World trends in bioethanol and biodiesel production in the context of sustainable energy development

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Abstract: The article outlines the current state of increasing consumption and demand for primary energy resources due to exhaustion and avalanche-like growth of their world prices. The effects of excessive use of non-renewable energy resources that have led to global climate change and deterioration of the natural environment are highlighted. The priority of sustainable development of the world energy sector is based on increasing consumption of renewable energy resources. The processes of the general world consumption of various types of primary energy and the dynamics of indicators of world bioethanol and biodiesel production during 2000–2018 are analysed. The forecast of consumption of the primary world energy and the production of liquid biofuels has been made for 2019–2025. The results indicate that the world market of bioethanol and biodiesel tends to expand, providing from an economic point of view rational use of energy resources, reducing gasoline and diesel consumption.

Keywords: global energy consumption; fossil fuels; environmental change; sustainable development; renewable energy; bioethanol; gasoline replacement; biodiesel; diesel replacement; correlation and regression analysis; economic development.

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1 Introduction

The process of energy resource consumption has to be as purpose-oriented and adequately organised concerning the ever-increasing needs of society and enterprises. The beginning of the 21st century is characterised by profound transformations of ideas about the consumption of the most efficient and the most rational types of energy resources (Jaeger and Machry, 2014; Kander et al., 2013). At the present stage, humanity has already approached the threshold of primary energy resources exhaustion for oil and natural gas. The last is related to a significant increasing energy demand, which has led to rise in global fossil fuel prices (Fouquet, 2014; IRENA, 2018). The current global economic problems are to ensure global food security, the growth of production costs and specific investment in the energy sector, and elaboration by world community the regulatory methods and a coherent strategy for the global energy development (Bodirsky et al., 2015; Cox et al., 2016; Ito and Sallee, 2014). Additionally, one should mention the problem of convergence not only within the specific states but also within the globe (Li et al., 2019).

Consequently, the issue of energy saving is characterised by considerable diversity and is a necessary strategic direction of efficient use of production capacities with optimal energy costs. Strengthening the world economic system and improving the living standards of the population will largely depend on the rational energy use. Nevertheless, the world oil market operates extremely efficiently the resources of oil and natural gas could be exhausted in this century (Fawcett, 2016; Goldthau, 2014). A significant increase in energy prices predetermines their economical use, which is observed in most countries of the world, primarily in industrialised countries. Activities in the field of energy-saving are characterised not only by high economic efficiency but also related to reduction of anthropogenic pressure on the environment (Sotnyk and Mazin, 2015; Sotnyk, 2016). However, energy-saving does not allow to completely solve the problem of oil and natural gas exhaustion (Bouzarovski and Petrova, 2015; Burchell et al., 2015; Sineviciene et al., 2017).

Harmful emissions from burning oil, coal, gas lead to the greenhouse effect, and the emergence of threats to public health (Kubatko and Kubatko, 2017, 2019). Unregulated economic growth and industrialisation worsen the state of the environment, which is caused by negative phenomena of modern life, e.g., pollution, industrial noise, emissions, deterioration of the aesthetic appearance of most industrial cities, significant traffic congestion, etc. (Brand and Hunt, 2018; Gillingham and Palmer, 2014). Problems of the world's energy relations are also aggravated, and alternative energy sources can replace fossil fuels. The existing economic and environmental situation requires new ways to provide humanity with energy, the transition to renewable energy resources (Fouquet, 2015). On the contrary, there is a direct positive effect of fourth and fifth industrial revolutions on the environmental sustainability of economic systems and reduction of environmental conflicts (Melnyk et al., 2019; Sabadash and Denysenko, 2018).

The change in the competitive energy technologies and the structure of energy resources is needed for the production of electricity and heat based on hydrocarbons that use renewable energy resources (Gough, 2015; Kurbatova et al., 2019; Royston et al., 2017). Returning to renewable energy would help to mitigate the climate change and help to meet the energy needs of future generations (Owusu and Asumadu-Sarkodie, 2016). The consumption of an excessively large amount of energy resources has caused a significant negative impact on the Earth's environment and provoked an increased frequency of environmental disasters (desertification of territories, destruction of the ozone layer of the atmosphere, unprecedented development of erosion processes on field lands, intense acid rain, deterioration of drinking water quality, reduction biodiversity, global climate change, the greenhouse effect of anthropogenic origin, etc.). The emergence of a real threat to the existence of human civilisation is due to the inconsistency of economic growth with the capabilities of the natural environment (Aghion et al., 2014; Sotnyk and Kulyk, 2014; Walker, 2014). Therefore, there is an urgent need for an early transition to sustainable development (Holden et al., 2017). The basic idea of sustainable development reflects the complexity of the relationship between the ecological activities of people and the environment. Due to the presence of significant environmental factors and the considerable limited global reserves of non-renewable energy resources, there is a specific limit to the development of the energy sector and the closely related economy (IEA, 2017; Kaletnyk and Klymchuk, 2013). Melnyk and Kubatko (2012) stated about the urgent necessity of economic valuation of environmental goods and services to guaranty long-run sustainable development.

Renewable energy sources are one of the important criteria for the sustainable development of the world community. Moreover, they allow to attract financial resources for sustainable community development (Chortok et al., 2019). As stated by Hens et al. (2018), the national economy's sustainable development includes a wide variety of indicators for achieving its integral assessment. Under the market economy, the solution to the global energy security became one of the key areas. Due to incentives, tax breaks, and defined government programs for many developed countries, bioenergy is one of the priorities and main direction of renewable energy (Kurbatova, 2018; UN General Assembly, 2015). Energy security is recognised at the national and international levels as one of the major and priority issues, since it is a sufficient incentive for further socio-economic development, country's sovereignty, its stable financial growth (Sotnyk et al., 2015; Sovacool, 2014).

The evolutionary process of the development of biofuel production technologies also reflects the evolution of world public opinion, economic opportunities, environmental threats, and scientific forecasts, divided into certain stages (Mohr and Raman, 2013). At first, the primary idea was about the possibility of biofuel usage along with fossil energy sources (Zilberman et al., 2012). The most significant impetus for scientific research in the area of biofuel technologies development was the awareness of exhaustion of existing oil and natural gas reserves. Evidence of the threat of oil stocks ending is the fact that over the recent period, it has not been opened new large world deposits and there was a steady price rising tendency for this type of raw materials (Bentivoglio and Rasetti, 2015). Oil stocks shortages became a national security matter for many countries of the world, as it was during the twentieth century. The significant increase in the oil and natural gas use during the twentieth century has become a key factor that led to the rise in carbon dioxide emissions into the atmosphere, provoked environmental changes on the planet and created a threat to global warming (Zhang et al., 2013). The next stage in the evolution of biofuel technology development was the practical implementation of scientific researches and commercialisation of the global biofuels market (Popp et al., 2014). Biofuel production is considered green industries innovations to deal with resource fluctuations (Melnyk and Kubatko, 2013). The modern world biofuel market is characterised by all the signs of innovative markets:

1 research is constantly conducted in the area of improving production technologies

2 there is an improvement in the physicochemical properties of various types of biofuels

3 many production lines and program goals are announced; significant informational pressure

4 society is created in economic, energy and environmentally concern.

The first-generation of biofuels, which at the present stage of development have the most practical use, include bioethanol made from sugar cane, sugar beet, corn, wheat, and other cereals and biodiesel made from oilseeds – soybean, canola, palm trees, sunflower, and others. The high-productivity cultivation of these crops requires high-quality of arable land, significant use of agricultural equipment, as well as fertilisers and pesticides. Under such conditions, the biofuel production is characterised by direct competition with the food sector of the economy (Boucher et al., 2014). However, the world energy market is marked by intensive development of the biofuel industry, causing a steady increase in the production and consumption of liquid biofuels (Klymchuk, 2017). General calculations indicate that in case of converting all types of carbohydrates (starch and sugar crops) into ethanol, it could replace up to 40% of the world's gasoline consumed every year. World production of vegetable oils is not able to provide even 10% of the diesel fuel used. The above information points out the existence of a different potential of the raw material base in the liquid biofuel production and the need to use a differentiated approach concerning the world rates of increasing the bioethanol and biodiesel production. *The purpose of the article is related to* development of a promising model for ensuring sustainable energy development, and to establish the pace of global liquid biofuel production for gasoline and diesel fuel consumption reduction.

2 Research methodology

The economic globalisation does not let aside any of the state on the planet. Economically developed countries support the principles of the Energy Charter, as well as the Global Charter, in shaping sustainable energy development. The priority task of these interstate agreements is to open the energy sector in each country and to establish international competition. It will be a significant positive if industrialised countries begin to work closely with third world countries in the field of the formation and development of renewable energy sources to meet the energy needs of these countries. For the convenience of calculations and comparisons of various types of energy, consumption of any fuel type was compared with the use of the so-called oil equivalent (OE). In industrialised countries, such an equivalent is fuel, with the complete one-kilogram combustion out of which is allocated 41.84 × 106 J of energy corresponding to the oil energy intensity indicator. The article uses the metric – tons of oil equivalent (TOE).

When calculating the replaced gasoline amount under using bioethanol, the following indicators were taken into account: the gasoline density – 0.75 g/cm^3, and bioethanol density – 0.79 g/cm^3; the calorific value of gasoline is 46.0 MJ/kg or 34.5 MJ/l, and calorific value of bioethanol, respectively 27.0 MJ/kg or 21.3 MJ/l. Therefore, relative to gasoline, the specific energy consumption of 1 kilogram of bioethanol is approximately equal to 59%, and 1 liter – 62%. To calculate the amount of replaced diesel fuel by biodiesel, the following indicators were taken: the diesel fuel density – 0.85 g/cm^3, and biodiesel density – 0.88 g/cm^3; the calorific value of a diesel fuel is 41.8 MJ/kg or 35.5 MJ/l, and calorific value of biodiesel is respectively 37.5 MJ/kg or 33.1 MJ/l. Therefore, relative to diesel fuel, the specific energy consumption of 1 kg of biodiesel is approximately equal to 90%, and 1 liter – 93%.

The analysis of total world consumption of various types of primary energy and indicators of world bioethanol and biodiesel production was carried out using correlation analysis and multiple linear regressions. Multiple regression models are characterised by accuracy in the assessment and provide an opportunity to show the strength and direction of individual factors. A forecast about the trend of the studied indicator was made through the approximating function, based on the discrete data. By constructing this line and continuing it to the right beyond the limits of the known time range, we obtain the desired prediction. The following general and unique scientific methods and techniques were used: *economic and historical* (identifying the economic nature of fuel and energy resources and optimising their use in a historical context); *graphic* (providing a visual perception of the main study results); *correlation and regression analysis and modeling* (determining the strength and directions of the link between two or more study object signs; logical establishment of known causal relationships between the studied indicators; *forecasting* (the formation of the conceptual framework of regulation and development strategy for the global liquid biofuels production and the prospects for further research).

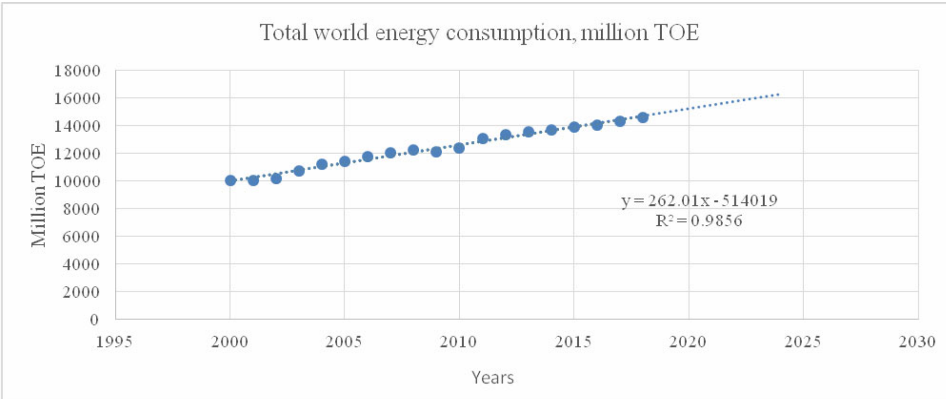
3 Results and discussions

3.1 World primary energy consumption

The human began its energy history with the careful use of renewable energy resources (solar energy, wind energy, biomass, hydropower, geothermal energy, etc.), but subsequently turned to over-exploitation of non-renewable energy sources (coal, oil, natural gas). However, now it is returning to the use of renewable energy resources at a qualitatively new level (with the latest technologies and higher efficiency ratio). Even though during the evolutionary development process, the depletion or abandonment of one or another type of energy resource was carried out, their new sources are being constantly discovered. Historical events in the world market of fuel and energy resources, which took place in the 70s of the twentieth century, were considered by most developed countries as an oil crisis. As a result, the complexity of the energy development problem at the end of the twentieth and early twenty-first centuries is largely determined by the ratio of the quantitative and qualitative economic growth characteristics.

Increasing the economic efficiency of the social production of various types of goods and services requires the creation of a reliable energy base. Since the 21st century, more than 10,000 million tons of different primary energy types are consumed annually on Earth (Figure 1).

Figure 1 Trend line for total world primary energy consumption (see online version for colours)



Source: Data from 2000 to 2018 (World Energy Outlook, 2019) and authors' calculations

The obtained results indicate a positive trend in the annual growth in the consumption of various primary energy types. Only in 2009, the primary energy consumption rate was lower by 1.1% compared with 2008. Starting in 2010, current growth rates of energy resources consumption averaged 2.1% per year. There are definite positive links between the amount of energy used and civilisation development. Energy is one of the fundamental basic needs of human society, and an effective means of improving the qualitative characteristics of life. On average, about 20% of the population in the most industrialised part of our planet consumes about 60% of the total amount of energy produced. In comparison, the remaining 80% of the population in most developing countries use only 40% of the total energy amount, indicating uneven distribution and primary energy consumption. This phenomenon leads to a constant aggravation of the struggle in the energy sector for the possession of industrial reserves of energy resources and the coordination of the infrastructure their supply and distribution, which often leads to various level conflicts.

The strategic goal of state policy in developed countries is environmental and energy efficiency. Improving the global structure of energy supply and demand should be carried out through the development and integrated introduction of renewable energy sources and the constant increase in the efficiency of their use. Having experienced two oil crises during the past century, the world community has begun an active search for alternative fuels, in particular biological fuels, based on renewable raw materials. After conducting long-term scientific and practical research and the introduction of liquid biofuels into production, it became clear that they could not completely replace oil. The most effective among the biological fuels are biodiesel (contains about 90% of the diesel fuel energy) and bioethanol (contains about 60% of the gasoline fuel energy).

The existing economic, energy, and environmental situation require an early transition to renewable energy resources, which is characterised by rational direction of stable existence, further development, and providing humanity with energy. Such a strategic direction of energy production and consumption corresponds to the conditions declared by the world community for sustainable development worldwide and the stable economic existence of society. Due to the constant shortage of petroleum fuels in energy-independent countries, there is a growing demand for own production and consumption of their substitutes (biodiesel and bioethanol) (Klymchuk, 2013).

3.2 World bioethanol production

Bioethanol is a product of bioconversion of carbohydrate-containing raw materials (biomass and/or organic fractions of waste) with a regulated amount of concomitant and denaturing additives. The process of alcoholic fermentation consists of converting simple sugars (glucose, fructose) under the influence of enzymes into ethyl alcohol (C_2H_5OH) and carbon dioxide (CO_2). The technology of bioethanol production consists of two main stages: the production of raw alcohol and ethanol dehydration. Ethanol can be anhydrous or hydrous. Anhydrous ethanol, with a water content of not more than 1%, can be mixed with gasoline in various proportions both to reduce the consumption of gasoline fuels and to reduce air pollution. Hydrous bioethanol contains 93% ethanol and 7% water.

Table 1 Dynamics of world bioethanol production

Year	*World ethanol production*			*Dynamics of bioethanol production, ±%*	*An equivalent amount of replaced gasoline*	
	Bill l	*Mill t*	*Mill TOE*		*Bill l*	*Mill t*
2000	29.4	23.2	15.0	–	18.1	13.6
2001	31.3	24.7	15.9	6.5	19.3	14.5
2002	34.1	26.9	17.4	8.9	21.1	15.8
2003	39.0	30.8	19.9	14.4	24.1	18.1
2004	40.7	32.2	20.8	4.4	25.2	18.9
2005	44.3	35.0	22.6	8.8	27.3	20.5
2006	51.3	40.5	26.1	15.8	31.7	23.8
2007	49.7	39.3	25.4	–3.1	30.8	23.1
2008	66.8	52.8	34.1	34.4	41.3	31.0
2009	76.9	60.8	39.2	15.1	47.6	35.7
2010	88.2	69.7	45.0	14.7	54.5	40.9
2011	84.8	67.0	43.2	–3.9	52.4	39.3
2012	82.6	65.2	42.1	–2.6	51.1	38.3
2013	88.7	70.1	45.2	7.4	54.8	41.1
2014	93.1	73.5	47.4	5.0	57.5	43.1
2015	97.2	76.8	49.6	4.4	60.1	45.1
2016	100.6	79.5	51.3	3.5	62.3	46.7
2017	102.4	80.9	52.2	1.8	63.3	47.5
2018	108.1	85.4	55.1	5.6	66.8	50.1
Average	68.9	54.4	35.1	7.8	42.6	32.0
Total	1,309.2	1,034.3	667.5	–	809.3	607.1

Source: Renewable Fuels Association (2019) and authors' calculations

Now bioethanol as a fuel is used mainly in the transport sector: it is sold at gas stations in the form of mixtures with gasoline or in purely. Also, the obtained ethanol can be used as a renewable raw material. Ecological modernisation of the transport system for green growth in the Sumy region (Ukraine) was estimated by Shkarupa et al. (2017). Thus, the main propositions were related to the implementation of environmentally friendly fuel. It is generally accepted that bioethanol from renewable plant materials is one of the most promising types of liquid biofuels. Today in all countries, there are about 580 plants for bioethanol production with a total capacity of about 85 million tons (Table 1).

The data in Table 1 indicates that the industrial bioethanol production in 2018 compared with 2000 increased almost 3.7 times. The decline in production relative to the previous year was observed only in 2007, 2011, and 2012, when production volumes decreased by 3.1, 3.9, and 2.6%, respectively. However, for the study period (2000–2018), the average annual increase in industrial bioethanol production is 7.8%. As a result, the equivalent amount of gasoline replaced is 809.3 billion l of 607.1 million t.

As can be seen from the above results, from 2014 to 2017, the annual growth of bioethanol production increased from 5.0 to 1.8%, and only in 2018, the increase was 5.6%. The highlighted results indicate that an urgent global problem in this direction is the need to seek alternative raw materials and the construction of new bioethanol plants.

For industrial production of bioethanol as raw material (Table 2) can be used sugar-containing (sugar cane, sugar and fodder beet, sugar sorghum, etc.) and starch-containing (corn, rye, triticale, etc.) crops, as well as by-products of beet and sugar production (molasses).

Table 2 Technological characteristics of sugar-containing and starch-containing crops for the industrial production of bioethanol

Crop	*Variation in carbohydrate content, %*	*Range of yield levels, ton/ha*	*The output of bioethanol, l*	
			of 1 ton of raw material	*from 1 ha of area*
Sugar beet	16–18	35.0–50.0	85–120	4,250–6,000
Molasses	45–50	0,5–0.8	300–350	–
Corn	67–76	5.0–1.2	400–470	3,600–5,640
Potato	18–21	20.0–45.0	98–120	4,410–5,400
Sugar sorghum	19–22	60.0–80.0	90–95	7,200–7,600
Artichoke	17–20	30.0–35.0	80–100	2,800–3,500
Chicory	15–19	20.0–25.0	90–100	2,000–2,500
Wheat	58–70	4.0–6.0	350–430	1,720–2,580
Rye	59–65	3.0–4.0	320–380	1,280–1,520
Triticale	60–67	4.0–7.0	340–400	2,380–2,800
Sorghum	68–76	3.0–5.0	360–420	1,800–2,100
Sugar cane	15–20	100.0–150.0	65	5,000–10,000

Source: Systematised by authors based on Palamarchuk et al. (2010)

At an industrial level, the yield of bioethanol per unit area of sugar beet (4,250–6,000 l/ha) exceeds all crops sown in temperate countries. However, corn (3,600–5,640 l/ha) is also considered to be one of the most productive crop plants for bioethanol yield. World agriculture is increasingly paying attention to the cultivation of maize hybrids, which cover 20% of the arable land and provide more than 30% of the gross grain harvest. In today's context, this culture is a leader in both grain yield and gross yield. It is evident that the energy balance of corn in the production of bioethanol from it will depend, first of all, on the level of grain yield per unit area: with increasing returns, the production efficiency of 1 ton of bioethanol will increase.

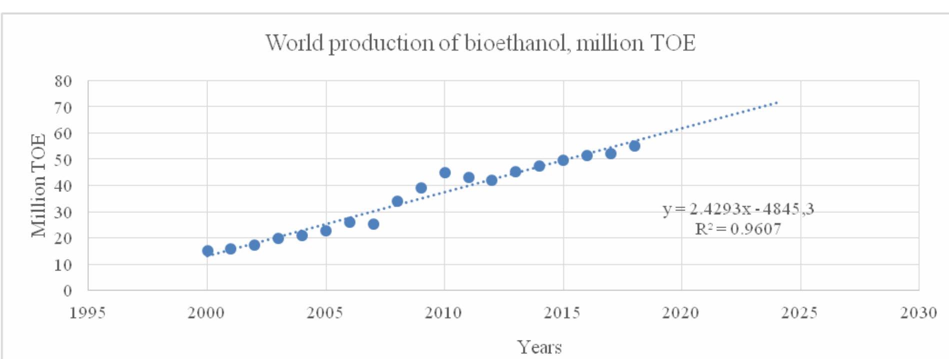
Even in the United States, where corn is very cheap due to its high grain yield levels, sustaining bioethanol production requires government subsidies. For other countries, creating a cost-effective production process is only possible if the cost of the biofuel is substantially reduced. The US Department of Agriculture has found that bioethanol recovers 134% of the energy spent on growing, harvesting, and processing corn, while gasoline recovers only 80% of its energy.

At the present stage, the largest world producers of bioethanol are the USA, Brazil, the EU, China, and Canada, where sugar cane, corn, sugar beet, and grains are used as the primary raw material. Conventional fuel ethanol is a high-octane oxygen-containing additive (octane number is 105 units) with an average density of 790 kg/m^3, produced by fermentation of sugar or carbohydrate-containing raw materials. It can be used in modern internal combustion engines (without changing their design) up to 15% mixed with gasoline, thereby increasing the octane number of the latter, or directly as fuel.

Bioethanol consumption is about ten times less carbon dioxide intensive than the gasoline combustion, due to the simple structural formula and the insignificant size of the molecules, which contributes to more 'clean' biofuel combustion. Also, the decay process reduces the number of transition compounds of chemical origin that may be toxic. Another advantage of bioethanol is that it does not pollute the groundwater in an accidental spill event, quickly decomposing naturally and without harming the environment. Carbon dioxide released over bioethanol combustion has a primary atmospheric origin and constitutes an environmentally safe closed cycle. Accordingly, the higher the level of plant biomass productivity, the more carbon dioxide is absorbed out of the atmosphere.

The use of fuel based on bioethanol, which has covered a significant part of the global energy market, is becoming increasingly relevant every year since experts have predicted an increase in production worldwide in the near future (Figure 2).

Figure 2 Trend line of the current state and prospects of world bioethanol production, million TOE (see online version for colours)



Source: Renewable Fuels Association (2019) and authors' calculations

The increase in industrial production capacity and bioethanol consumption indicates that the global market for this renewable energy production has progressive dynamics and excellent prospects for the future. The analysis of the modern market of technological equipment and technologies proves that there are no significant obstacles to industrial bioethanol production from the technical side. The economic effect of bioethanol use increases due to the right choice of technology for growing and processing bio-raw materials, reasonable location of the necessary equipment in the places of its accumulation, as well as the integrated use of the products obtained during the processing.

In general, the fuel balance of gasoline is much worse than the bioethanol use, since the first requires a significant amount of energy to explore for oil deposits, its production, the construction of transport arteries and facilities (pipelines, tankers), processing, delivery, etc. the bioethanol use could be considered as an innovation potential of ecological modernisation for green growth (Shkarupa et al., 2016).

However, despite the significant prospects for the development of the global bioethanol industry, the main root causes of bankruptcy of companies producing fuel ethanol should be defined as the following: technical problems associated with engineering errors, excess interest rates of bank loans over revenues, miscalculations in management activities, the impact of large capital in a business absorption, etc.

3.3 World biodiesel production

With the consumption and the existing deficit of diesel fuel, it can be quite effectively replaced by biodiesel, which in the vast majority is produced from various types of oilseeds. This trend is due to the widespread use of vegetable oil for energy purposes, as well as the rapid increase in the gross oilseed yield worldwide, which is an essential factor in improving energy security and reducing the anthropogenic impact of energy on the environment.

The increased interest in biodiesel causes its environmental friendliness. Although biodiesel fuel is not entirely environmentally friendly, compared with the oil analogue, it is still cleaner, and when consumed, fewer harmful compounds and emissions are released into the environment. Thus, the use of biodiesel as a motor fuel reduces the emission of almost all harmful substances, namely: hydrocarbon emissions are reduced by 56% compared with the OE, 55% for particulate matter, 43% for carbon oxides, 5–10% for nitrogen oxides, soot – 60% (Kaletnik et al., 2012). Such biofuel, when released into soil or water, undergoes almost complete biological decay (by 99%) in 28 days due to the activity of natural microorganisms. A closed carbon cycle occurs in the production of biodiesels: it contains almost no sulfur; it is a relatively safe fuel because the combustion temperature exceeds 100°C.

Biodiesel is a highly efficient fuel made from vegetable oil, which can be used for internal combustion engines as an additive to conventional diesel fuel or in pure form. Its production for use in its pure form requires considerable additional investment, so in most countries, they introduce mixing of fuel oil with rapeseed oil or use it as an additive in the range of 5–30% to traditional diesel fuel.

Biodiesel fuel is widely used in many countries of the world and also (like bioethanol production) is characterised by positive dynamics in the growth of total world production (Table 3).

Table 3 Dynamics of world biodiesel production

Year	*World production of biodiesel*			*Dynamics of biodiesel production, ± %*	*An equivalent amount of replaced diesel*	
	Bill l	*Mill t*	*Mill TOE*		*Bill l*	*Mill t*
2000	0.8	0.7	0.6	–	0.7	0.6
2001	1.0	0.9	0.8	25.0	0.9	0.8
2002	1.4	1.2	1.1	40.0	1.3	1.1
2003	1.9	1.7	1.5	35.7	1.8	1.5
2004	2.4	2.1	1.9	26.3	2.2	1.9
2005	3.7	3.3	3.0	54.2	3.5	3.0
2006	6.6	5.8	5.2	78.4	6.1	5.2
2007	11.0	9.7	8.7	66.7	10.2	8.7
2008	16.0	14.1	12.7	45.4	14.9	12.7
2009	17.0	15.0	13.5	6.2	15.9	13.5
2010	19.0	16.7	15.0	11.8	17.6	15.0
2011	21.4	18.8	16.9	12.6	19.9	16.9
2012	22.5	19.8	17.8	5.1	20.9	17.8
2013	26.3	23.1	20.8	16.9	24.5	20.8
2014	29.7	26.1	23.5	12.9	27.6	23.5
2015	33.2	29.2	26.3	11.8	30.9	26.3
2016	35.3	31.1	28.0	6.3	32.9	28.0
2017	38.0	33.4	30.1	7.6	35.4	30.1
2018	40.7	35.8	32.2	7.1	37.9	32.2
Average	17.2	15.2	13.7	26.1	16.0	13.7
Total	327.9	288.5	259.6	–	305.1	259.6

Source: *Biodiesel Production by Countries* (2019) and authors' calculations

The data in Table 3 indicates that the industrial biodiesel production in 2018 compared with 2000 increased by almost 54 times. During the study period (2000–2018), the average annual increase in industrial biodiesel production was 26.1%. As a result, the equivalent amount of diesel fuel replaced is 305.1 billion l of 259.6 million t.

As can be seen from the above results, since 2011, the indicator of world biodiesel production is more than 20 billion l. For the period 2000–2018, on average, 17.2 billion liters of biodiesel were produced annually. However, during 2016–2018, there is a certain drop in annual growth rates of biodiesel production in the range of 6.3–7.6%. Illuminated results also indicate that a pressing global problem in this direction is the need to find alternative raw materials and build new biodiesel plants.

In the context of the global energy crisis and the need to increase the consumption of diesel fuel, the structure of the sown areas of oilseeds and their gross collection needs to be revised. A considerable amount of oilseeds can be used to ensure the industrial production of biodiesel from vegetable fats (Table 4).

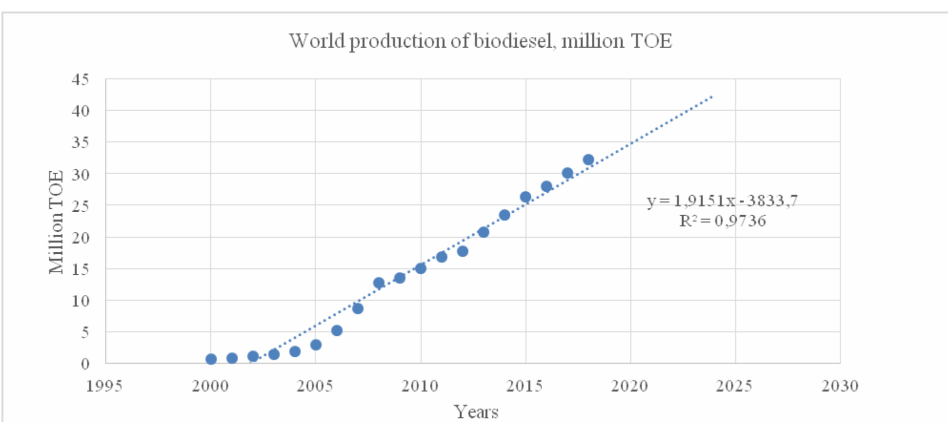
Table 4 Technological characteristics of oilseeds for industrial production of biodiesel

Oilseed culture	*Variation of vegetable fat content, %*	*Range of yield levels, ton/ha*	*The output of vegetable fats, l*	
			of 1 ton of raw material	*of 1 ha of crops*
Sunflower	45–57	2.0–5.0	380–450	375–1900
Winter rapeseed	45–50	1.5–5.5	350–420	630–1890
Spring rapeseed	35–45	1.2–3.6	280–370	440–1300
Soy	16–25	1.2–3.5	140–220	350–770
Mustard	35–47	1.0–2.7	320–400	320–880
Linseed oil	40–48	1.0–1.6	370–440	370–700
Poppyseed oil	46–56	0.8–1.5	400–480	320–720
Redhead	33–46	0.8–1.8	300–380	240–680
Hemp	30–38	0.8–1.5	260–340	250–510
Castor-oil plant	47–58	0.9–1.5	420–500	380–750
Peanut	41–56	1.4–2.6	380–480	530–1200

Source: Systematised by authors based on Palamarchuk et al. (2010)

The above indicators show that the highest yield of vegetable fats per unit area is obtained from the cultivation of sunflower and winter rape, respectively 1900 and 1890 l/ha. However, a sunflower is the main food crop of Eastern European countries, so winter rape is a leading crop for biodiesel production in EU countries. The expansion of acreage under oilseeds to produce food oil, as well as the production of biodiesel, requires the selection of high-yielding oilseeds and their response to intensification factors. It is necessary to expand the crop area under spring rapeseed, soy, mustard, redhead, castor-oil plant, oil linseed, and oil poppy seed to strengthen the raw material base in the production of biodiesel.

Figure 3 Trend line of the current state and prospects of world biodiesel production, million TOE (see online version for colours)



Source: *Biodiesel Production by Countries* (2019) and authors' calculations

The rapid growth processes in the production and consumption of biodiesel indicate that the global market has progressive dynamic and great prospects for the future (Figure 3). The development of the processes of world production and consumption of biodiesel fuel is an innovative priority direction of ensuring the energy security of both the agricultural sector and the state economy as a whole.

With the growth of the production capacity of biodiesel plants, the efficiency indicators of their activity increase, and the cost of manufacturing products decreases. An analysis of the biodiesel production features in developed countries confirms that biodiesel plants with a capacity of up to 5 thousand tons of products per year are not profitable because they cannot compete with large plants with an annual capacity ranging from 20 to 100 thousand tons of biodiesel (Kaletnik et al., 2012).

3.4 Forecast of world primary energy consumption and liquid biofuels production

Calculation of projected indicators of world primary energy consumption and liquid biofuel production for the period 2019–2025 is characterised by different growth rates (Table 5).

Table 5 Forecast of world primary energy consumption and liquid biofuel production

Year	*World consumption of primary energy*		*World bioethanol production*		*World biodiesel production*	
	Mill TOE	*Growth, ± %*	*Mill TOE*	*Growth, ± %*	*Mill TOE*	*Growth, ± %*
2019	14,969	–	59.4	–	32.8	–
2020	15,231	1.8	61.8	4.0	34.7	5.8
2021	15,493	1.7	64.3	4.0	36.6	5.5
2022	15,755	1.7	66.7	3.7	38.6	5.5
2023	16,017	1.7	69.1	3.6	40.5	4.9
2024	16,279	1.6	71.6	3.6	42.4	4.7
2025	16,541	1.6	74.0	3.4	44.3	4.5
Average	15,755	1.7	66.7	3.7	38.6	5.2

Source: Authors' calculations

The results indicate that from 2023, world primary energy consumption will exceed 16,000 million TOE with an average annual growth of 1.7%, and biodiesel production will exceed 40 million TOE with an average annual growth of 5.2%. The global bioethanol production since 2024 can exceed the figure of 70 million TOE, based on the average annual growth of 3.7%.

Despite the long-term perspective of renewable energy, the market is still not investing enough in research and development, so governments should stimulate such innovation processes. Thus, modern regulatory systems promote traditional energy sources, which in the past, have enjoyed strong government support for conducting large-scale research and further introducing the latest developments. To make energy efficiency and renewable energy attractive for the private sector, it is needed to guarantee confidence, reliability, and efficiency in the political decision-making process, as well as to ensure the profitability of financial revenues to renewable energy sources for the long term. Under ideal conditions, political leaders need to impartially compare the potential capabilities of all renewable resources and determine the chances of these technologies on the market to provide them with adequate, but not excessive support.

The problem of industrial production of liquid biofuels derived from plant material today is at the centre of heated discussions regarding their further suitability of use. Often, there are fundamentally opposite opinions about the efficiency and prospects for liquid biofuel production, which requires additional research and generalisations. It should be noted that the world community is still at the stage of making an informed decision on the feasibility of liquid biofuel production. Biofuel has split the world into two opposing sides: the former is in favour of using it, the latter insist on finding other alternative energy sources. However, high food prices generated by biofuel production, which is a problem for humanity as a whole, on the other hand, facilitate enhancing the agricultural sector development, reduce the need for government funding to support the agricultural sector, contribute to the creation of additional jobs. Thus, countries with an agricultural specialisation (including many countries with a high proportion of the poor) have a chance to get corresponding benefits from this situation, leveling the food problem (Vasa et al., 2017; Yatsiv and Kolodiychuk, 2017).

During the transition period, it is necessary to use a system of organisational and economic mechanisms to accelerate biofuel production development in the energy sector. It is needed to minimise losses and the presence of conflict situations and successfully solve the complex problems of regulated entrepreneurship, free competition, justified risk, business integration, and the like. The mechanism of the free market is considered the only regulator of business processes, and the most important state functions should be focused on protecting the existing system and ensuring equal competition conditions for all market players. To increase the production of biofuels the support must be provided based on government incentives and control, and the proper adoption and implementation of regulatory legal acts. It is also needed to introduce the entire set of tools for the use of qualified personnel policy and governance levers of a democratic country focused on the innovative development of the economy. The effect of introducing innovations in biofuel production does not need to be seen as a powerful leap forward, and it should mainly be formed based on small gradual steps, which ultimately would lead to a gradual increase in biofuel production and consumption.

4 Conclusions

A strategy for the sustainable development of the world energy industry cannot be implemented without solving complex environmental problems and ensuring the necessary level of environmental protection from pollution. The negative impact of traditional energy on the environment is manifested not only in the growing volumes of annual emissions of pollutants but also in the withdrawal of large land areas, water resources, disruption of the territorial landscape, influence on climatic factors, as well as storage of large amounts of secondary resources. Economic and energy development should be carried out using the most efficient innovative technologies, providing partial or full replacement of traditional fuel with renewable energy resources. For this, it is necessary to increase the level of efficiency in the use of non-renewable energy resources and, at the same time, carry out the large-scale introduction of renewable energy sources, among which the most dynamic and progressive development characterises the biofuel industry. The relevant issue is the process of economic stimulation of the transition to the use of biological energy types with its ecological and socio-economic foundation.

The global liquid biofuel market tends to expand, providing a significant increase in crop biomass prices, which is the raw material for the production of these renewable energy sources. The process of using vegetable bio-raw materials for energy purposes ensures the rational use of energy resources, reduces the consumption of gasoline and diesel. From an energy side, biodiesel use makes the transition to sustainable energy development. From an environmental point, biodiesel use leads to a decrease in environmental pollution. From a social side, the biodiesel use allows to create new processing enterprises increasing the employment level. Large-scale production of liquid biofuels is possible only if they are competitive compared to their counterparts. It is also necessary to carry out the priority realisation of innovative projects aimed at reducing the energy intensity and resource costs of production.

In the context of the formation of global energy security and the rational use of available bio-resources, bioethanol is an important and practically the only effective oil substitute on a global scale. It worth noting that following the results obtained (Tables 1 and 3) for the period 2000–2018, on average, it has been produced 35.1 million TOE of bioethanol, 13.7 mill TOE of biodiesel, which is respectively 71.9% and 28.1% in favour of bioethanol. According to the predicted average values (Table 5), in the structure of total world consumption, bioethanol will account for 0.4% and biodiesel fuel – 0.2%, which indicates the need to increase the rate of liquid biofuel production for its share to grow in global energy consumption. This process should be carried out based on expanding the resource base: in the bioethanol production – the use of lignocelluloses raw materials (second-generation biofuels) and in the biodiesel production – the use of microalgae (third-generation biofuels).

The liquid biofuel development requires government regulation, because excessive enthusiasm for this process may result in the structural changes of sown areas in favour of bioenergy crops and, as a result, an imbalance in prices for various types of crop products. Significant expansion of acreage for growing bioenergy crops can hurt the global food market, lead to higher prices for the latter and destabilise the socio-political situation in countries with unstable and unfavourable political regimes. Also, the industrial production of liquid biofuels requires the use of high human and material costs. At the same time, the steady increase in population on the planet and the corresponding increase in global consumption of energy resources, primary oil, requires a sober assessment of the role and place of liquid biofuels in the global energy market. The real liquid biofuel production significantly lags behind the total oil demand of the countries worldwide, which is important argument in the overall context of diversification of energy sources. Considering the prospects for the development of liquid biofuel production and consumption, it is necessary to understand which factors are the driving force of such development and which can slow down or make the production impossible. Among such positive factors, the main attempt is to find a reasonable alternative to fuel oil sources, given the positive environmental aftereffect.

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