuses mainly on one of the areas of use of renewable energy sources – energy stored in biomass.

Bioenergy is a scientific and technical field that studies the processes of converting energy contained in biomass into electrical, thermal and other forms of energy. It also covers the development and implementation of new types of biomass fuels that are more convenient to use and environmentally friendly.

Each stage of bioenergy development reflects not only technological progress, but also a paradigm shift in the attitude towards resources, ecology and energy security. Bioenergy is transforming from a primitive energy source into a strategic component of the global energy transformation.

The development of bioenergy in independent Ukraine has gone through several stages, starting from the period of independence in 1991. The listed main stages of bioenergy development in Ukraine are reflected in Table 3.1.

Despite significant progress in the development of bioenergy in Ukraine, there are certain challenges, such as instability in legislation, financial difficulties and the need for further investments in research and infrastructure. However, the general trend points to a positive development of this sector, which is of great importance for the energy security and sustainable development of Ukraine. At the same time, an important task remains the adaptation and implementation of best international practices that will contribute to increasing the efficiency and competitiveness of domestic bioenergy.

Table 3.1

Evolution of bioenergy development in independent Ukraine

№	Stage of evolution of bioenergy in Ukraine	Characteristic
1	Early 1990s	During the transition to a market economy after independence, Ukrainian agriculture underwent significant changes. At that time, there was a transition from collective and state farms to private agricultural enterprises. Although the first attempts to use biomass for energy began during this period, the development of bioenergy was limited by a lack of funding and technological equipment.
2	Mid-1990s – early 2000s	During this period, the Ukrainian government began to more actively support the development of renewable energy sources, in particular bioenergy. Legislative acts and programs were adopted aimed at stimulating the production and use of biofuels and biogas.
3	2000s	During this period, Ukraine has seen an increased interest in growing energy crops such as rapeseed, soybeans, sunflowers, etc., with the aim of using them for biofuel production. Several projects have also been launched to produce biogas from agricultural waste and biomass.
4	From the 2010s to the present	Ukraine is experiencing further development of bioenergy. Legislative acts have been adopted to support the production of electricity from renewable sources, in particular from biomass. New enterprises and projects for the production of biofuels, biogas and biomass have appeared.

Source: adapted from [2]

It should be noted that the development of this industry in the EU countries followed similar stages. The development of bioenergy in the European Union (EU) countries took place in several stages and included a number of strategic steps and measures aimed at increasing the share of renewable energy sources, in particular biomass. A general overview of the stages of bioenergy development in the EU countries is shown in Table 3.2.

Table 3.2

Evolution of bioenergy development in the European Union countries

№	Stage of evolution of bioenergy in the EU	Characteristic
1	Early stage (1990s)	The first steps in the development of bioenergy in the EU countries were taken in the 1990s. During this period, solid biofuels, such as wood, straw, briquettes, etc., began to be actively used for heating in industrial and agricultural facilities.
2	Stimulating biomass production (2000s)	In the 2000s, EU countries began to actively stimulate biomass production and the development of bioenergy technologies. Special programs, legislation and initiatives were adopted aimed at increasing the share of renewable energy sources in the overall energy balance.
3	European Union strategies	In 2009, the EU Renewable Energy Directive (Directive 2009/28/EC) was adopted, setting binding targets for the use of renewable energy sources in total energy consumption. This contributed to further growth in investment in bioenergy.
4	Technology development	During the 2000s and 2010s, bioenergy technologies have undergone significant development. New projects have been launched to produce biofuels, biogas, biomass, and other types of bioenergy. Efficient technologies and processes for using biomass have been developed.
5	Diversification of biomass sources	European countries have been actively working to diversify biomass sources. The use of different types of raw materials (forest biomass, agricultural biomass, organic waste, etc.) has allowed for sustainable bioenergy production.
6	Objectives of the European Green Deal	The current stage of bioenergy development in the EU is linked to the implementation of the European Green Deal. This strategy sets ambitious targets for reducing greenhouse gas emissions and transitioning to clean and sustainable energy. It also envisages increasing the use of bioenergy as a key component of the energy mix.

Source: adapted from [2]

Today, the study of bioenergy is given considerable attention by many scientists who investigate it from various scientific positions – energy, environmental, agricultural, economic and technological. In this regard, a large number of approaches to the interpretation of the concept of "bioenergy" have been formed.

Some scientists consider it as a branch of energy based on the use of biomass for the production of heat, electricity and fuel, others - as an interdisciplinary field that combines knowledge about energy conversion in biological systems and their practical application in energy technologies. Such a variety of approaches reflects the complex nature of bioenergy as a science and an applied field, as well as its close connection with the problems of sustainable development and energy independence. At the same time, the systematization of scientific approaches allows us to understand the content of this concept more deeply and determine the directions of further research in the field of bioenergy. The interpretation of the essence of the concept of "bioenergy" is systematized in Table 3.3.

Table 3.3

Interpretation of the essence of the concept of "bioenergy"

Author	Author's opinion
1	2
Kaletnik G.M.	Bioenergy is an industry that, through the production and consumption of biofuels, is able to provide agriculture with its own energy resources and reduce production costs for fuel resources. In addition, one of the requirements of the European Union for candidate countries is that the level of use of renewable energy sources is not lower than the European average.
Lutkovska S.M.	Bioenergy is a key element of the "green" energy transition both globally and for Ukraine. Biomass and biofuels can effectively replace traditional energy sources. Given Ukraine's significant energy dependence on imports, in particular natural gas, and the presence of significant biomass potential, the development of bioenergy is one of the priority and strategically important areas in ensuring the country's energy security.
Dubinina M.V.	Bioenergy is emerging as a modern sector of the economy that integrates energy security issues with environmental responsibility. It serves as a means of reducing anthropogenic impact on the environment through the use of renewable energy sources. From a technical point of view, bioenergy can be defined as an energy sector focused on obtaining energy by processing biomass using specialized technologies.

(End of Table 3.3)

1	2
Roik M.V.	Bioenergy is an interdisciplinary, environmentally oriented branch of science and agro-industry, covering the cultivation of energy crops and the processing of bio-raw materials (plant, animal, wood, algae, organic waste) into various types of biofuels: liquid (bioethanol, biodiesel, methanol), solid (pellets, briquettes) and gaseous (biogas, synthesis gas). It also includes the storage, transportation and sale of bio-products, forming an effective system of bio-energy resources, which contributes to the energy security of the country.
Bilokinna I.D., Tokarchuk D.M.	Bioenergy as an industry plays a key role in ensuring energy security and supporting sustainable development, integrating environmental, economic and social factors. For Ukraine, it is particularly promising due to the strong agricultural sector and significant volumes of available bioresources. Bioenergy potential is considered as the possibility of converting biological resources into energy, capable of contributing to energy self-sufficiency and environmentally balanced development.
State Agency for Energy Efficiency and Energy Saving of Ukraine	Bioenergy is a field of knowledge and practice that studies the processes of converting biomass (organic matter of plant, animal, or microbial origin) into energy in a useful form - thermal, electrical, or mechanical.
Kovalchuk M.M.	Bioenergy is a science and applied field that encompasses the production, conversion, storage, and use of energy derived from biological raw materials or biological waste.
Brovko O.M.	Bioenergy is an interdisciplinary science that combines biology, energy, chemistry, and ecology to develop technologies for producing energy from biological raw materials, taking into account the principles of sustainable development.
Institute of Renewable Energy of the National Academy of Sciences of Ukraine	Bioenergy is a renewable energy sector based on the use of biomass as a renewable energy source to produce heat, electricity, or motor fuel.

Source: systematized by the authors according to [1, 3-7]

Fuel produced by processing organic raw materials of biological origin (biomass) is defined as biofuel. Biofuels are classified by their state of aggregation into three main groups: solid, liquid and gaseous.

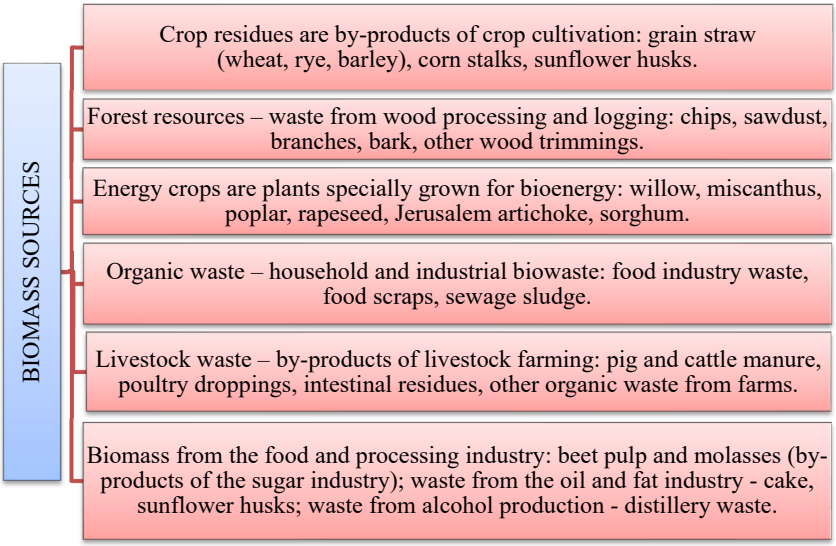

Figure 3.1. Main sources of biomass

Source: compiled by the authors

Solid biofuels include wood and agricultural waste, pellets, briquettes, straw, wood chips and other types of biomass, which are used mainly for combustion.

Liquid biofuels include biodiesel and bioethanol, which can be used as substitutes for traditional petroleum products.

Biodiesel is a transport fuel made from vegetable oils or animal fats.

Bioethanol is a transport fuel made from biomass or raw ethyl alcohol [9].

Gaseous biofuels are represented by biogas and biomethane, which are usually used to produce heat and electricity.

Biogas is a gas obtained from biomass. Possible sources of biogas include animal farm waste, wastewater or organic matter in landfills. Biogas is a mixture of methane (60-70%), CO2 and small amounts of other gases. Biogas can be used to generate electricity and to meet heating and cooking needs.

Biomethane is almost 100% methane, produced either by biogas enrichment or by gasification of solid biomass. Enriched biomethane is indistinguishable from natural gas and can therefore be transported and used in the same way. Biomethane has the advantages of natural gas while remaining carbon neutral [9].

In Ukraine, the economically justified energy potential of biomass is estimated at approximately 20-25 million tons of fuel equivalent per year [10].

In addition to the main sources of biomass, in the future the potential of bioenergy can be significantly expanded by attracting new sources of raw materials – such as by-products and waste from the food industry (from sugar, alcohol, brewing, meat processing, oil extraction enterprises, etc.), solid household waste from landfills and waste sorting stations, sewage sludge from treatment plants, as well as cover crops grown in the off-season or after the main harvest.

Below is a generalized table of the most energy-intensive types of bioresources, including major agricultural crops, energy crops, and livestock waste (Table 3.4). The data are approximate, as they depend on the variety, growing conditions, and processing technology.

The highest energy intensity among the presented resources is demonstrated by perennial energy crops, in particular miscanthus, energy willow and poplar. Their advantage is due to the combination of high dry biomass yields (10-20 t/ha and more). Due to this, the total energy output of these crops can reach 170-360 GJ/ha, which significantly exceeds the indicators of most annual agricultural crops.

Among annual crops, corn for grain and silage corn have a relatively high energy potential. The high biomass of silage and favorable fermentation parameters provide a significant biogas yield, which makes it one of the most effective substrates among traditional agricultural crops.

Livestock waste, despite its stability of formation and suitability for anaerobic processing, has a significantly lower energy yield per unit mass due to its high humidity (75-98%) and lower organic matter content. The energy value of such substrates per 1 ton is usually several times lower than that of plant dry biomass.

Therefore, from the standpoint of specific energy intensity and energy output per hectare, perennial energy plants are the most efficient, while

other crops and livestock waste play an additional or supporting role in the overall bioenergy balance.

Currently, approximately 70% of bioenergy in Ukraine is generated by burning solid biomass. Biogas energy provides about 15%, and another 15% is from liquid biofuels, including bioethanol and biodiesel [10].

Table 3.4

Energy characteristics of bioresources

Resource	Yield/Output	Energy output	Typical use
Wheat (straw)	3-5 t/ha	45-85 GJ/ha	Pellets, briquettes
Corn (grain)	8-12 t/ha	130-190 GJ/ha	Bioethanol
Corn (silage)	35-45 t/ha	70-110 GJ/ha	Biogas/biomethane
Rapeseed (seeds)	2-3 t/ha	40-60 GJ/ha	Biodiesel
Sunflower (husk)	1.5-2 t/ha	25-36 GJ/ha	Pellets
Sugar beet	40-60 t/ha	90-140 GJ/ha	Bioethanol, biogas/ biomethane
Artichoke	40-50 t/ha	80-120 GJ/ha	Biogas/biomethane
Miscanthus	10-20 t/ha (dry mass)	170-360 GJ/ha	Briquettes, pellets
Willow energy	10-15 t/ha (dry mass)	180-285 GJ/ha	Wood chips, solid fuel
Energy poplar	10-12 t/ha (dry mass)	160-230 GJ/ha	Wood chips, solid fuel
Energy sorghum	20-30 t/ha	140-200 GJ/ha	Biogas/biomethane
Technical hemp	8-12 t/ha (dry mass)	135-215 GJ/ha	Biomass
Cattle manure	20-25 t/year per head	1,3-1,6 GJ/ha	Biogas/biomethane
Pig manure	2-3 t/year per head	0,5-0,7 GJ/ha	Biogas/biomethane
Bird droppings	2-3 t/1000 heads	1,3-1,6 GJ/ha	Biogas/biomethane

Source: compiled by the authors

To understand the meaning of the concept of “bioenergy potential”, in addition to the term “bioenergy”, it is important to consider the definition of the term “potential”.

Potential is a set of available or possible resources, means and conditions that can be used to achieve a certain goal or implement a certain activity.

Bioenergy potential is a scientifically based assessment of the possible amount of energy that can be obtained from biomass (plant, animal, microbial origin, organic waste, etc.) provided that it is rationally collected, processed and used, taking into account technological, economic, environmental and social factors [11].

In a broad sense, bioenergy potential is divided into:

– theoretical – the total amount of energy contained in all available bioresources;

– technical – the part of the theoretical potential that can be realized using existing technologies;

– economic – the amount of energy, the production of which is economically feasible under current conditions;

– environmentally acceptable – the amount of bioenergy that can be obtained without harming the environment, biodiversity and sustainability of agroecosystems [11].

This concept is key in developing energy security strategies, planning the use of renewable energy sources and forming a "green" economy.

Therefore, bioenergy potential is the ability of biological resources to be converted into energy that can contribute to achieving sustainable development and ensuring energy self-sufficiency (Fig. 3.2).

According to experts, Ukraine has one of the highest levels of bioenergy potential among the countries of Central and Eastern Europe. Thanks to a developed agricultural sector, a large area of agricultural land, a high volume of organic waste and favorable climatic conditions, our country is able to produce a significant amount of bioenergy from local resources. This creates the prerequisites for the formation of decentralized energy systems, energy-independent communities and the implementation of the principles of sustainable development on a national scale.

At the same time, it is necessary to take into account the factors that currently hinder the effective development of the bioenergy complex in Ukraine:

1. Underdeveloped fuel market structure and the presence of monopoly restrictions in the heat supply sector. The need to introduce fair competition and create an effective regulatory framework that would regulate the activities of heat supply market participants.

2. Complicated interaction with heating network operators, as well as a shortage of biological raw materials, which causes an increase in the cost of energy resources.

3. Limited investment attractiveness of bioenergy projects, which hinders their development.

4. Insignificant support for the cultivation of energy crops, which makes it impossible to provide bioenergy facilities with raw materials in a stable manner. The agricultural sector is not interested in the development of this area due to low profitability.

5. Complicated process of obtaining access to logging residues (biomass) and problems with their transportation [11].

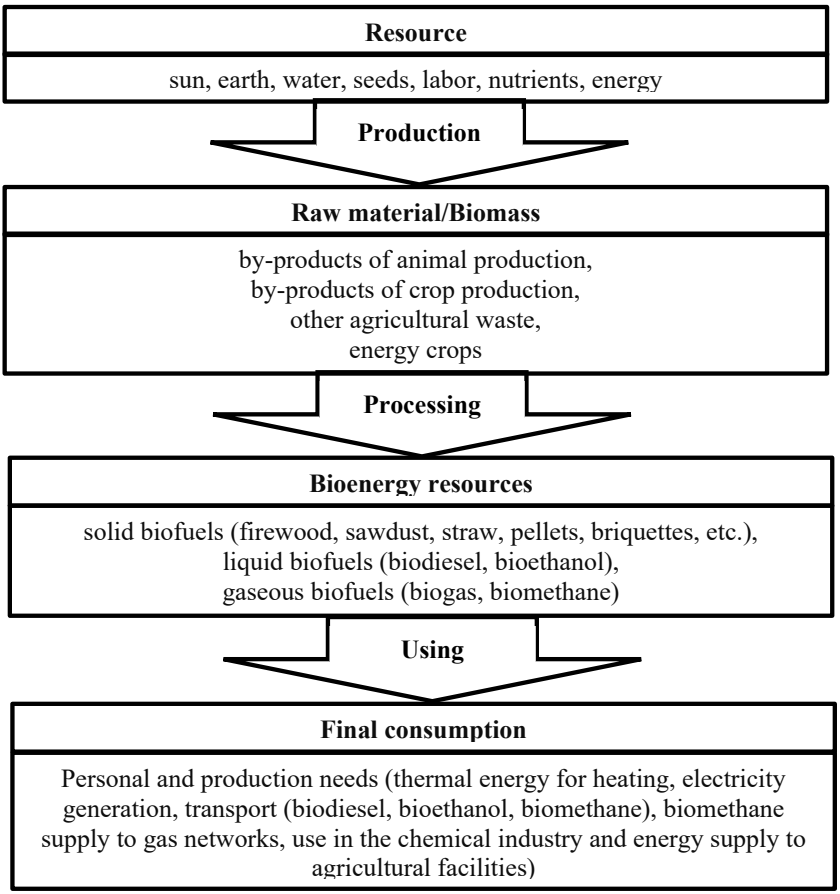

Figure 3.2. Scheme of formation of bioenergetic potential

Source: compiled by the authors based on [3]

Thus, the need to realize the bioenergy potential of Ukraine is due to the urgent need to reduce energy dependence on imported fossil resources, primarily natural gas. In the context of geopolitical instability and the high cost of traditional fuels, the development of bioenergy is becoming a strategically important direction for ensuring the country's energy security, the provision of which should begin with local production of biofuels in rural areas and territorial communities.

In addition, bioenergy meets the principles of sustainable development, contributes to the reduction of greenhouse gas emissions and the disposal of organic waste, which has a positive impact on the environment. The realization of bioenergy potential also stimulates the development of rural areas, creates new jobs, activates the local economy and contributes to the decentralization of energy systems. Thus, the development of bioenergy is not only an energy, but also a socio-economic and environmental priority for Ukraine.

3.2 Implementation of International Experience in the Development of Bioenergy in Ukraine

The global energy crisis and the need to reduce dependence on traditional fossil resources contribute to the active development of the biofuel market. Biofuels are considered an important component of energy security, especially for countries with limited fossil fuel reserves. The global demand for biofuels is growing, which makes their production a promising industry for investment [12].

In addition, the development of biofuel production stimulates the agricultural sector, because the raw materials for it are renewable resources – agricultural crops and waste of plant or animal origin. This opens up new opportunities for farms, creates jobs in rural areas and increases the level of food and energy security of the state.

World experience shows that liquid biofuels are becoming a promising and popular type of energy resources. Today, two types of liquid biofuels are used in the world:

1. Biodiesel is made from vegetable oils (soybean, rapeseed, palm) or animal fats by a chemical reaction – transesterification. This fuel can be used in diesel engines without significant modifications. Biodiesel is highly

biodegradable, does not contain sulfur, and helps reduce environmental pollution.

2. Bioethanol (ethyl alcohol) for gasoline engines, which is obtained by fermenting sugar (sugar beet, sugar cane) or starch (wheat, corn). It is used mainly as an additive to gasoline or as a separate fuel for cars with appropriately adapted engines [13].

The world's largest producers of biofuels are the United States of America (further – USA) and Brazil, which together produce a significant portion of the world's ethanol and biodiesel.

One of the first countries to take a decisive step towards the introduction of biofuels was Brazil. Since the 1970s, the country has been experiencing an energy crisis caused by a sharp increase in oil prices. This was the impetus for the creation of the state program Proalcool (Programa Nacional do Alcool), which aimed to replace part of the gasoline with ethanol produced from sugar cane. The government provided benefits to farmers, supported scientific research and stimulated the automotive industry to develop engines that run on a mixture of fuels.

Ethanol production in Brazil has been a real technological breakthrough. The use of sugarcane has allowed for the creation of an efficient closed production cycle, as the waste of sugarcane – bagasse – is used to generate electricity needed by the factories themselves. This makes the process virtually waste-free and environmentally friendly. In addition, ethanol from sugarcane has a high energy coefficient: for each unit of energy spent on production, up to eight units of finished fuel are obtained. Figure 3.3 shows the main stages of ethanol production from sugarcane.

In 2024, Brazil maintained its status as the world leader in the share of biofuels in the energy balance: biofuels and waste accounted for more than a third of the country's total energy supply. As can be seen from the energy balance (Fig. 3.4), the main share is made up of oil and oil products (36%), while biofuels and waste provide 33%, hydropower – 11.4%, and natural gas – 8.6%. This structure confirms the multicomponent and sustainability of Brazil's energy system, which is based on a combination of traditional and renewable energy sources.

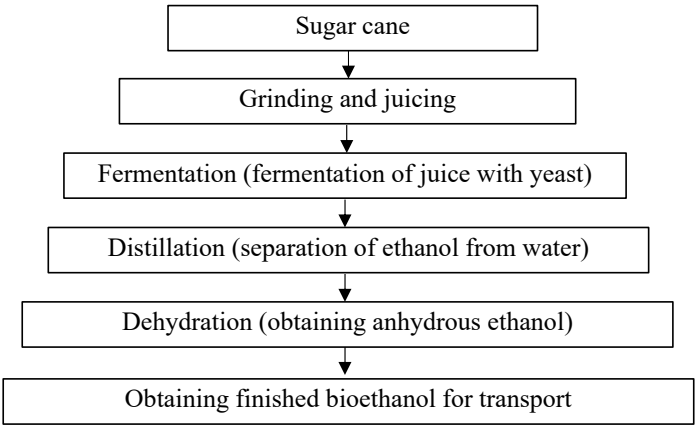

Figure 3.3. Scheme of ethanol production from sugar cane

Source: generated by the author

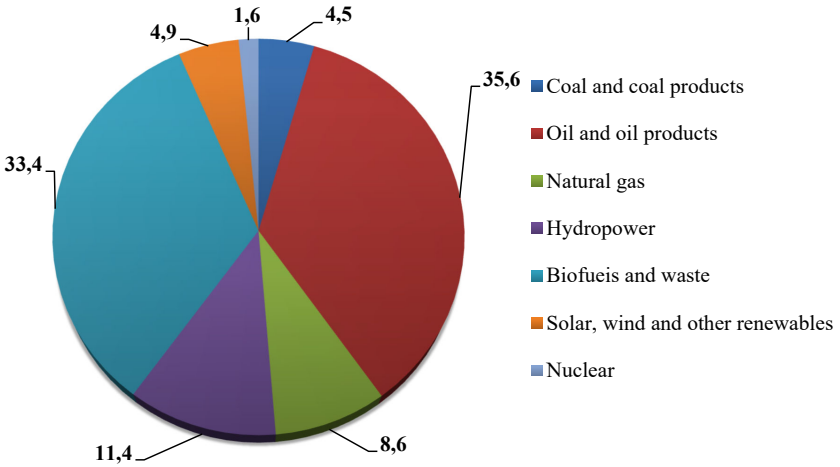

Figure 3.4. Largest sources of energy in Brazil, 2024 (%)

Source: compiled by the author based on data from [14]

Brazil is significantly developing its biofuel consumption infrastructure. The country's gas stations offer a wide range of fuel blends, including pure ethanol (E100), and the vast majority of modern cars are flex-fuel, meaning they can run on either gasoline or ethanol in any ratio. The introduction of the biofuel program has provided not only economic but also environmental benefits: the reduction in CO_2 emissions when using ethanol reaches 90% compared to traditional gasoline.

The experience of the USA is one of the most indicative in the field of development of the bioethanol industry, as the country occupies a leading position in the world in terms of biofuel production. The main raw material for the production of bioethanol in the USA is corn, which is due to its high yield, availability and developed agricultural infrastructure of most states. A significant role in the dynamic development of this industry is played by state support, which is implemented through the Renewable Fuel Standard (further – RFS) program, introduced in 2005 [15]. The program provides for an annual increase in the share of renewable components in transport fuel, stimulating both producers and consumers to use environmentally friendly energy resources.

The RFS program divides biofuels into four main categories, each with its own emission reduction criteria (Table 3.5).

Table 3.5

Biofuel classification according to RFS requirements

Biofuel category	Minimal reduction of greenhouse gases	Fuel types	The main raw material
Renewable Fuel	20%	Bioethanol, biodiesel	Corn, soybeans
Advanced Biofuel	50%	Biodiesel, biogas, bioethanol from non-food crops	Waste, oilseeds
Cellulosic Biofuel	60%	Bioethanol, biogas	Cellulose waste, straw, wood
Biomass-Based Diesel	50%	Biodiesel, renewable diesel	Soybean oil, animal fats

Source: compiled by the authors based on [16]

The analysis of the data in Table 1 shows that the biofuel classification system within the RFS program has a clearly expressed environmental focus. The higher the level of greenhouse gas emission reduction, the greater the environmental efficiency and strategic importance of the respective type of biofuel. In particular, Cellulosic Biofuel demonstrates the highest potential in reducing the carbon footprint, as it is produced from waste and unused biomass. Such a system stimulates innovation in the field of biofuel production, contributes to the diversification of the raw material base and reduces dependence on food crops.

In addition to the RFS, the United States has numerous government programs to support the production and use of biofuels. The state is actively investing in the development of the bioenergy sector through the United States Department of Agriculture (further – USDA) and the United States Department of Energy (further – DOE), which ensures the formation of a comprehensive infrastructure for the production, processing and implementation of advanced biofuels. USDA programs are mainly aimed at supporting producers, agricultural enterprises and landowners engaged in the cultivation of biomass and the construction of biorefineries. In turn, DOE programs are focused on financing innovative research, the development of new technologies for the processing of lignocellulosic raw materials and improving the efficiency of production processes.

Table 3.6 summarizes the main government programs to support the development of biofuels in the United States.

Thanks to a combination of economic incentives, innovation, and effective public policy, USA biofuel production capacity increased by 7% in 2023, reaching 24 billion gallons per year by early 2024 (Figure 3.5).

The country's developed infrastructure – an extensive network of biofuel plants, logistics centers and gas stations with gasoline and ethanol blends (E10, E85) – ensures stable market functioning and promotes the integration of biofuels into the national energy system. As a result, the United States not only reduces dependence on fossil energy resources, but also makes a significant contribution to reducing greenhouse gas emissions, forming an effective model of transition to sustainable energy development.

Table 3.6

State programs supporting biofuel production in the USA

Program/ Initiative Name	Implementing agency	Main content of the program	Type of support
Biorefinery, Renewable Chemical, and Biobased Product Manufacturing Assistance Program	USDA	Support for the construction or modernization of biorefineries producing biofuels, biochemicals and bio-based products	Credit guarantees up to 250 million USD
Advanced Biofuel Payment Program	USDA	Financial payments to producers of advanced biofuels (not from corn starch) for actual production volumes	Cash payments (production bonuses)
Biomass Crop Assistance Program (BCAP)	USDA	Support for the cultivation, collection and transportation of biomass for biofuel production	Financial assistance to landowners and farmers
Bioenergy Technologies Office (BETO)	DOE	Conducting research and development in the field of bioenergy, improving lignocellulosic raw material processing technologies, reducing the cost of biofuels	State funding of scientific projects, grants
Feedstock Technologies R&D	DOE	Development of technologies for preparing biomass for conversion, research into lignocellulosic resources	Financing R&D projects

Source: compiled by the authors based on [17-21]

Asian countries, including China and India, are also actively increasing biofuel production. Since the late 1990s, the Chinese government has been implementing large-scale programs to support the production of bioethanol and biodiesel, aimed at diversifying the energy balance. The main raw materials are corn, cassava, wheat, rice husks, as well as agricultural waste – straw, corn stalks, sugarcane residues. Thanks to these initiatives, more than 30 large bioethanol plants and several hundred small biomass processing enterprises have been established in the country.

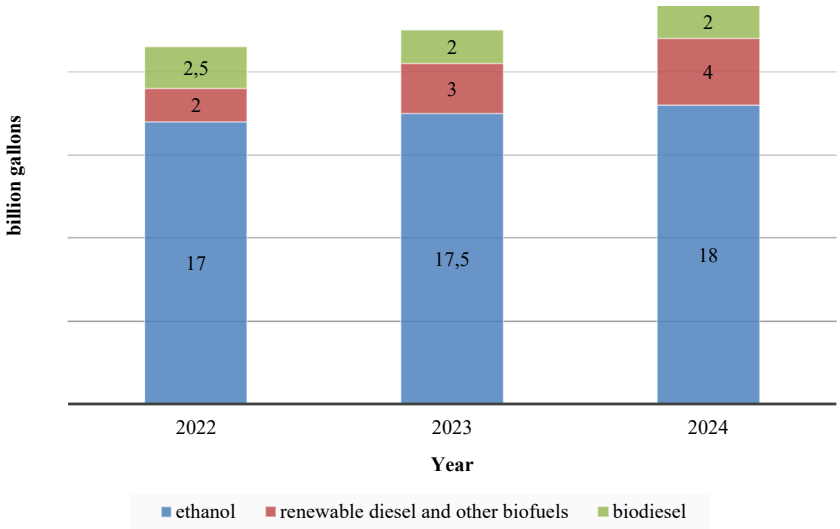

Figure 3.5. Annual U.S. biofuels production capacity as of Jan 1, 2022-2024

Source: compiled by the author based on data from [22]

China ranks third in the world in terms of bioethanol production after the USA and Brazil, which indicates a high level of technological development of the industry. At the initial stage, most enterprises focused on the production of bioethanol from food crops – mainly corn, wheat and sorghum. However, in order to prevent risks to food security, the state limited the use of food raw materials and stimulated the development of second-generation biofuels. This direction is officially enshrined in the Bioenergy Development Program "China Bioenergy Development Plan (2021-2035)", which provides for a gradual transition to the use of cellulosic biomass, agricultural and forest waste, as well as special energy crops such as miscanthus and hard grasses [23].

The development of second-generation technologies has allowed China to combine environmental efficiency with high economic profitability. Thanks to state investments in research and development, laboratories are being created to study biotechnological processes of fermentation

and chemical processing of cellulosic raw materials. Some provinces, in particular Jilin and Heilongjiang, have become regional centers for the production of bioethanol from agricultural waste, which provides local economic effects, including job creation and the development of raw material processing infrastructure.

In parallel with the development of bioethanol and biodiesel production, diversification of biofuel use is underway. One of the most promising areas has become the aviation biofuel sector (SAF – sustainable aviation fuel). Chinese oil refining and chemical companies are actively implementing technologies for processing waste cooking oil into high-quality fuel for aviation transport, which allows for a significant reduction in greenhouse gas emissions [24; 25].

Thus, the Chinese approach, as in other countries, is based on the principle of combining economic feasibility with environmental responsibility. In particular, the transition to biofuels has avoided the annual emission of more than 12 million tons of CO_2, which is equivalent to the emissions of about 5 million passenger cars.

Like China, India is actively developing its own bioenergy policy aimed at reducing oil imports. The main sources of raw materials for bioethanol production in India are sugarcane, molasses, corn, wheat and, to some extent, cassava. The country has a powerful sugar industry, so it is the waste from sugar production that has become the basis for the development of the bioethanol sector [26].

An important role in the development of the Indian biofuel market is played by the government program E20 (Ethanol Blending Programme), which provides for the mandatory addition of ethanol to gasoline throughout the country [27]. This program not only reduces dependence on oil imports, but also creates new opportunities for farmers, as it allows them to effectively sell surpluses of sugarcane and cereals. Thanks to the development of the bioethanol industry, the annual income of farmers has increased by more than 5%, and the creation of new processing facilities has provided more than 60 thousand jobs in rural areas.

In addition to ethanol, India is focusing on biodiesel production from non-food oilseeds such as jatropha, mahua and castor oil. The development of this direction involves the use of degraded lands unsuitable for food crops, which allows avoiding competition between fuel and food production.

In 2022, India produced about250 million liters of biodiesel, and by 2030 it is planned to increase this figure to 1 billion liters.

India is also investing in second-generation biofuels, i.e., energy production from agricultural waste, rice straw, corn stalks, woody biomass, etc. In 2021, the government launched the "Waste to Wealth" initiative, which envisages the construction of 12 industrial plants for processing waste into bioethanol [28]. One of the first such plants in the city of Panipat (Haryana) has a capacity of 100,000 liters per day and uses about 200 tons of rice straw daily. This not only contributes to energy independence, but also helps solve the problem of burning agricultural residues, which is a major source of air pollution in the region.

Germany's approach to regulating the use of alternative energy sources is comprehensive and multifaceted, reflecting its commitment to the transition to a sustainable economy. The regulatory framework in Germany is designed to promote the development and integration of renewable energy sources into the national energy system.

The basis of regulation is the Renewable Energy Sources Act (EEG – Erneuerbare-Energien-Gesetz), adopted back in 2000. This law has become a key instrument that has stimulated the rapid growth of electricity production from biomass, biogas, wind and solar. It provides for feed-in tariffs for producers of "green" energy, ensuring a stable income and encouraging investment in the sector. The EEG also establishes priority for the connection of renewable energy facilities to the grid [29].

In addition, Germany has biofuel laws (Biokraftstoffquotengesetz). According to this law, fuel suppliers are obliged to ensure a certain minimum share of renewable components in petrol and diesel fuel every year. These quotas are gradually increased in line with the European Union targets set in the EU Renewable Energy Directive (RED II). As a result, biofuels are considered not only as a tool for reducing greenhouse gas emissions, but also as an important element in implementing the state's climate policy.

German legislation sets environmental and certification criteria for biofuels, enshrined in the Biofuel Sustainability Regulation (Biokraftstoff-Nachhaltigkeitsverordnung). Producers must prove that the raw materials for biofuels do not contribute to deforestation, land degradation or biodiversity loss. Only certified fuels can be counted towards the quota [30].

Germany is thus demonstrating a comprehensive approach to the development of bioenergy, combining economic incentives, legislative mechanisms and environmental policy.

Taking Sweden into account, we can see that this country is one of the leaders in the European Union in terms of the share of renewable energy sources in the total energy balance, which exceeds 60%, of which about 36% is bioenergy resources. This result was made possible thanks to the long-term and consistent implementation of the state energy transition policy, focused on the complete abandonment of fossil fuels by 2045, which is enshrined in the National Energy Strategy of Sweden.

One of the key areas of implementation of the Swedish energy policy is the development of the biogas industry, which includes more than 280 biogas plants located near large cities and agro-industrial centers [31]. The main raw materials for biogas production are food industry waste, wastewater, organic residues from agriculture and biomass of forest origin. Biogas is used both in the transport sector and for the production of electricity and heat, including for district heating. This approach contributes to the decentralization of energy supply, reducing energy dependence on fossil fuel imports and increasing the energy security of the state.

Currently, more than 65% of public transport in Sweden runs on biofuels. In the capital, Stockholm, more than 90% of buses run on biogas produced from municipal waste, which significantly reduces carbon emissions and improves air quality. In the cities of Malmö, Linköping and Gothenburg, E85 ethanol fuel, which contains 85% bioethanol and 15% gasoline, is actively used. The development of the bioethanol market is facilitated by state tax breaks, programs to stimulate ecological transport and investment support for enterprises that introduce the production of ecological fuels.

A special place in the bioenergy system of Sweden is occupied by the production of biodiesel, for which the main raw materials are rapeseed oil, technical fats, used cooking oils and other organic waste. Biodiesel is used mainly in freight transport, marine fleet and agricultural machinery. The largest producers of biodiesel are the companies Preem AB and Neste, which introduce modern technologies for hydroprocessing vegetable and technical oils. This produces high-quality fuel of the HVO100 type (Hydrotreated Vegetable Oil), which can completely replace traditional diesel without technical modifications to the engine.

The government policy to support the bioenergy sector in Sweden is based on a combination of legislative, economic, investment and scientific mechanisms. One of the most important elements of this system is tax incentives. Biofuels are exempt from energy and carbon taxes, which makes them more competitive compared to fossil fuels and stimulates demand among consumers. In addition, the government provides financial support through the "Climate Leap" (Klimatklivet) program, implemented by the Swedish Environmental Protection Agency. It provides grant funding to municipalities, companies and public organizations that implement projects to reduce greenhouse gas emissions, in particular in the field of building biogas plants, biomethane filling stations, modernizing waste processing systems and creating infrastructure for alternative transport [32].

The Swedish Energy Agency (Energimyndigheten) also plays an important role, funding research and development programs in the field of second-generation biofuels, biomass gasification, synthetic fuels and low-carbon technologies for transport. Such investments ensure innovative development of the industry and contribute to the creation of high-tech jobs.

An additional area of support is the development of transport infrastructure for biofuels. The state is investing in the creation of a network of filling stations for biogas, bioethanol and HVO fuels, ensuring their accessibility for the population and transport enterprises. At the same time, the government promotes international cooperation within the framework of European Union programs, such as Horizon Europe and IEA Bioenergy, which allows attracting additional financial resources and integrating national achievements into the pan-European decarbonization system.

Thus, state support for bioenergy in Sweden is a multi-level system that includes tax, financial, institutional and scientific instruments aimed at stimulating the production and consumption of environmentally friendly energy. Thanks to an integrated approach, Sweden has not only achieved a high level of energy self-sufficiency, but also created an effective model of sustainable development, focused on climate neutrality, rational use of natural resources and socio-economic stability.

The development of biofuel production in Ukraine during martial law is a critically important issue that requires immediate attention and a systematic approach. Military actions have led to significant destruction of infrastructure, reduced investments and disruption of supply chains, which

complicates the provision of the country with energy resources [33]. In such conditions, the development of domestic biofuel production becomes not only an element of energy security, but also a strategic direction of post-war economic recovery.

Bioenergy is considered one of the most promising renewable energy sectors in Ukraine, as the country has significant potential for biomass of agricultural, forest and household origin. According to experts, agricultural biomass alone can provide over 25-30 million tons of equivalent fuel per year, which is equivalent to 15-20% of the total national energy consumption. Given the high level of development of the agro-industrial complex, Ukraine has all the prerequisites for creating an effective system of collection, processing and use of biomass for the production of bioethanol, biodiesel, biogas and solid biofuels.

An important factor is that biofuel production can not only partially compensate for the deficit of fossil fuels, but also create added value in agriculture, stimulate the development of the regional economy and ensure energy autonomy of territorial communities.

Despite the existing difficulties associated with military operations, potential prospects for the development of the bioenergy sector remain (Table 3.7). The main factors determining these opportunities are reduced dependence on energy imports, economic benefits, environmental advantages, and support from international partners and organizations interested in the development of renewable energy sources.

In the post-war period, the key task of state policy should be the formation of a National Program for the Development of Bioenergy of Ukraine, aimed at creating conditions for the stable functioning of the bioenergy sector. Such a program should encompass a set of measures of a strategic, institutional, financial, and scientific and technological nature.

The main provisions of such a program should include:

1. Introduction of a system of tax and financial incentives for investors and producers in the biofuel sector, in particular, reducing the tax burden, introducing preferential loans and state subsidies for the modernization of production facilities.

2. Expansion of public-private partnership programs, which will facilitate the attraction of capital and advanced technologies from international companies, while ensuring the creation of new jobs in rural regions.

3. Support for scientific research and technological innovations in the field of bioenergy, in particular, the development of new methods of biomass processing, production of second and third generation biofuels, biogas technologies, as well as improving the energy efficiency of installations.

4. Development of the logistics infrastructure necessary for the collection, transportation, storage and primary processing of biomass, which will allow reducing raw material losses and optimizing supply chains.

5. Attracting international grants and credit resources to finance pilot projects aimed at testing new technologies and creating demonstration enterprises that can become an example for further scaling up.

Table 3.7

Prospects for the development of biofuel production in Ukraine

Prospects	Characteristic
Reducing dependence on energy imports	Domestic biofuel production can reduce Ukraine's dependence on oil and gas imports, which is especially important in times of war.
Economic benefit	Biofuel production can create additional jobs and stimulate the development of rural areas.
Environmental benefits	Biofuels are more environmentally friendly compared to fossil fuels, which will help reduce greenhouse gas emissions.
Support from international organizations	Ukraine can count on the support of international organizations and partners interested in the development of renewable energy sources.

Source: [33-34]

In addition, the effective formation of a national program for the development of bioenergy requires not only the definition of domestic priorities, but also taking into account international experience. Analysis of foreign practices allows us to identify a number of strategic directions that Ukraine can borrow to accelerate the development of its own biofuel market.

First of all, it is advisable to improve the regulatory framework and create an effective system of state incentives for the development of bioenergy. As the practice of the USA, Germany and Sweden shows, the effective functioning of the biofuel market is ensured by introducing quotas for the

mandatory share of biofuels in transport fuel, tax breaks for producers, preferential lending for investment projects, as well as certification of biofuels in accordance with the environmental standards of the European Union. The use of such mechanisms in Ukraine will contribute to the creation of a transparent competitive market for bioenergy resources.

The second important direction is the diversification of the raw material base and the introduction of second-generation biofuel production technologies. The experience of countries such as China, India and the USA shows that the use of agricultural and forest waste, cellulosic biomass, as well as the cultivation of energy crops (miscanthus, willow, poplar) allows to minimize competition with the food sector and ensure the stability of the supply of raw materials. In Ukraine, given the presence of significant areas of low-yielding lands, there is potential for large-scale development of such crops and the creation of sustainable biomass supply chains.

Bioenergy infrastructure also needs further development. The example of Sweden demonstrates the feasibility of creating a network of bioenergy enterprises, biofuel filling stations, as well as regional bioenergy clusters that combine agricultural producers, processing plants and energy companies. Such an approach will contribute to the decentralization of energy supply, the development of regional economies and increased energy security.

The development of scientific and technical research in the field of bioenergy deserves special attention. Similar to the programs implemented in the USA (DOE) and Sweden (Energimyndigheten), it is advisable for Ukraine to expand support for scientific initiatives aimed at improving biomass conversion technologies, in particular enzymatic hydrolysis, gasification and synthetic fuel production. The creation of innovation centers based on universities and scientific institutions will help increase the efficiency of the industry and attract investment.

An equally promising direction is the development of the biogas industry. Given the successful experience of Sweden and Germany, Ukraine can actively introduce biogas plants at agricultural and municipal enterprises. Biogas is a universal energy source suitable for heating, electricity generation and transport, which will simultaneously contribute to reducing the volume of organic waste and improving the ecological condition of territories.

It is also important to expand international cooperation within the Horizon Europe and IEA Bioenergy programs, which will allow Ukraine to harmonize its own standards with European ones, receive grant funding and implement joint projects for the development of bioenergy.

In addition, the domestic market for biofuel consumption needs to be stimulated. The example of Brazil shows that the use of biofuel blends (E10, B20, HVO100) in transport can be a significant factor in reducing the consumption of traditional energy carriers. Ukraine should introduce requirements for the use of biofuels in state and municipal transport, as well as develop a network of biofuel filling stations, which will ensure stable demand for the industry's products.

Therefore, the strategic development of Ukraine's biofuel sector should be based on a combination of state support, innovation, effective use of agricultural potential and active integration into European energy markets. The implementation of these areas will contribute to strengthening the state's energy independence and its transition to a sustainable development model.

3.3 Regulatory and Legal Framework for the Development of Bioenergy Potential

Regulatory and legal frameworks are the foundation for the sustainable development of bioenergy in Ukraine, as they define the rules, principles and tools for implementing policies in the field of using biomass as an energy source. The effectiveness of the implementation of bioenergy technologies, attracting investments, as well as Ukraine's integration into the European energy space depends on the availability of clearly formulated laws, strategies and regulatory mechanisms. A systematic regulatory and legal framework contributes not only to the active development of the existing biomass potential, but also ensures transparency, environmental responsibility and economic feasibility of the implementation of relevant projects.

The main legislative acts of bioenergy are:

– Law of Ukraine “On Alternative Energy Sources” No. 555-IV of March 20, 2003 (as amended), which establishes the basic concepts in the field of alternative energy, in particular bioenergy, defines the forms of state support and principles of using biomass as an energy source [35].

– Law of Ukraine “On Heat Supply” No. 2633-IV of June 2, 2005 (as amended), which provides for the possibility of using biomass for the production of thermal energy, regulates the procedure for access to thermal networks and the establishment of tariffs for alternative heat [36].

– Law of Ukraine “On the Electricity Market” No. 2019-VIII of April 13, 2017 (as amended), which contains provisions on supporting producers of electricity from renewable sources, in particular under a “green” tariff and an auction mechanism, including for bioenergy facilities [37].

– The Law of Ukraine "On Waste Management" No. 2320-IX of June 20, 2022 (as amended), which provides for the use of organic waste as a resource, stimulates the development of composting technologies, biogas plants and thermal conversion of biomass [38].

It is worth highlighting the potential of biomethane production among domestic bioenergy, in particular in the context of the regulatory framework for its development. Today, the regulatory framework for biomethane production in Ukraine is at the stage of active formation and development, providing for integration into the gas transportation system, certification and support in accordance with European standards (Table 3.8).

Table 3.8

Basic regulatory legal acts of Ukraine in the field of biomethane production

№	Title of the legislative act	Main provisions
1	2	3
1	Law of Ukraine No. 1820-IX of October 21, 2021 “On Amendments to Certain Laws of Ukraine Regarding the Development of Biomethane Production”	Contains the legislative framework for the development of the biomethane market in Ukraine and its export. In particular, a biomethane register and a system for issuing guarantees of origin have been introduced, and the definition of the term “biomethane” has been officially established [39].
2	Resolution of the Cabinet of Ministers of Ukraine “On Approval of the Procedure for the Operation of the Biomethane Register” dated July 22, 2022 No. 823	Establishes requirements for the operation of the biomethane registry and assigns the State Agency for Energy Efficiency and Energy Saving the responsibility for its creation and operation [40].

(End of Table 3.8)

1	2	3
3	DSTU EN 16723-1:2023 "Natural gas and biomethane in transport and biomethane for injection into the natural gas network", approved by the order of the State Enterprise "Ukrainian Research and Training Center for Standardization, Certification and Quality" "On the adoption of national standards" dated April 3, 2023 No. 55	The document contains a detailed description of the technical characteristics of biomethane required for its supply to distribution and main networks. The standard was developed by the Technical Committee for Standardization of the Ivano-Frankivsk National Technical University of Oil and Gas in accordance with the main requirements of the EU [41].
4	Law of Ukraine No. 3311-IX of August 9, 2023 "On State Support for Investment Projects with Significant Investments in Ukraine"	For projects aimed at the production of bioethanol, biogas and biomethane, with a total investment of over 12 million euros, the following benefits are provided: - exemption from payment of certain taxes and fees; - exemption from import duty on new equipment and components for it; - granting of preferential rights to use land plots of state or municipal property; - financing of construction of engineering and transport infrastructure facilities from the state budget or compensation for the costs of such construction; - reimbursement of costs for connection to engineering transport networks; - exemption from payment of compensation for losses of forestry production [42].
5	Law of Ukraine No. 3613-IX of March 20, 2024 "On Amendments to the Customs Code of Ukraine and Other Laws of Ukraine Regarding the Peculiarities of Customs Control and Customs Clearance of Certain Categories of Goods"	Customs control and customs clearance of biomethane transported by pipeline across the customs border of Ukraine within the framework of foreign economic agreements (contracts) are carried out in accordance with the procedure established by the legislation of Ukraine in the field of customs affairs for natural gas [43].

Source: Legislation of Ukraine. Official web portal of the Parliament of Ukraine [44]

The potential for biomethane production in Ukraine is estimated to be significant, taking into account the existing volumes of organic waste in agriculture and the possibility of their processing into renewable fuel.

Thus, today in Ukraine the foundations of legislative regulation in the field of biomethane production have already been formed. Although this base still needs to be finalized, important first steps have already been taken.

Strategic documents and national programs of Ukraine define the priorities for the development of bioenergy as a key element of energy security and the transition to sustainable renewable energy in the context of European integration obligations. Such documents include:

Energy Strategy of Ukraine until 2050. This key national policy document defines general guidelines for the energy sector in the long term. The strategy recognizes bioenergy as one of the priority areas for the development of renewable energy sources (RES), especially in terms of replacing natural gas in heat production. It provides for a gradual increase in the share of biomass in the energy balance, infrastructure development, the creation of a biofuel market, and the stimulation of investments in energy production from agricultural waste and energy crops. Bioenergy is considered as a tool for reducing energy dependence and increasing the sustainability of the energy system.

National Renewable Energy Action Plan until 2030. This document sets the goal of achieving at least a 27% share of RES in total final energy consumption. Particular attention is paid to biomass as the most accessible and resource-rich energy source in the agricultural sector of Ukraine. The plan provides for specific steps to stimulate the production of heat and electricity from biomass, the development of local biofuel markets, simplification of conditions for connecting such capacities to the energy system, as well as the introduction of support mechanisms for producers.

National Energy Efficiency Plan. This document focuses on reducing the energy intensity of the economy and increasing energy efficiency. One of the key areas is the modernization of heat-generating capacities with an orientation towards the transition to alternative heat sources, in particular biomass. The plan stimulates the use of solid fuel boilers in the budget sector, municipal institutions and the private sector, the introduction of biomass cogeneration plants, as well as the energy utilization of agricultural and forestry waste.

Association Agreement between Ukraine and the EU (2014). According to the Agreement, Ukraine has undertaken to harmonize its national legislation with the law of the European Union, including provisions in the field of energy and ecology. Of particular importance is the implementation of the provisions of Directive 2018/2001/EU on the promotion of the use of energy from renewable sources (RED II), which establishes requirements for guarantees of origin of bioenergy, sustainability criteria for biofuels, integration of biomethane into gas networks, as well as conditions for stimulating local energy production from biomass. The implementation of these obligations opens up opportunities for the participation of Ukrainian bioenergy producers in the European market [44; 49].

Energy Community Treaty. Ukraine has been a full member of the Energy Community since 2011. This is an international organization that unites EU countries and neighboring states to form a common energy market. Within the framework of this cooperation, Ukraine:

– has committed to implementing EU directives on renewable energy, in particular RED II;

– participates in the development of decarbonization and energy transition policies;

– annually reports on achievements in the development of bioenergy.

Paris Climate Agreement (2015). Ukraine ratified the Paris Agreement in 2016. Under this agreement, the country committed to reducing greenhouse gas emissions and transitioning to a low-carbon economy. Bioenergy, as a carbon-neutral energy source, is an important component in the implementation of Ukraine's Nationally Determined Contribution (NDC) to the Paris Agreement.

International Renewable Energy Agency (IRENA). Ukraine is a member of IRENA, an intergovernmental organization that supports countries in the transition to renewable energy sources. IRENA provides Ukraine with:

– analytical support for the development of bioenergy potential;

– economic feasibility assessments;

– access to global databases and technological solutions.

The United Nations Sustainable Development Goals (SDGs), in particular SDGs 7 and 13:

– SDG 7 "Ensure access to affordable, reliable, sustainable and modern energy for all;

– SDG 13 "Action against climate change and its impacts".

Ukraine has committed to adapting its policies to the SDGs, and the development of bioenergy directly contributes to the achievement of these goals by reducing CO_2 emissions, increasing energy security and energy efficiency [44; 49].

Therefore, in addition to Ukraine's national programs, the international regulatory framework to which Ukraine has joined forms a strategic and legal framework for the sustainable development of bioenergy. Its compliance is critical for access to European markets, attracting investment, integration into the EU's single energy space, and fulfilling global environmental obligations.

In the field of bioenergy technologies implementation in Ukraine, state policy is implemented and coordinated by certain specialized ministries, departments and state authorities (Fig. 3.6).

Figure 3.6. State authorities regulating the bioenergy sector

Source: systematized by the author based on [45]

The Ministry of Energy of Ukraine:

– formulates and implements state policy in the energy sector, in particular on the development of renewable energy sources, including bioenergy;

– develops regulatory acts, strategies and support programs;

– is responsible for the balance of energy resources and energy security.

The Ministry of Economy, Environment and Agriculture of Ukraine:

– is responsible for the use of agricultural biomass and the development of energy crops;

– coordinates programs for the utilization of agricultural waste in bioenergy;

– supports agricultural producers in the field of sustainable energy supply;

– provides environmental assessment of bioenergy projects;

– coordinates the policy on reducing greenhouse gas emissions and adapting to climate change;

– regulates the issue of sustainable use of biomass and its impact on the environment.

The State Agency for Energy Efficiency and Energy Saving of Ukraine:

– a key body in the field of bioenergy development;

– coordinates programs to stimulate the use of biomass, biogas, biomethane;

– provides information, analytical and expert support;

– administers the mechanisms of the "green tariff", stimulation of RES, certification of biofuels.

The State Statistics Service of Ukraine:

– collects and publishes statistical data on the production, use and export of bioenergy;

– provides an analytical basis for assessing the bioenergy potential.

The National Commission for State Regulation in the Spheres of Energy and Utilities:

– licenses producers of energy from biomass;

– sets tariffs and provides conditions for connection to electricity networks;

– regulates the market for electricity from renewable sources.

The State Agency of Forest Resources of Ukraine:

– is responsible for the use of forest biomass, forest waste and wood for energy needs;

– supports the policy of sustainable forest management taking into account the bioenergy direction.

Regional state administrations and local governments:

– implement regional programs for the development of bioenergy;

– implement projects at the local level, in particular in the field of municipal heating;

– promote the attraction of investors and the development of local biomass markets [45].

These bodies jointly form the regulatory, economic and organizational framework for the development of bioenergy in Ukraine, which is an important component of energy security and decarbonization of the economy.

By the way, today there are the following mechanisms to support bioenergy: a green tariff for electricity from biomass (until 2030); preferential loans for the installation of equipment; state co-financing of pilot projects; tax breaks for biofuel producers (for example, bioethanol and biodiesel).

Thus, the regulatory framework for the development of Ukraine's bioenergy potential forms the legislative basis for the effective use of biomass, stimulating investment and integration into the European energy space.

3.4. Formation of a Strategy for the Development of Bioenergy Potential of Rural Areas

The formation of a strategy for the development of the bioenergy potential of rural areas is a key element in achieving energy security, increasing energy efficiency and stimulating local economic growth. In modern conditions of decentralization and increasing requirements for the rational use of resources, communities receive a unique opportunity to independently plan and implement initiatives in the field of renewable energy, in particular bioenergy. The presence of agricultural land, agro-industrial enterprises and household organic waste creates favorable conditions for the use of local resources as an energy source. The implementation of a strategic approach allows you to systematize the existing potential, determine priorities, attract investments and ensure long-term sustainable development of rural areas.

In our opinion, biogas (biomethane) production is one of the most promising areas of bioenergy in rural areas and in Ukraine as a whole. Biogas and biomethane are characterized by a number of technologically and environmentally sound advantages compared to other types of biofuels. Their production is continuous and does not depend on the seasonality of biomass formation, which ensures the stability of energy supply throughout the year. Anaerobic fermentation allows processing a wide range of organic raw materials, including waste from livestock and the agro-industrial sector, while the production of bioethanol or biodiesel requires high-quality crops with competition for food resources. The methane fermentation process is accompanied by the utilization of methane emissions from organic waste and the formation of digestate, which is returned to agricultural systems as fertilizer, forming a closed biogeochemical cycle. Deep purification of biogas allows to obtain biomethane, which in terms of parameters corresponds to natural gas and can be fed into gas transmission networks or used as motor fuel, providing one of the highest greenhouse gas reductions among biofuels. In addition, the lack of dependence on fluctuations in food prices and the reduction of logistical risks make biomethane technology more economically sustainable compared to solid and liquid biofuels.

The potential for biogas/biomethane production in Ukraine is shown in Table 3.9.

Table 3.9

Biogas/biomethane production potential in Ukraine per year

Indicator	billion cubic meters of CH4
Biogas from animal waste	0,9
Biogas from crop waste	5,2
Biogas from food industry waste	0,7
Biogas from household waste	0,5
Biogas from sewage sludge	0,1
Biogas from corn silage	3,8
Biogas from cover crops	9,8
Biogas from thermal gasification	1,0
Total	22

Source: [46]

Therefore, based on Table 3.9, the top three most productive substrates for biogas and biomethane generation include: cover crops, crop waste, and corn silage as one of the most efficient energy resources.

A development strategy is a scientifically based, systematic and long-term action plan aimed at achieving specific socio-economic, environmental and institutional goals through the effective use of available resources, the potential of the territory, management tools and the involvement of stakeholders.

In modern economic conditions, especially during the period of martial law, the implementation of strategies for the development of the bioenergy potential of rural areas faces a number of significant challenges and barriers. Current barriers to the development of bioenergy and possible ways to overcome them are shown in Table 3.10.

So, having analyzed the existing modern barriers to the development of bioenergy with possible ways to overcome them, we systematize this into a strategy for the development of the bioenergy potential of rural areas of Ukraine.

Specific strategies for the development of the bioenergy potential of rural areas, formed taking into account their resource supply and modern challenges (in particular, martial law), are reflected in Table 3.11.

Taking into account the above, along with the strategies for developing the bioenergy potential of territorial communities, it is worth highlighting the model of functioning of the territorial bioenergy cluster (Fig. 3.7).

A bioenergy cluster is a form of spatial and organizational integration of business entities, research institutions, local governments and other participants who unite for the purpose of effective production, processing, storage, transportation and use of energy from biomass. Such a cluster operates on the principles of cooperation, shared use of infrastructure, resources and innovations, contributing to the development of sustainable energy supply at the local level, increasing energy efficiency, economic self-sufficiency of rural areas and the territorial community as a whole, as well as attracting investments in the field of renewable energy.

Table 3.10

Barriers to the development of bioenergy and possible ways to overcome them

Barriers	Ways to overcome
Lack of an approved roadmap for the development of bioenergy until 2050 and an action plan until 2025	To consider and officially approve the developed drafts of the above documents.
Underdevelopment of the solid biofuel market	Introduce an electronic trading system (ETS) for solid biofuels using electronic auctions with quality assurance of biofuels in the ETS.
Insufficient state support for biomass and biofuel producers	Provide state support to companies growing energy crops.
Lack of mechanisms to stimulate the production and consumption of biomethane	Introduce a definition of the term “biomethane”. Introduce a system of guarantees of origin for biomethane.
Delays or incomplete payment for electricity at the “green” tariff	Ensure the financial stability of the “Guaranteed Buyer” and grant renewable electricity producers the right to leave the balancing group of the “Guaranteed Buyer” and freely sell electricity on the market with the possibility of receiving compensation (contracts for difference).
Discriminatory imbalance payment conditions for electricity producers from biomass and biogas compared to electricity producers from solar and wind energy	Introduce for producers of electricity from biomass and biogas an allowable deviation of the actual volumes of electricity supply from the supply schedule at the level of at least 5% (currently the allowable deviation is 0%).
Lack of auctions for state support for renewable energy projects	Start providing state support for renewable energy generation projects as soon as possible.
Difficulties of biomass thermal energy producers with connection to district heating networks	Introduction of a competitive thermal energy market.
Imperfect mechanism for forming tariffs for thermal energy produced from alternative energy sources	Provide producers of thermal energy from renewable energy sources with the opportunity to choose the procedure for setting the tariff.
The need for mandatory state registration of digestate from biogas plants for use as organic fertilizer	Remove the requirement for mandatory state registration of digestate, specified in the Law “On Pesticides and Agrochemicals”. Develop and approve a national standard for digestate when used as an organic fertilizer or soil improver.

Source: [4]

Table 3.11

Strategies for developing the bioenergy potential of rural areas of Ukraine

№	Strategy name	Goal	Key actions
1	Bioenergy cluster development strategy	Creation of a bioenergy cluster based on existing agricultural enterprises, a sugar factory, forestry, etc.	• Formation of partnerships between agricultural producers, industrial enterprises, scientific institutions and local governments. • Development of a business model for joint collection, processing and use of biomass. • Implementation of instruments for joint financing of infrastructure solutions (logistics, storage, transportation of bio-raw materials).
2	Infrastructure strategy	Ensuring technical feasibility for launching bioenergy projects	• Installation of biogas plants based on local operating entities with available bio-raw materials for processing organic waste. • Modernization of heat-generating plants in social infrastructure (schools, kindergartens, medical facilities) with the transition to biofuel. • Connection of potential consumers (farms, enterprises) to the created biofuel energy supply system.
3	Educational and information strategy	Raising awareness and engaging the public in the development of bioenergy	• Conducting educational campaigns for residents of rural areas or the community as a whole on the benefits of using biofuels. • Organizing training for farmers, entrepreneurs and workers in the field of bioenergy. • Developing pilot projects for energy-independent households based on biofuels.
4	Economic strategy to stimulate investment	Attracting internal and external investors	• Development and promotion of an investment passport for the community bioenergy cluster. • Implementation of local co-financing programs for small biofuel producers. • Search for donor support (grants, credit lines) through international energy initiatives.
5	Environmental strategy for sustainable resource management	Ensuring environmental safety and preserving natural resources	• Stimulating the implementation of waste-free biomass processing technologies. • Using biofuel residues as organic fertilizers in local agriculture. • Environmental monitoring of the activities of bioenergy facilities within the community.

Source: suggested by the author

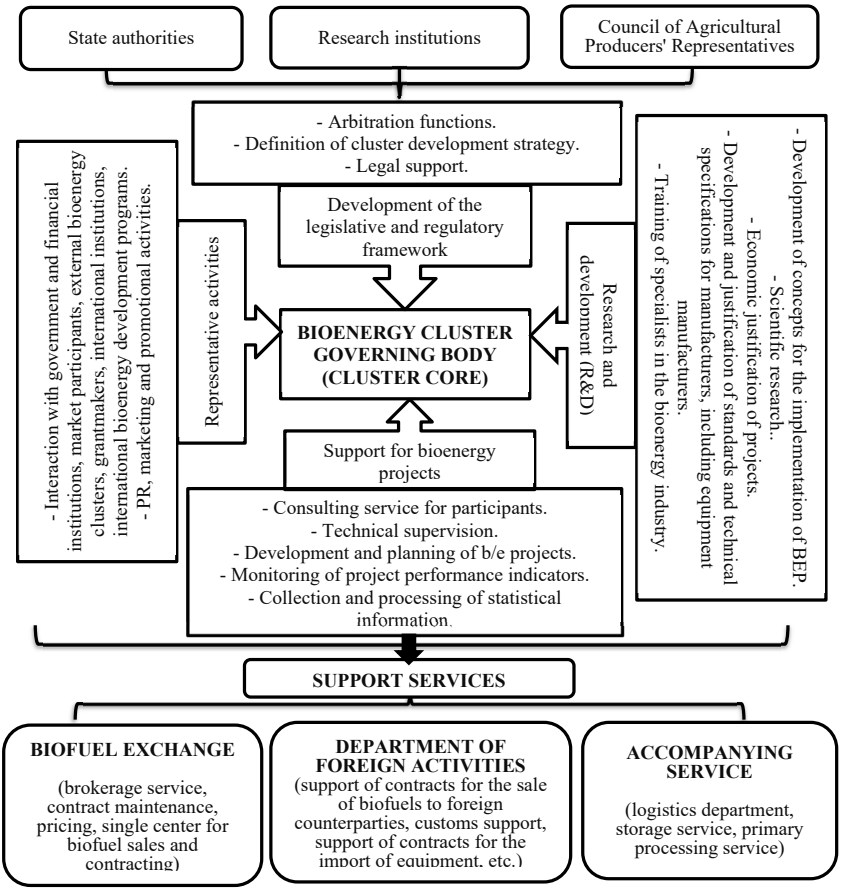

Figure 3.7. Territorial bioenergy cluster model

Source: [47; 48]

The formation of such clusters at the level of administrative-territorial units (settlements, communities, districts, regions) opens up opportunities for their further unification into bioenergy superclusters of a regional scale. Such an approach, firstly, will help overcome the territorial dispersion of bioenergy market participants, and secondly, the formation of powerful

regional centers ("mass centers"), which can become points of concentration of resources, technologies and investments.

In our opinion, the formation of bioenergy clusters within territorial communities can become a powerful catalyst for the development of the bioenergy sector, as it creates conditions for building a unified infrastructure, forming a favorable business climate, and strengthening interaction between business entities, scientific institutions, and local governments.

The main prospects that the cluster approach opens up for rural areas and communities are as follows [2]:

1. Shared infrastructure: the functioning of bioenergy clusters allows rural areas, communities and enterprises to jointly use infrastructure facilities – from biomass collection and transportation to biofuel storage and processing.

2. Rational resource management: clusters ensure more efficient use of local natural, technical and labor resources, which allows reducing production costs and increasing economic efficiency for participants and the territorial community.

3. Innovative synergy: thanks to close cooperation between enterprises, agricultural producers, educational and scientific institutions, a platform is created for the development of new technologies, modernization of production processes and dissemination of innovative practices.

4. Investment attraction: organized clusters with a clear structure and common prospects significantly increase the attractiveness of the industry for domestic and foreign investors, which, in turn, contributes to the development of public infrastructure.

5. Formation of a complete value chain: clusters make it possible to organize all stages of production – from growing energy crops to the final consumption of bioenergy – within one territorial community or united communities, which ensures the preservation of added value on the ground.

6. Support for regional development: bioenergy clusters can unite different communities around common goals, creating a platform for communication, partnership and exchange of experience, which contributes to the activation of local business and the development of rural areas.

7. Marketing integration: the cluster approach contributes to the development of a single marketing policy, which strengthens the position

of bioenergy products on the market, promotes the recognition of the community as an innovative energy producer and strengthens the brand of the territory [2].

Therefore, the creation of bioenergy clusters at the level of territorial communities in rural areas can ensure the comprehensive development of the bioenergy sector, accelerate the economic growth of local territories, strengthen the energy independence of communities, and promote the sustainable development of rural and semi-urbanized regions.

In modern conditions, an important factor for the effective development of the bioenergy sector is targeted state support, which should include a set of measures aimed at stimulating the production and consumption of bioenergy, reducing greenhouse gas emissions, activating investment activities and creating a favorable environment for the development of the industry at the national and regional levels. The main instruments of such stimulation may include [2]:

1. Financial and economic levers:

– providing subsidies, grants and other forms of non-repayable financial support for the launch or modernization of facilities operating on bioenergy technologies;

– creating investment platforms and targeted programs aimed at attracting private capital to the bioenergy sector.

2. Regulatory and legal mechanisms:

– introducing stable and economically justified "green" tariffs for electricity from biomass;

– providing fiscal benefits (tax discounts, payment deferrals) for enterprises investing in the production and use of biofuels.

3. Infrastructure support:

– state co-financing of the construction or modernization of infrastructure for the procurement, transportation, storage and processing of biomass;

– promoting the development of logistics networks that ensure a stable supply of raw materials to bioenergy facilities.

4. Regulatory and technical support:

– development and implementation of biofuel quality standards and requirements for environmental safety of bioenergy processes in order to unify and increase the efficiency of the sector.

5. Educational, scientific and information activities:

– support of specialized educational programs, training of specialists, financing of applied research in the field of bioenergy;

– conducting large-scale information campaigns among the population, business and government bodies to form a positive perception of bioenergy.

6. Territorial cooperation and regional projects:

– stimulation of the creation of local bioenergy clusters as forms of unification of the agricultural, industrial, scientific and administrative potential of regions for the effective development of the sector.

7. System planning and control:

– formation of a state strategy for the development of bioenergy taking into account national energy priorities and climate goals;

– regular monitoring of the effectiveness of the implemented instruments, adjustment of policies and programs based on the results obtained.

Therefore, the application of these measures will not only expand the use of renewable energy sources in Ukraine, but also create conditions for sustainable energy development, environmental safety, innovative breakthroughs, and employment growth in rural and industrial and agricultural regions.

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