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Innovative Technology for Managing Biofuel Production from Timber Industry Waste

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Abstract

The relevance of this study is determined by the growing worldwide interest in renewable energy sources against the backdrop of depleting fossil fuel reserves. This study aims to develop an innovative technology for managing biofuel production from wood waste, including a set of interrelated economic and mathematical models focused on maximizing the fuel and energy efficiency of biofuels depending on the location of waste generation, feedstock moisture content, and distance to the biofuel production site. This technology should also combine the main directions of international research in the field of environmental responsibility of countries in terms of carbon dioxide (CO_2) emissions and the Paris Climate Agreement. The methodological basis of the research comprises the authors' innovative technology based on a set of interconnected economic and mathematical models and managerial decision-making systems, methods for nonlinear programming, system analysis, an information approach to the analysis of systems, accepted technological processes, norms, and standards established in the international practice of the timber industry. This innovative technology was implemented in practice using the capabilities of the MathCad and MS Excel software products. The article determines the optimal operating parameters of timber industry enterprises at which the specific thermal energy of the produced biofuel exceeds by at least 15% the thermal energy spent on processing this biofuel as an energy carrier. Wood waste biofuel production is profitable if the distance for feedstock transportation to the production site does not exceed 80 km and the relative humidity of the raw materials does not exceed 60%.

Keywords:

Paris Agreement;
CO_2 Emissions; Ecology;
Economic and Mathematical Model;
Fuel and Energy Efficiency;
Profitability;
Nonlinear Programming;
Fossil Fuel; Biofuel.

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1- Introduction

The issues of developing renewable energy sources, including promising technologies for managing the production of biofuel from timber processing complex (TPC) waste, have attracted the attention of many Russian and foreign scholars and experts in the field of energy generation [1–3]. Significantly increased emissions of carbon dioxide (CO_2) from coal-fired thermal power plants cause irreparable damage to the environment [4, 5]; therefore, the need for models and tools for managing energy production with a low greenhouse effect is increasing. Such studies are especially relevant for countries with an undeveloped alternative energy industry [6]. As shown in numerous studies [6–8], focusing solely on reducing carbon dioxide emissions is not a sufficient incentive for the development of a low-carbon, environmentally friendly economy and increased investment in such industries. More ambitious and cost-effective investment projects are needed, aimed at increasing the energy efficiency of the economy, introducing new technologies [9], and stimulating the growth of its macroeconomic indicators [10]. Therefore, it is important to study the relationship between "green" investments and energy efficiency [11].

Biofuels produced from renewable sources have lower greenhouse gas emissions than traditional energy sources, helping to reduce climate impact and provide a cleaner source of energy. According to international practice, the highest demand for high-quality wood biofuels [12] is observed in the countries of the European Union, as it ensures the compliance of their economies with the requirements of the Paris Climate Agreement of December 12, 2015 [13]

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regarding carbon dioxide emissions. Biofuel production contributes to the development of local and regional economies and agriculture, creating new jobs and contributing to sustainable regional development. The use of social financial technologies, which are widely and in detail covered, for example, in Kostyrin & Sokolov (2023) [14], enables working citizens, owners, and the state to harmoniously unite their interests in TPC waste biofuel production. These united efforts make it possible to ensure an increase in wages for citizens working at forestry enterprises and increase their contributions to the development fund of such enterprises. The owners of enterprises and the entire workforce are primarily interested in this innovation because it ensures an increase in their income, the possibility of constant modernization and updating of technological equipment, and the release of new competitive products. The amount of funds flowing into budgets of all levels also increases, which makes it possible for the state to solve a number of important social tasks. The innovative technologies for managing TPC waste biofuel production considered in this study represent a promising and highly sought-after set of measures for organizing virtually waste-free production, which significantly reduces the economic costs of the enterprise in the form of recycling fees or fines in the event of spontaneous illegal waste dumps from the forestry enterprises' activities, fire hazards for forests, and bacterial contamination.

Some researchers have noted that the greatest impact on the properties of wood fuel pellets is exerted by the feedstock moisture content [15-17] and the distance to the production site. This, in turn, affects the quality of the final product [18], and hence, its consumer value and price. Therefore, in this study, the following most important factors were selected as influencing the economic efficiency (profitability) of TPC waste biofuel production: distance from the waste generation site, feedstock moisture content, and distance to the biofuel production site.

Currently, enterprises of the TPC of the Russian Federation produce 68–74 million m^3 of wood waste and secondary raw materials, while using and processing no more than 48%–58%. In other words, approximately 30–36 million m^3 of wood waste is disposed of for good. At the same time, as the experience of other countries shows [19-21], it is advisable to use wood waste for energy purposes, which determines the relevance of this study.

In countries that lack fossil fuels, the percentage of biofuel production and consumption is steadily growing [22]. For example, in Indonesia, it makes 18%, and this is although the lion's share of raw materials must be imported. In the Russian Federation, domestic consumption of biofuel is 1.1% of the production of the fuel and energy complex (16.36 times less than that of Indonesia!), which is only 0.1% of the country's gross domestic product [23].

The final fuel and energy product generated from forestry waste in the form of briquettes of various shapes and sizes has different names: wood fuel pellets, in international practice – torrefied fuel pellets [24], pellets, briquettes [25].

Primary production waste is the raw material for biofuel production. At the stage of biofuel production from the main production waste, additional added value is created. We will show its creation as exemplified by woodworking production:

1. In the primary (main) production of lumber, an additional value is formed, as for any product obtained during the production process.
2. After lumber production, waste remains from which biofuels are made. In the process of creating a new product (fuel wood pellets, briquettes), another added value is formed.
3. As a result, two added values are obtained for the same source material in primary (main) production and production from primary production waste (secondary production).
4. According to Federal Law No. 268-FZ of July 14, 2022 "On Amendments to the Federal Law "On Waste Production and Consumption" [26] and the international practice of re-involving waste back into the production process (recycling), forestry enterprises are obliged to dispose of waste from production activities. Waste disposal increases the cost of finished products in terms of variable costs, thereby reducing the profit of the enterprise. Fines for unauthorized dumping of wood waste in forest areas are quite high, which also negatively affects the company's activities and goodwill [27]. The unique innovative technology for wood waste biofuel production developed in this study makes it possible to recycle the waste and obtain a new product. This enables the enterprise to receive a double economic effect, regardless of the specific primary production.

This study develops an innovative technology for managing the production of biofuel from forestry waste, including a set of interconnected economic and mathematical models. The practical implementation of this technology makes it possible to maximize the fuel and energy efficiency of biofuel depending on the location of waste generation, the moisture content of the feedstock, and the distance to the point of biofuel production. It also helps manage biofuel production on the basis of an assessment of the fuel-energy and economic efficiency of the final product for various options and stages of production. The purpose of this scientific article corresponds to international research in the field of countries' environmental responsibility in terms of carbon dioxide (CO_2) emissions, based on the Paris Climate Agreement dated December 12, 2015 [13], signed by 192 countries and ratified by more than 110 countries. Thus, this research is focused on achieving the following goals and objectives stated in the Paris Agreement: reducing the impact on the climate system; strengthening the global response to the threat of climate change in the context of sustainable development of countries and regions; ensuring an overall reduction in global greenhouse gas and CO_2 emissions and others.

The object of this research is the rational use of waste from timber processing industries as a way to increase the fuel-energy and economic efficiency of forestry enterprises.

The subject of this research covers socio-economic processes, models, and tools for managing wood waste biofuel production by forestry enterprises in all organizational and legal forms.

Research Hypothesis: The development and practical implementation of innovative technology for TPC waste biofuel production makes it possible to maximize the energy efficiency coefficient (EEC) of biofuels and determine the optimal combination of factors influencing it: the density and relative humidity of wood waste, the distance of waste transportation to the site of waste processing and biofuel production, and the waste accumulation location.

2- Literature Review

Ilyina et al. (2020) [28] explored the issues of energy security of the national economy, but simultaneously paid insufficient attention to the heat and fuel-energy efficiency of alternative energy sources [29], the development and practical implementation of economic and mathematical models, and innovative technologies for managing the production of biofuel from various sources, including TPC waste. Dong et al. (2023) [30] and Kolodiy & Sytenok (2021) [31] made bold attempts to forecast the demand for fossil fuels with regard to the increased requirements for energy security of individual countries and national economies. At the same time, models for managing biomass energy production are currently attracting the increasing attention of scholars from different countries as a renewable alternative to fossil fuels, as can be seen in Wahab et al. [32], while research is being conducted not only in the forestry industry but also in other sectors of the national economy [33, 34]. Although Ferrari (2023) [35], Ma et al. (2023) [36], and Penev & Andreev (2020) [37] present prospects for the development of the bioeconomy as part of the implementation of strategic cluster initiatives in the forestry industry, they do not pay due attention to models and breakthrough technologies for the sustainable development of regions introducing innovative technologies for TPC waste biofuel production. In Chotikhun et al. [2], Joshi & Chalise (2022) [38], and Mikheevskaya et al. [39], the properties of wood and the peculiarities of its use in biofuel production are studied in detail.

Biofuels are considered from the standpoint of the simplest and most accessible type of fuel and in the context of their conversion into gaseous, solid, and liquid fuels [4]. The technology for wood pellet production [24] is constantly being improved [9], but the problems of assessing the fuel and energy efficiency of TPC waste biofuel production [40] remain key issues.

An attempt to resolve these issues was made by Marchenko & Solomin (2021) [41]. This research is closest to the current study, but at the same time, the authors failed to develop a comprehensive biofuel production management system based on an interrelated set of economic and mathematical models enabling the assessment of the fuel and energy efficiency of reusing TPC waste in the production of fuel pellets. The efficiency of the production of wood-based fuel pellets was assessed by Furtula et al. (2022) [42] and Höglund (2008) [12]; however, unlike our study, where the main emphasis is on assessing the energy utility of the products, Serbian and Swedish colleagues based their studies on environmental certification tools for wood pellets.

The calorific capacity of solid biofuels is considered when assessing energy efficiency by a number of researchers [43-46], which is an integral part of our study for determining energy costs at different stages of the production process. Russian scientists pay attention to the issues of biofuel calorific capacity when compiling a comparative analysis of the different types of wood [46]. Based on the above-mentioned studies of Russian and foreign scholars, for the purposes of this study, we have established that the moisture content of the feedstock exerts the greatest influence on the properties of wood fuel pellets [13, 15], and the distance to the place of production also affects the quality of the final product [18], and therefore its use value and price.

Sokolov & Kostyrin (2019) [14], the authors consider social financial technologies as a tool for increasing wages of working citizens and making contributions to the enterprise development fund, including the fuel and energy complex. They fill budgets at all levels, which can undoubtedly be useful and interesting in the development of innovative technologies for managing TPC waste biofuel production. However, within the framework of this study, the authors limited themselves to the analysis and assessment of the quantitative parameters of factors that affect the profitability of forestry enterprises, leaving beyond the scope of this study the influence of the economic efficiency of the activities of such enterprises on the growth of the working citizens' well-being, the development of the country's enterprises, and the economy as a whole. In addition, a distinctive feature of this study is the presentation of an innovative technology for managing biofuel production in the form of interconnected economic and mathematical models, in which the objective function and model limitations depend on the waste generation site, the feedstock moisture content, and the distance to the biofuel production site, allowing the person making managerial decisions to evaluate the fuel and energy efficiency of the final product based on the energy utility coefficient (EUC).

A comparative analysis of the scientific results obtained by the authors and those of other scientists and specialists dealing with certain aspects of the problems raised in the article is presented in Table 1.

Table 1. Comparison with other studies and scientific increase in knowledge

No.	Research directions	Scientific results	Scientific novelty
1	Energy consumption productivity	An economic and mathematical model for managing energy costs in biofuel production was developed, the objective function of which is to maximize the energy utility coefficient (EUC)	Unlike the models used in practice for managing wood waste biofuel production [30, 47, 48], the developed economic and mathematical model is based on the EUC as an indicator of the fuel and energy efficiency of biofuel production, which depends on the location of waste generation, the humidity of the initial raw materials, and the distance to the biofuel production site.
2	Production management	The fuel and energy efficiency of timber industry waste biofuel production was analyzed and assessed (Tables 4 and 5), ensuring its minimum economic profitability, which allows us to estimate the ratio of the amount of thermal energy per fuel unit volume to the amount of thermal energy consumed for processing this fuel as an energy carrier at various stages of biofuel production.	Unlike the well-known models for assessing and analyzing biofuel production management [10, 12, 25], this approach makes it possible to simultaneously consider the energy efficiency of the produced fuel pellets with the identification of three options for waste accumulation according to the technological flowcharts of primary production (see Figures 1 to 3) with the use of machinery and equipment involved in this process, on the basis of the norms and regulations established in the timber industry, and within the acceptable profitability threshold for the industry.
3	Environmental effect and energy security	Waste-free production was integrated into the forestry industry management, which ensures its sustainable development and promotes the conservation of natural resources and the rational use of renewable energy sources instead of fossil fuels, thereby reducing the load on the ecosystem and carbon dioxide emissions. The economic feasibility of investments in the development of a low-carbon, environmentally friendly economy was assessed, which makes it possible for resource-poor countries to ensure their energy security	This study aims to fill the gaps in previous studies focusing on the properties of raw materials for biofuel production [42, 49-51] and factors affecting the final product. In addition, a distinctive feature of the author's approach is that it is targeted to minimize energy costs and optimize the use of resources according to the criterion of the excess of the thermal energy amount per fuel unit volume over the amount of thermal energy consumed for processing this fuel as an energy carrier at various stages of its production.
4	Non-linear programming	A new formulation and approach to solving a nonlinear programming problem was proposed to determine the optimal combination of parameters that maximize EUC	Unlike the publications of well-known scholars devoted to solving nonlinear programming problems [4, 30, 51], in the author's approach, the innovative technology is a set of interconnected economic and mathematical models, each having its own objective function and system of limitations, which enables the user to apply the model required to solve the problem depending on the forest waste generation site, and then integrate the results obtained into the overall integrated managerial decision-making system.
5	Business process management	An economic-mathematical model for managing timber industry waste biofuel production was developed, characterized by a systematic combination of methods of nonlinear programming, economic-mathematical modeling, and process management. This model makes it possible to create tools for managing waste-free production, minimize the costs of biofuel production, and develop standard designs for managerial decision support systems with the prospect of their integration into existing forestry complex enterprises and future information and analytical systems.	The developed economic and mathematical model of process management makes it possible to find the optimal scientifically substantiated managerial solution for breaking down the complex task of determining energy consumption depending on the raw material production site and their quality at the stages of the production cycle. This solution applies well-known nonlinear programming methods, and then the results obtained are integrated into a complex system for making managerial decisions at the stage of practical implementation through the use of additional criteria: waste moisture, its density, and distance from the waste generation sites and final product manufacturing sites, which benefit from previously developed models for managing business processes in biofuel production [13, 21, 24].

Thus, the literature review presented in Table 1 showed the lack of studies aimed at maximizing the EEC as an indicator of the fuel and energy efficiency of biofuel production depending on the location of waste generation, the moisture content of the feedstock, and the distance to the site of biofuel production, with regard to existing and promising technologies for managing their production from TPC waste, process management of financial flows in the activities of TPC enterprises, awareness of the need to develop a mechanism adequate to the current state of the industry, and the prospects for its development to stimulate the transition of thermal power plants from fossil fuels to renewable energy sources in hard-to-reach regions of the world and the Russian Federation, in particular.

Studies by Russian and foreign specialists in the field of energy efficiency and safety, mathematicians, and economists do not present economic and mathematical models of process management for TPC waste biofuel production and the development of enterprises engaged in deep processing of waste and ensuring energy sovereignty. They also do not consider progressive technologies of labor incentives for citizens working at TPC enterprises and provide no complete and consistent description of the technological processes of biofuel production from logging waste accumulated at timber-handling sites and wood processing waste using the principles of structural system analysis and design.

Currently, there is no universal approach to the development of scientifically sound economic and mathematical models and mechanisms for assessing the efficiency of TPC waste biofuel production. The problems of economic and mathematical description of the operation of such a complex have not been completely resolved. Deep processing of TPC waste into products with high fuel and energy efficiency also needs to be improved about the increasing requirements for energy security and energy sovereignty of the Russian Federation and the whole world, which requires the development of scientifically based tools that are adequate to the current state of the industry.

3- Material and Methods

We consider the EEC as an indicator of fuel and energy efficiency, which we define as the ratio of the amount of thermal energy per unit volume of fuel (Q_g) to the amount of thermal energy consumed to process this fuel as an energy carrier at various stages of biofuel production (Q_n):

$$EEC = \frac{Q_g}{Q_n}, \tag{1}$$

where Q_n is the sum of operations of the production process for the collection of waste, its delivery to the sites of processing and production of briquetted fuel with a functional dependence on the parameters characterizing this technological process. In each function, the set of parameters may differ in number and their impact on a specific operation of the production process.

The value of Q_g is determined by the calorific value of the substance. The calorific value is the amount of heat released during the combustion of 1 kg of fuel. Higher and lower calorific values are distinguished in thermal engineering calculations. The higher calorific value is characterized by the amount of heat released during the combustion of 1 kg of fuel with the complete condensation of all water vapors formed during combustion, with the release of heat consumed to evaporate moisture (latent heat of evaporation). Q_g, the higher calorific value of fuel from different wood species, is almost the same and amounts to 4,600 kcal/kg (19,900 kJ/kg). The calorific value of 1 kg of standard fuel is 7.000 kcal (29,300 kJ). Accordingly, the indicator Q_g hereinafter is considered to be a constant value equal to 4,600 kcal/kg: 7.000 kcal/kg = 0.657 kg of standard fuel (kgoe).

Based on several studies [13, 28, 52], considering the experience of specialists in managing wood biofuel production in the logging [23] and woodworking industries [53], studies on assessing the energy intensity of pressing wood raw materials in biofuel production [39], and determining the feedstock moisture content [46, 54], logistics [55], assessment of regional experience [3, 56], process flowcharts were developed for TPC waste biofuel production, as shown in Figures 1 to 3.

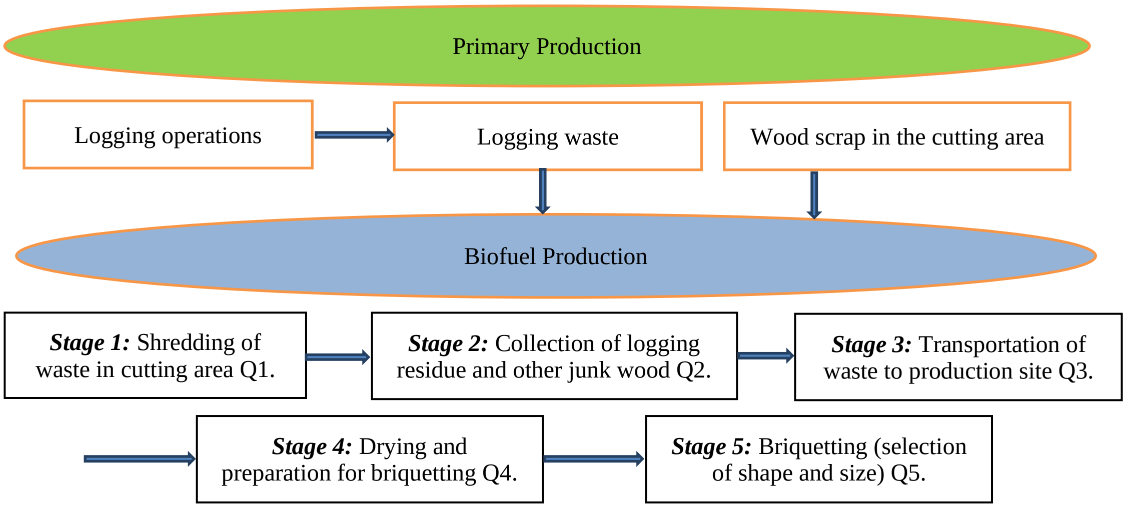

Figure 1. Process flowchart for logging waste biofuel production (D1)

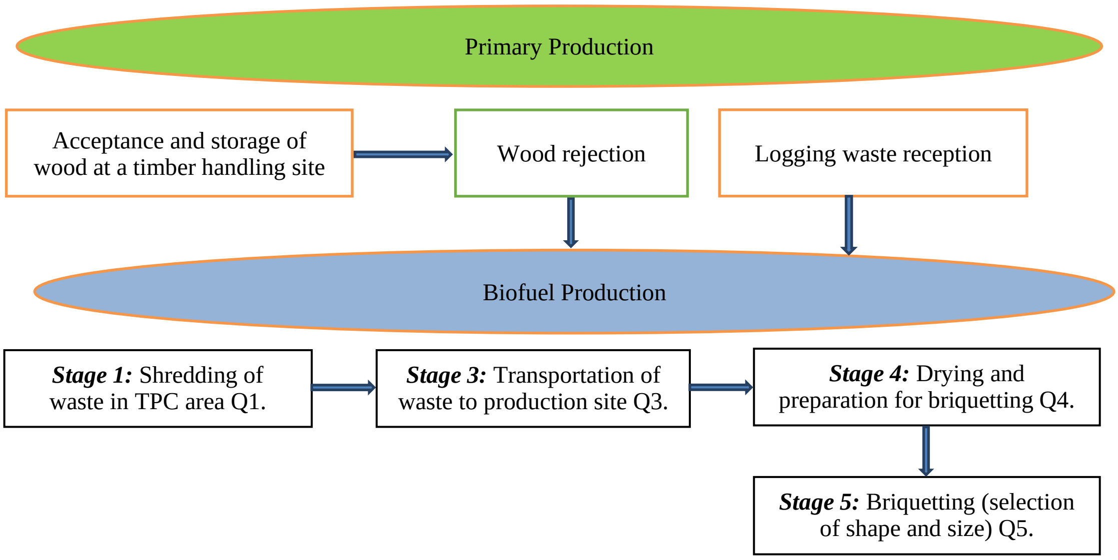

Figure 2. Process flowchart for biofuel production from waste accumulated at the timber-handling sites (D2)

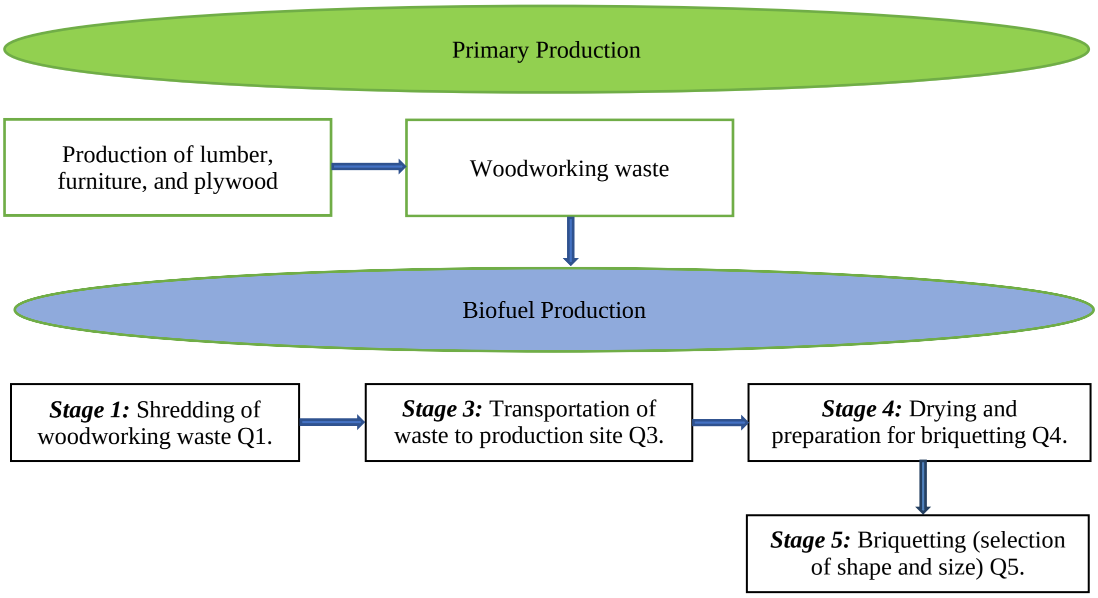

Figure 3. Process flowchart for woodworking waste biofuel production (D3)

Let us consider the production management process from the standpoint of energy and economic efficiency and highlight the following options for waste accumulation to develop an organizational and economic mechanism for managing TPC waste biofuel production (see Figures 1 to 3):

1) The first option for waste accumulation is in the logging area (D1).

2) The second option for waste accumulation is at timber-handling sites (D2).

3) The third option for waste accumulation is in wood processing enterprises (D3).

Energy consumption is determined on the basis of the adopted process flowchart, machines and equipment involved in this process using the rules and regulations established in the TPC. The general scheme for producing briquetted fuel from TPC waste is presented in Figure 4.

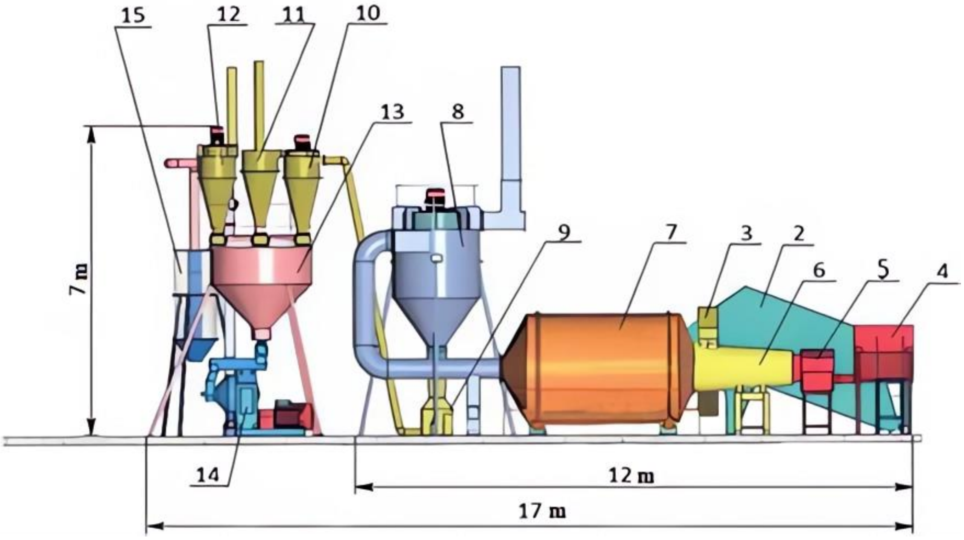

Figure 4. Wood waste pelletizing line OGM-1.5 (sawdust, peat) [23, 57]: 1. Elevating feed channel; 2. Biomass feeder; 3. Drag conveyer; 4. Fuel storage hopper; 5. Combustion chamber; 6. Heat generator; 7. Rotary dryer; 8. Centrifugal outlet for dried biomass; 9. Hammer crusher; 10. Centrifugal outlet for crushed biomass; 11. Passive centrifugal collector; 12. Drum cooler centrifuge; 13. Pelletizer storage hopper; 14. OGM-1.5 pelletizer; 15. Drum cooler.

Fuel wood pellets or briquettes of various sizes and shapes can be manufactured on the same production lines by replacing the pelletizer (item 14) with a press pelletizer or another briquetting mechanism.

In general, the determination of the EEC, concerning the concentration, production, and use of wood waste as an energy carrier, includes four to five stages depending on the location of waste accumulation: at logging operation sites (D1), at timber-handling sites (D2), and at wood processing enterprises (D3), as shown in Table 2.

Table 2. Stages of the production cycle depending on the waste accumulation option

Waste accumulation option	Symbols for the waste accumulation option	Stages of biofuel production	Symbols for the biofuel production stages	Equations for calculating the amount of thermal energy consumed to process biofuel as an energy carrier	Designations of variables included in the Equations for calculating the amount of thermal energy	Restrictions on the range of changes in the variables included in the Equations	Note
1	**2**	**3**		**4**	**5**	**6**	**7**
Obtaining raw materials by collecting waste from logging operations (Figure 1)	D1	Shredding of the primary waste	Q1	$Q_1(Y,G_1,P_1)=\frac{G_1\cdot g_1\cdot k_m\cdot k_t\cdot k_p}{P_1\cdot g_2\cdot g\cdot 1\,000\cdot(1-Y)}$ (2)	G_1 – fuel consumption of the logging residue chopper, l/hour; g_1 – specific weight of the liquid fuel kg/l; k_m – motor power utilization factor; k_t – motor utilization factor over time; k_p – average equivalent of fuel conversion into conventional fuel; P_1 – hourly productivity of the grinder, st.m^3/hour; g_2 – density of crushed waste, ds.m^3/st.m^{3*}; g – average density of wood, kg/ds.m^3; Y – average moisture content of waste before drying, fractions of a unit	$0.05 \leq Y \leq 0.95$	
		Wood waste collection	Q2	$Q_2(Y,G_2,P_2)=\frac{G_2\cdot g_1\cdot k_m\cdot k_t\cdot k_p}{P_2\cdot g_2\cdot g\cdot 1\,000\cdot(1-Y)}$ (3)	G_2 – manipulator fuel consumption, l/hour; P_2 – hourly productivity of the manipulator, st.m^3/hour	$0.05 \leq Y \leq 0{,}95$	
		Transportation of waste to the production site	Q3	$Q_3(Y,R,G_3,P_3)=\frac{2\cdot G_3\cdot g_1\cdot k_p\cdot R}{P_3\cdot g_2\cdot g\cdot 1\,000\cdot(1-Y)}$ (4)	2 – a coefficient considering the mileage of a woodchip truck in the cargo and idle directions; G_3 – linear rate of liquid fuel consumption for removal (transportation) of logging residues, l/km; P_3 – load capacity of the woodchip truck, st.m^3; R – distance of wood waste removal and transportation, km	$0.05 \leq Y \leq 0.95$ $0 \leq R \leq 100$ km	
		Primary waste drying	Q4	$Q_4(Y)=\frac{Y\cdot\gamma\cdot 1\,000}{1-Y}\cdot\frac{1}{\varphi}$ (5)	γ – heat consumption for evaporation of 1 kg of moisture, MJ/kg; φ – calorific value of 1 kg of standard fuel	$0.05 \leq Y \leq 0.95$	Lines 1-7 Figure 4
		Primary waste briquetting to the final product	Q5	$Q_5(M_5,P_5)=\frac{M_5\cdot k_m\cdot k_t\cdot k_p}{P_5}$ (6)	M_5 – installed motor capacity, kW; k_p – average equivalent of electricity conversion into standard fuel; P_5 – hourly productivity of the pressing area, kg/h		Lines 9-15 Figure 4
Obtaining raw materials at the timber-handling site (Figure 2)	D2	Primary waste shredding	Q1	Q_1 at site D2 is calculated similarly to Q_1 at site D1 (Equation 2)	Designations for Q_1 at site D2 are similar to designations for Q_1 at site D1	$0.05 \leq Y \leq 0.95$	
		Transportation of waste to the production site	Q3	Q_3 at site D2 is calculated similarly as Q_3 at sites D1 and D3 (Equation 4)	Designations for Q_3 at site D2 are similar to designations for Q_3 at sites D1 and D3	$0.05 \leq Y \leq 0.95$ $0 \leq R \leq 100$ km	
		Primary waste drying	Q4	Q_4 at site D2 is calculated similarly Q_4 at sites D1 and D3 (Equation 5)	Designations for Q_4 at site D2 are similar to designations for Q_4 at sites D1 and D3	$0.05 \leq Y \leq 0.95$	Lines 1-7 Figure 4
		Primary waste briquetting to the final product	Q5	Q_5 at site D2 is calculated similarly as Q_5 at sites D1 and D3 (Equation 6)	Designations for Q_5 at site D2 are similar to designations for Q_5 at sites D1 and D3		Lines 9-15 Figure 4
Obtaining raw materials from woodworking waste (Figure 3)	D3	Primary waste shredding	Q1	$Q_1(M_1,P_1,Y)=\frac{M_1\cdot k_m\cdot k_t\cdot k_p}{P_1\cdot g_2\cdot g\cdot 1\,000\cdot(1-Y)}$ (7)	M_1 – installed motor capacity	$0.05 \leq Y \leq 0.95$	
		Transportation of waste to the production site	Q3	Q_3 at site D3 is calculated similarly as Q_3 at sites D1 and D2 (Equation 4)	Designations for Q_3 at site D3 are similar to designations for Q_3 at sites D1 and D2	$0.05 \leq Y \leq 0.95$ $0 \leq R \leq 100$ km	
		Primary waste drying	Q4	Q_4 at site D3 is calculated similarly as Q_4 at sites D1 and D2 (Equation 5)	Designations for Q_4 at site D3 are similar to designations for Q_4 at sites D1 and D2	$0.05 \leq Y \leq 0.95$	Lines 1-7 Figure 4
		Primary waste briquetting to the final product	Q5	Q_5 at site D3 is calculated similarly as Q_5 at sites D1 and D2 (Equation 6)	Designations for Q_5 at site D3 are similar to designations for Q_5 at sites D1 and D2		Lines 9-15 Figure 4

[*] *Note:* A distinction is made between dense cubic meters (ds.m^3) and stacked cubic meters (st.m^3). A dense cubic meter is a cube with sides of 1 m. The entire space of such a cube is entirely occupied by wood without gaps or voids. A stacked cubic meter has the same dimensions, but the entire space of such a cube is occupied not only by wood but also by the voids between individual logs [58].

Thus, according to the criterion for making a managerial decision and Equations 1 to 7, which are presented in Table 2, we have economic and mathematical models shown in Table 3 and maximizing EEC depending on the location of waste generation, the feedstock moisture content, and the distance to the biofuel production site, which makes it possible to manage biofuel production based on an assessment of the fuel-energy and economic efficiency of the final product for various options and stages of the TPC waste biofuel production [37].

Table 3. Innovative technology for managing TPC waste biofuel production

Waste accumulation option		Economic and mathematical model for managing TPC waste biofuel production
Description	**Symbol**	
1	**2**	**3**
Obtaining raw materials by collecting logging waste	D1	$EEC(R,Y) = Q_g \cdot \left(\frac{G_1 \cdot g_1 \cdot k_m \cdot k_t \cdot k_p}{P_1 \cdot g_2 \cdot g \cdot 1\,000 \cdot (1-Y)} + \frac{G_2 \cdot g_1 \cdot k_m \cdot k_t \cdot k_p}{P_2 \cdot g_2 \cdot g \cdot 1\,000 \cdot (1-Y)} + \frac{2 \cdot G_3 \cdot g_1 \cdot k_p \cdot R}{P_3 \cdot g_2 \cdot g \cdot 1\,000 \cdot (1-Y)} + \frac{Y \cdot \gamma \cdot 1\,000}{1-Y} \cdot \frac{1}{\varphi} + \frac{M_5 \cdot k_m \cdot k_t \cdot k_p}{P_5}\right)^{-1} \rightarrow max \quad (8)$
Obtaining raw materials at a timber handling site	D2	$EEC(R,Y) = Q_g \cdot \left(\frac{G_1 \cdot g_1 \cdot k_m \cdot k_t \cdot k_p}{P_1 \cdot g_2 \cdot g \cdot 1\,000 \cdot (1-Y)} + \frac{2 \cdot G_3 \cdot g_1 \cdot k_p \cdot R}{P_3 \cdot g_2 \cdot g \cdot 1\,000 \cdot (1-Y)} + \frac{Y \cdot \gamma \cdot 1\,000}{1-Y} \cdot \frac{1}{\varphi} + \frac{M_5 \cdot k_m \cdot k_t \cdot k_p}{P_5}\right)^{-1} \rightarrow max \quad (9)$
Obtaining raw materials from woodworking waste	D3	$EEC(R,Y) = Q_g \cdot \left(\frac{M_1 \cdot k_m \cdot k_t \cdot k_p}{P_1 \cdot g_2 \cdot g \cdot 1\,000 \cdot (1-Y)} + \frac{2 \cdot G_3 \cdot g_1 \cdot k_p \cdot R}{P_3 \cdot g_2 \cdot g \cdot 1\,000 \cdot (1-Y)} + \frac{Y \cdot \gamma \cdot 1\,000}{1-Y} \cdot \frac{1}{\varphi} + \frac{M_5 \cdot k_m \cdot k_t \cdot k_p}{P_5}\right)^{-1} \rightarrow max \quad (10)$

The criterion for making a managerial decision lies in the need to exceed the amount of thermal energy per unit volume of fuel (Q_g) over the amount of thermal energy consumed for processing this fuel as an energy carrier at various stages of its production (Q_n) with a reserve, which, according to management theory [14], should be not less than 10%–15%. Therefore, according to Equation 1, the minimum EEC value accepted in economic and mathematical models (8)–(10) is 1.15. In other words, if EEC ≥ 1.15, wood biofuel production will be profitable; if EEC < 1.15, production will be unprofitable, i.e., it is necessary to search for another managerial solution on the issue of waste disposal generated as a result of the main production activities of a logging or woodworking enterprise.

Considering the above, the block diagram of the research algorithm is presented in Figure 5.

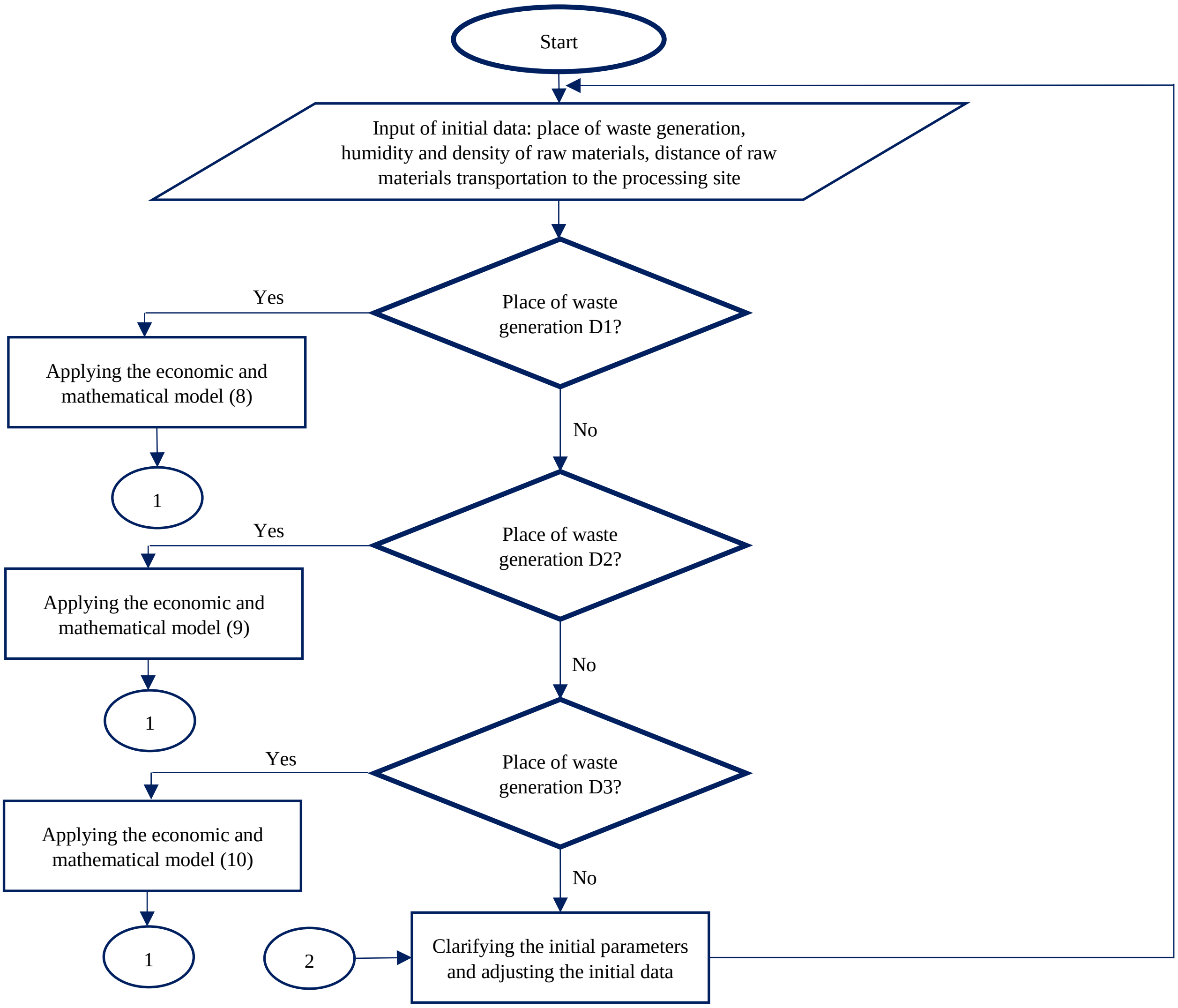

Figure 5. Research algorithm flowchart (continued)

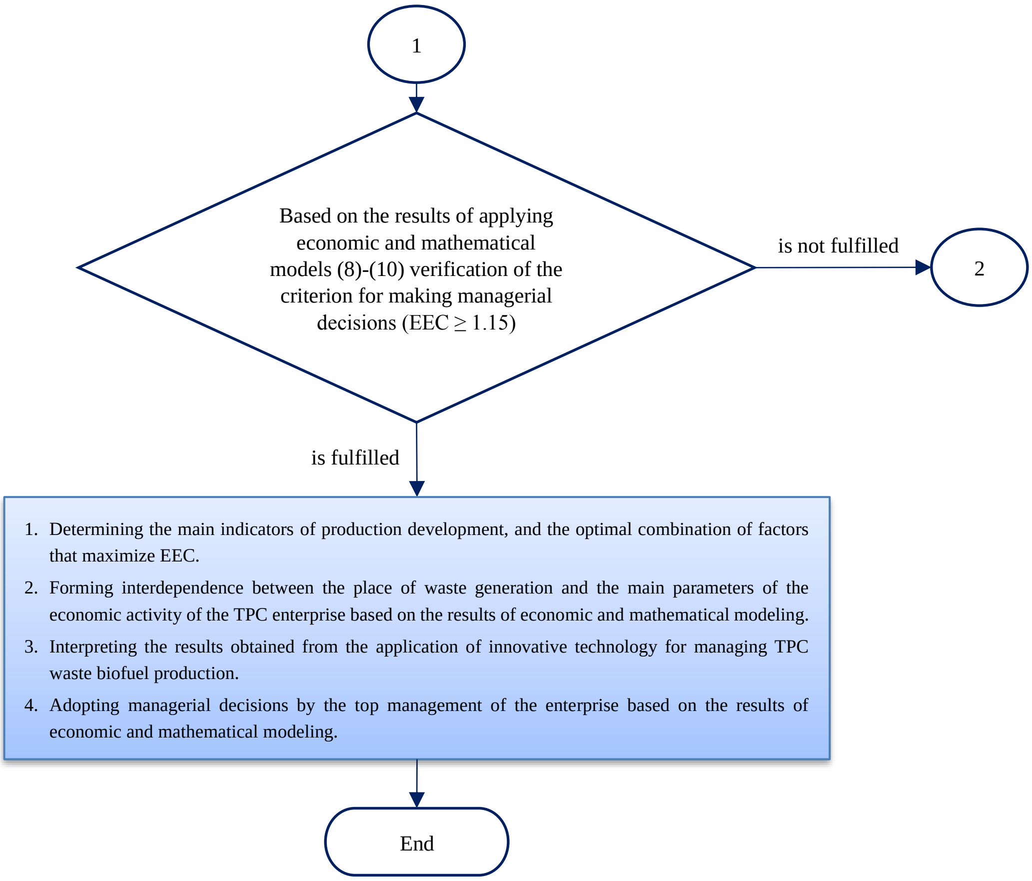

Figure 5. The research algorithm flowchart

Figure 5 presents a flowchart of an integrated process system for managing the energy efficiency of TPC waste biofuel production, which details the main aspects and criteria for making key managerial decisions related to the optimal combination of factors that have a direct impact on fuel and energy efficiency indicators and ultimately determine the profitability of TPC enterprises in the production and sale of wood waste biofuels.

3-1- Innovative Technology Algorithm for Managing TPC Waste Biofuel Production

Step 1. Determining the place of waste generation: At this stage, the location of waste accumulation is determined: at logging sites (D1), at timber-handling sites (D2), or in wood processing enterprises (D3), and its impact on the energy costs of production and use of wood waste as an energy carrier is assessed. After a comprehensive assessment of the waste generation site, we move on to the next stage of algorithm fulfilment.

Step 2. Entering initial data to determine fuel and energy efficiency: At this stage, the initial parameters for economic and mathematical modeling are clarified and adjusted, if necessary, with regard to the characteristics of the technological process, the machines and equipment used, and the norms and regulations established in the TPC. The following initial parameters are included in models (2)–(10): average distance of primary waste transportation, km; average density of primary waste, kg/st.m^3; relative humidity of primary waste, %, and other data that may affect the results of economic and mathematical modeling.

Step 3. Using MathCad and MS Excel software, practical implementation of innovative technology for managing the TPC biofuel waste production was conducted to determine the optimal combination of factors that maximize EEC as a key fundamental indicator of fuel and energy efficiency. At this stage, it is also necessary to verify the obtained EEC value for compliance with the criterion for making a managerial decision: EEC exceeding the minimum value is accepted in economic-mathematical models (8)–(10) as equal to 1.15. As follows from Equation 1, this value is equivalent to a 15% excess of the amount of thermal energy per unit volume of fuel (Q_g) over the amount of thermal energy consumed for processing this fuel as an energy carrier at various stages of its production (Q_n).

Step 4. Evaluation of the results obtained: At this stage, it is necessary to assess the extent to which the following factors influence the energy and economic efficiency of TPC waste biofuel production: the wood waste density and relative humidity, the distance of waste delivery to the processing and biofuel production sites, and the location of waste accumulation. This is followed by the verification of the obtained results according to the criterion of maximizing the objective functions (8)–(10) and acceptance of those results that meet the requirements for the profitability of wood biofuel production, and therefore, for which EEC ≥ 1.15. If, with the factors calculated at this stage, the condition for maximizing the objective functions (8)–(10) is met, we proceed to the analysis of the results obtained for their practical feasibility and consistency, conclusions based on the research results and managerial decision-making, and completion of the innovative technology algorithm for managing TPC waste biofuel production. Otherwise, it is necessary to clarify the initial parameters, adjust the initial data, and then return to point 2 of the algorithms in question.

4- Results

4-1- Practical Implementation of the Developed Innovative Technology for Managing TPC Waste Biofuel Production

Problem statement: It is necessary to clarify the extent to which the following factors influence energy and economic efficiency indicators: wood waste density and relative humidity, the distance of waste delivery to the processing and biofuel production sites, and the location of waste accumulation.

Let us consider all stages of the production cycle as exemplified by waste generation at a logging site (waste accumulation option D1).

1. *Stage of the production cycle Q1–primary waste shredding:* At this stage of production, the change in energy consumption is affected by the relative humidity of the primary waste (Figure 6). As can be seen from Figure 6, with an increase in the feedstock moisture content, the energy consumption of the biofuel producer increases.

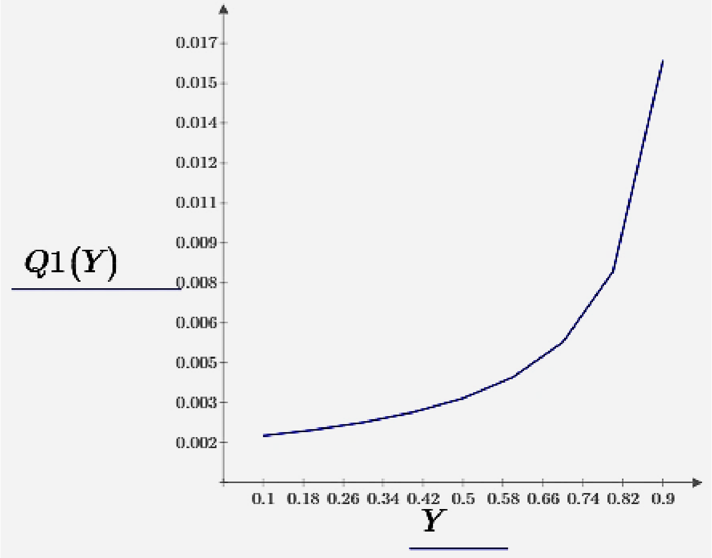

Figure 6. Influence of humidity on energy consumption at stage Q1–Primary waste shredding (Y – fractions of a unit, Q1 – kgoe/kg)

2. *Stage of the production cycle Q2* includes the collection of raw materials for the production of biofuels. At this stage of production, the change in energy consumption is influenced by the same indicator as that at the waste shredding stage, namely: the relative humidity of the primary waste (Figure 7). As can be seen from Figure 7, with an increase in the feedstock moisture content, the energy consumption of the biofuel producer also increases.

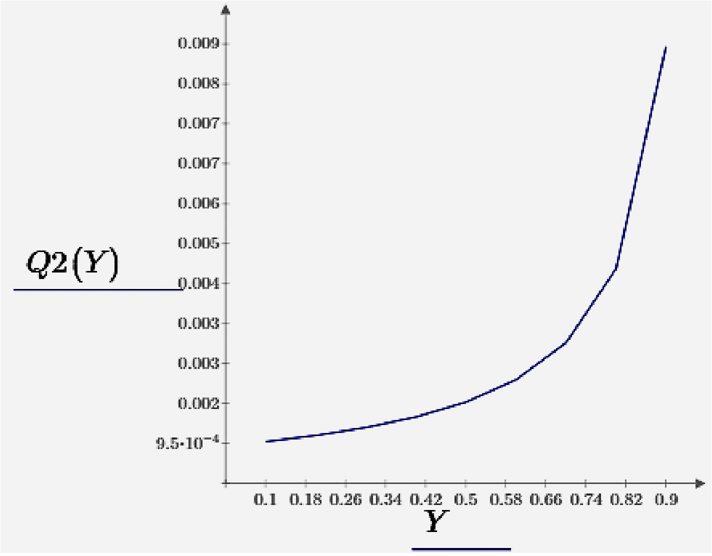

Figure 7. The influence of humidity on energy consumption at stage Q2 – collection of raw materials for biofuel production (*Y* – fractions of a unit, *Q2* – kgoe/kg)

3. *Stage of the production cycle Q3 – transportation of waste to the production site:* At this stage of production, changes in energy consumption and costs in the cost structure are influenced by two indicators: the relative humidity of the primary waste and the distance of raw materials transportation to the biofuel production site (Figure 8). As can be seen from Figure 8, the lower the feedstock moisture content and the shorter the distance to the production site, the lower the energy consumption.

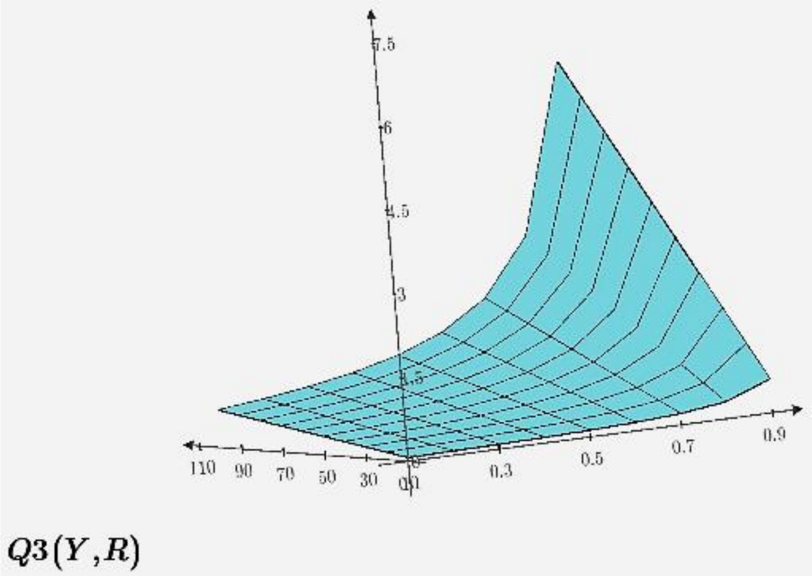

Figure 8. **Influence of humidity and distance on energy consumption at stage Q3–Transportation of waste to the production site**

4. *Stage of the production cycle Q4 – primary waste drying for further briquetting of products:* At this stage of production, the change in energy consumption is influenced by the relative humidity of the primary waste. As can be seen from Figure 9, with an increase in the feedstock moisture content, the energy consumption of the biofuel producer increases. Thus, at a humidity of 20% at stage Q4, the energy consumption is 0.032 kgoe/kg of absolutely dry wood, and with an increase in humidity to maximum values, the energy consumption increases to 2.43 kgoe/kg of absolutely dry wood.

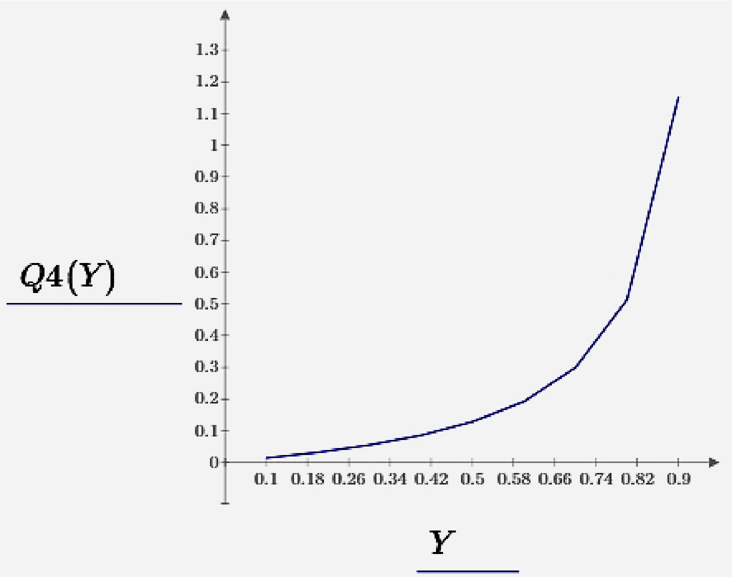

Figure 9. **Influence of humidity on energy consumption at stage Q4: Primary waste drying**

(Y – fractions of a unit, Q2 – kgoe/kg)

5. *Stage of the production cycle Q5–primary waste briquetting to the final product:* This stage of the production process depends solely on the choice of equipment with a certain engine power and its hourly productivity. At this stage of production, energy consumption is not affected by any of the analyzed indicators, and the value of Q5 is constant for all modeling options and amounts to 0.0094 kgoe/kg.

It should be noted that with an increase in energy consumption within the framework of the above-described technological process, the EEC in the production of biofuels decreases, i.e., the higher the energy consumption at any stage of biofuel production, the lower the EEC, and vice versa.

Analysis of Figure 10 shows that with increasing feedstock moisture content and distance to the biofuel production site, the EEC decreases. EEC use in practice makes it possible to assess the difference between the energy consumed to obtain each individual type of energy resource and the final energy that this energy resource will provide to the final consumer. For example, for waste accumulation option D3 (obtaining raw materials from waste from wood processing enterprises), we enter the following initial data: R = 50 km, Y = 60%. With such values, EEC = 0.9, which means that this combination of data will not be energy efficient for the production of biofuels. For the waste accumulation option D1 (obtaining raw materials by collecting waste from logging operations), we use the following initial parameters: R = 10 km, Y = 50%. In this case, EEC = 2.9, which means that this combination of influencing factors is effective in terms of energy consumption.

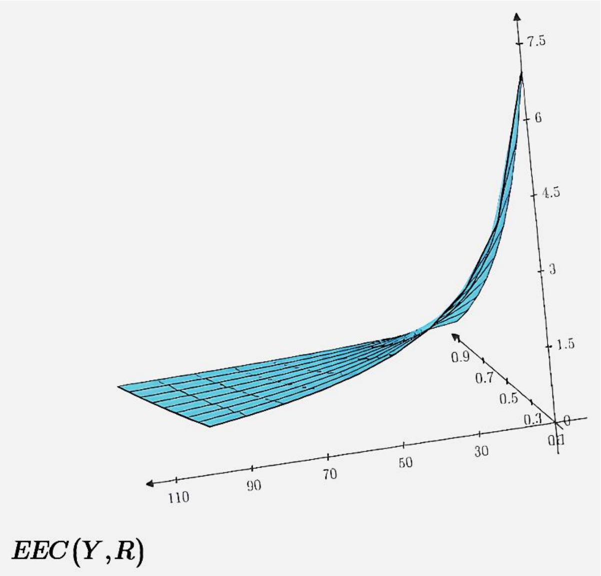

Figure 10. **EEC depending on humidity and distance using example D1**

Analysis of these graphs constructed in the Mathcad software environment indicates that if at all stages of the production process the distance to the biofuel production site and the feedstock humidity increase, energy costs will correspondingly increase, hence, the EEC will decrease.

4-2- Influence of Distance of Primary Waste Transportation

Using the MS Excel software product, let us analyze the extent to which the energy efficiency indicator is affected by a change in the distance of primary waste transportation to the processing site with fixed values of the relative humidity of the feedstock.

Table 4 provides data on changes in the EEC of briquetted fuel production depending on changes in waste transportation distances under conditions of constant relative humidity of 40%.

Table 4. **EEC in briquetted wood waste production depending on the distance of primary waste transportation. Initial data: The relative humidity of raw materials is 40%**

Designation of the waste generation site	Waste generation site	Waste transportation distance, km				
		0	40	60	80	100
D1	Logging site	6.63	1.68	1.27	1.00	0.82
D2	Timber-handling site	6.73	1.74	1.27	1.00	0.82
D3	Wood processing site	6.79	1.75	1.28	1.01	0.83

Analysis of Table 4 shows that the highest EEC value is observed in the absence of transportation of raw materials to the biofuel production site, i.e., in cases where the briquettes are manufactured at those enterprises where waste is generated. It is important to note here that distance has a large impact on changes in the EEC. As can be seen from Table 4, an increase in distance from 0 to 40 km results in an almost four-fold decrease in this coefficient, and with an increase in distance to 100 km, the EEC decreases by 87% of the initial value. At a distance of 80 km, the EEC value becomes critical, and already at 100 km, we see that EEC < 1, which means that the energy consumption in this scenario is inefficient. Considering the above criterion for making a managerial decision and relying on the analysis of the data presented in Table 4, we can conclude that from the standpoint of energy efficiency, organizing the production of briquetted fuel from waste is advisable at TPC enterprises with waste concentration by collection at one site for transportation distances not exceeding 60 km. Under such conditions, EEC = 1.27 (see Table 4).

4-3- Influence of Humidity

Relying on the modeling results obtained in the MS Excel software environment, we will analyze the extent to which the change in the feedstock moisture content (wood waste) affects the energy efficiency indicator.

Table 5 presents the calculated data on the amount of absolutely dry wood pulp (combustible substance) per unit volume of wood waste of the same density but different relative humidity.

Table 5. EEC in briquetted wood waste production depending on changes in the moisture content of primary wood waste. Initial data: Waste transportation distance is 40 km

Designation of the waste generation site	Waste generation site	Relative humidity of primary wood waste, %					
		5	30	40	50	60	70
D1	Logging site	3.37	2.14	1.74	1.37	1.05	0.75
D2	Timber-handling site	3.39	2.15	1.74	1.38	1.05	0.75
D3	Wood processing site	3.39	2.15	1.75	1.39	1.06	0.76

Analyzing the impact of humidity on the EEC indicator, we can conclude that, under given conditions, the production of briquetted fuel will be energy efficient when the humidity of the primary waste is no more than 50%.

An analysis of the influence exerted by the relative humidity of primary waste and the transportation distance showed that the organization of briquetting from wood processing waste is the most energy efficient. It should also be noted that biofuel from wood processing waste has a higher grade of products and, as a result, a higher price. The demand for this type of briquetted biofuel is highest in the European Union [12, 25,42]. In general, to organize briquetted fuel production, it is necessary to consider the seasonality of waste collection, condition and trafficability of forest roads, and the concentration of waste.

4-4- Main Scientific Results

- Process flowcharts for biofuel production were developed. The stages of the production process were highlighted as follows: stage Q1 – primary waste shredding; stage Q2 – collection of wood waste for biofuel production; stage Q3 – transportation of waste to the production site; stage Q4 – primary waste drying; and stage Q5 – primary waste briquetting to the final product.
- A comprehensive innovative technology for managing TPC waste biofuel production has been developed, which includes a set of interconnected economic and mathematical models for maximizing EEC based on selected stages of the production process, which allows the managerial decision-maker to assess the fuel and energy efficiency of the final product.
- As can be seen from Figure 6, with an increase in the feedstock moisture content, the energy consumption of the biofuel producer increases. Thus, at a humidity of 10% at stage Q1, the energy consumption is 0.0018 kgoe/kg of absolutely dry wood, and with an increase in humidity to maximum values, the energy consumption increases to 0.016 kgoe/kg of absolutely dry wood.
- Figure 7 shows a stage of the production process that is specific only to D1. Waste is collected only in the logging area (D1) because it is more concentrated at timber handling sites (D2) and wood processing enterprises (D3). As can be seen from Figure 7, energy consumption depends on the moisture content of the primary production waste. At the same time, Table 4 shows that with an increase in the feedstock humidity by a factor of 6 (from 5% to 30%), the EEC decreases by 36.5%.
- As can be seen from Figure 8, the lower the feedstock humidity and the distance to the production site, the lower the energy consumption. At a humidity of 5% and a raw material transportation distance of 5 km, the energy consumption was 0.04 kgoe/kg of absolutely dry wood. With an increase in humidity to 50% and a distance of up to 20 km, the energy consumption increased to 0.17 kgoe/kg of absolutely dry wood.
- At stage Q4, we considered the impact of the relative humidity of primary waste on changes in energy consumption. As can be seen from Figure 9, with an increase in the feedstock moisture content, the energy consumption of biofuel production increases.

- Figure 10 shows a distinctive feature of the graph from the previous ones; the curve is descending. This suggests that with increasing energy costs within the framework of the above-described technological process, EEC in the production of biofuels decreases, i.e., the higher the energy consumption at any stage of biofuel production, the lower the EEC, and vice versa. When considering the three options for the accumulation of waste, which serve as feedstock for biofuel production, it can be concluded that the higher the humidity and the longer the transportation route, the higher the energy costs and, accordingly, the lower the EEC values.

5- Conclusion

The production of biofuels from timber industry waste is profitable if the distance of feedstock transportation to the production site does not exceed 80 km and the relative humidity of the raw materials does not exceed 60%.

Analysis of Tables 4 and 5 makes it possible to conclude that the EEC indicator is influenced by the waste accumulation location. As can be seen from Table 4, an increase in distance from 0 to 40 km leads to an almost four-fold decrease in this coefficient, and with an increase in distance to 100 km, the EEC decreases by 87% of the initial value. At a distance of 80 km, the EEC value becomes critical, and already at a distance of 100 km, it can be seen that EEC < 1, which means that in this scenario, the TPC waste biofuel production is energy inefficient. According to Table 5, at constant values of transportation distance of 40 km, waste density of 200 kg/st.m3, and feedstock moisture content of 5% at production option D1, EEC = 3.37, and at D3, EEC = 3.39. All other things being equal, the EEC obtained from waste processing at wood processing enterprises (D3) is always greater than the EEC from waste processing in the places of their generation D1 and D2. In addition, according to European standards [12, 42, 28], the certified quality of the final product obtained at stage D3 is higher than that obtained at stages D1 and D2, and buyers from the European Union prefer wood pellets from wood processing waste (D3) to products obtained at stages D1 and D2.

The practical implementation of the economic and mathematical models (8)–(10) makes it possible to increase the economic efficiency of biofuel production management by optimizing fuel and energy efficiency and increasing the accuracy of managerial decisions.

5-1- Research Strengths and Limitations

The economic and mathematical model developed by the authors on the basis of the technological process of TPC waste biofuel production allows enterprises to:

a) make optimal managerial decisions in managing biofuel production; in particular, create enterprises for processing waste into biofuel based on TPC primary production, which will provide additional added value and reduce waste disposal costs;

b) assess energy costs under given scenarios and adjust the management of biofuel production by analyzing the data obtained using the fuel and energy efficiency indicators.

5-2- Model Limitations

1) To increase the accuracy of solving the problem of the optimal combination of factors influencing the EEC indicator in TPC waste biofuel production, it is recommended to consider the cost of manufacturing and selling products, which will allow the development of a comprehensive economic and mathematical model for managing biofuel production with regard to its economic efficiency (profitability).

2) The fuel and energy efficiency of biofuel production are significantly influenced by the technological process, machines and equipment used in production, production practices established at enterprises, and norms and standards applied. This research employed standard norms and regulatory requirements, typical technological process flow charts presented in Figures 1–3, and machines, equipment, and a wood waste pelletizing line (Figure 4) to assess fuel and energy efficiency according to the EEC indicator.

5-3- Recommendations and Directions for Future Research

The economic and mathematical management model of TPC waste biofuel production developed by the authors can be used to improve the accuracy, efficiency, and validity of managerial decisions in the interests of enterprise development, increasing the profitability of its activities, improving logistics, labor productivity, and equipment retrofitting.

The results of the scientific and methodological apparatus development and the implementation of practical tools for this study make it possible to conclude that the stated research purpose was achieved. The completed scientific research provides management decision-makers with effective tools for determining the energy efficiency of production management. Directions for further research are as follows: considering the efficiency of forestry waste briquetting from the standpoint of energy and economic efficiency; improving biofuel production management by reducing energy costs, concerning the seasonality of waste collection, the condition and trafficability of forest roads, and waste concentration; adapting the economic and mathematical model developed in this study for all TPC enterprises; and integrating the developed economic and mathematical tools for managing biofuel production into a unified information and analytical system and its interaction with widely used applied software products.

6- Declarations

6-1- Author Contributions

Conceptualization, A.E.M.; methodology, E.V.K.; validation, E.V.K.; formal analysis, E.V.K. and A.E.M.; investigation, E.V.K.; resources, A.E.M.; data curation, A.E.M.; writing—original draft preparation, A.E.M.; writing—review and editing, E.V.K.; visualization, A.E.M.; supervision, E.V.K.; project administration, E.V.K. All authors have read and agreed to the published version of the manuscript.

6-2- Data Availability Statement

The data presented in this study are available on request from the corresponding author.

6-3- Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

6-4- Institutional Review Board Statement

Not applicable.

6-5- Informed Consent Statement

Not applicable

6-6- Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancies have been completely observed by the authors.

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