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Evaluation of Economic Possibilities of Production of Second-Generation Spirit Fuels for Internal Combustion Engines in Poland

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Abstract: With the rapid growth in industrial development, there is a particular need for new environmentally balanced energy source utilization. Ethanol produced from biomass, especially lignocellulosic waste products, represents an attractive, sustainable energy source for fuel production. Until now, in Poland, bioethanol has been produced from edible plants containing sugars susceptible to fermentation. Due to the growing technical and economical needs for alternative biomass source utilization, in the present work, an attempt has been made to identify the most cost-effective strategy to analyze ethyl alcohol production from different lignocellulose sources. The concept of an installation for the first and second stages of bioethanol production was proposed. All of the most relevant elements of the bioethanol production cost analysis were identified and characterized. Cost analyses of all important production process elements showed their relative effects on the production cost and potential for the competitive advantage of applied raw material. The study demonstrates the importance of renewable energy source utilization and the cost-effectiveness of bioethanol production. Furthermore, the proposed less energy- and labor-demanding process, primarily achieved via the implementation of technological medium recovery and recirculation, reduces the production cost and results in higher production efficiency, and therefore has a significant effect on the overall process economy.

Keywords: lignocellulosic biomass; bioethanol; cost effectiveness; spirit fuels

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1. Introduction

Spirit fuels are an environmentally important alternative to crude oil and its derivatives, which is currently the main source of energy. Liquid biofuels are becoming increasingly important in the European Union (EU) energy mix. Concerns about reducing emissions of CO_2 and other damaging gases forced the EU to search for other renewable energy sources. However, growing restrictions on coal, gas, and oil usage could threaten global energy demand [1]. Therefore, the improvement of alternative energy sources, including spirit fuels, has received much attention due to their economic benefits and energy security [2]. The use of simple alcohols, methanol, and ethanol as an additive to petrol and diesel is a step towards reducing CO_2 emission [3], which is dictated by the 2003/30/EC Directive adopted by the European Union on 8 March 2003 [4]. In Poland, the obligation to use bio-components in liquid fuels is dictated by the Act of 25 August 2006 on bio-components and liquid biofuels. The Act introduced an obligation to meet the so-called National Indicative Targets (NIT), assuming a gradual increase in the share of biofuels in the total fuel sold on the market, which is expected to reach 10% in 2022. One of the ways of achieving the NIT requirements is to use dehydrated ethyl alcohol (bioethanol), which may be a transportation fuel itself in specially adapted engines or mixed with petrol.

Raw materials with high energy content are of great importance in the production of bioethanol for the transport sector [5]. Until now, spirit fuels in Poland have been produced mostly by edible plants such as cereals, sugar cane, maize, sugar beet, and other plants containing sugars susceptible to fermentation [6]. The obligation imposed by the European Commission to reduce the share of first-generation biofuels in favor of second- and third-generation biofuels makes it necessary to produce bioethanol from inedible plants or plant waste. Available technologies make it possible to obtain bioethanol as a result of the advanced hydrolysis and fermentation of lignocellulosic biomass [7]. The sources of cellulose biomass may be growing resources of coniferous and deciduous trees, plantations of fast-growing trees (willow, poplar), straw, hay, stems of cultivated plants, and wood waste from the pulp and paper industry [8]. Due to the high availability of lignocellulose raw materials in Poland, second-generation bioethanol may play an important role in the production of transport fuels [9]. The main benefit of lignocellulosic biomass use in bioethanol production is no competition with its consumption for food production, resulting in no possible impact on food prices [10]. On the other hand, the high costs of obtaining lignocellulose and transport logistics may represent a significant production issue [11]. Therefore, it is necessary to develop an effective and cost-effective technology for the production of second-generation bioethanol.

Currently, in Poland, the most common renewable biofuel biomass sources are corn grain (starch) and sugar cane (sucrose) [12]. It is expected that there will be limits to the supply of these raw materials shortly, therefore lignocellulosic biomass is seen as an attractive feedstock for future supplies of ethanol. However, bioethanol production from lignocellulosic biomass is a complex and time-consuming technical process that involves multiple steps from the resource to the final product [13]. The first step of pretreating biomass leads to the decomposition of chemical lignocellulosic complexes characterized as a critical step in the whole production process. Recently, several combinations of efficient wood-based materials' pretreatment methods have been described as enabling the industrial use of lignocellulosic materials [13]. According to recent scientific studies, the optimization of the bioethanol production process from lignocellulose by creating an easily decomposable lignocellulosic complex will make it possible to obtain cheap, high-quality fuel [14]. Therefore, the selection of the appropriate equipment and production scale represents an important factor enabling the cost reduction of bioethanol produced from lignocellulosic biomass [15].

In recent years, in Poland, a strong emphasis has been placed on aspects of biofuels' production processes, shipment, and storage. The call for and profitability of biofuels is also decided by way of governmental regulations, import taxes, and subsidies [2]. Due to technical and economical impediments to the development of commercial processes utilizing other sources of biomass, the primary objective of this study is to analyze and evaluate the optimum opportunities for the production of second-generation bioethanol in Poland in a changing economic and social environment.

The auxiliary objectives are:

1. Prioritizing factors influencing the costs of the production of second-generation bioethanol in Poland using the expert-mathematical method.
2. Determination of the magnitude of the production costs of bioethanol, from an extremely unfavorable to an extremely favorable economic and social environment.
3. Determination of the optimal strategy for the production of second-generation biofuel in Poland using individual choice criteria.

2. Materials and Methods

2.1. Expert Mathematical Method Prioritizing the Factors of Second-Generation Bioethanol Production in Poland Economic Effectiveness

The economic, social, and political factors influencing the development of the renewable energy production sector in Poland were prioritized via the use of the expert mathematical method as presented previously [16,17]. A group of 96 experts was selected based on criteria discussed in detail in the literature [18]. A research questionnaire was developed containing 9 tables into which the expert entered ratings of the significance of a given factor in the assessed group and possible supplementary information on the given expertise. The first three tables contained information about the expert's employment and seniority in the field under study. The remaining six tables contained the factors at levels II and III of the event tree, in which experts entered the assessment expressing the magnitude of the impact of a given group and individual factors on the potential production of 2nd-generation bioethanol in Poland. The factors listed in the tables were scored by the expert on a scale from 0 (irrelevant parameter) to 100 (maximum significance), with a total of 100 points (percentage) allocated to the individual parameters.

The minimum number of required experts was determined as presented by Yevlanov et al. [19]:

$$N_E = \frac{f\beta(b-1)}{(\gamma+1)(b-1)\Theta 0} \tag{1}$$

where $f\beta$ $(b - 1)$ is the distribution quantile of χ^2 corresponding to the confidence level and number degrees of freedom $b - 1$, γ is the assumed accuracy in assessing concordance, and Θ_0 is a critical value of the concordance coefficient.

2.2. Statistical Analysis

To provide the statistical significance of expert data analysis, the χ-square criterion was used. A result was considered significant when the probability of a random difference was less than 0.001 ($p < 0.001$). The concordance of experts was checked using the coefficient of variance V_j:

$$V_j = \frac{g_j}{m_j} \tag{2}$$

where g_j is the mean square deviation of the important factor and m_j corresponds to the local priority of the factor. As presented previously in the literature [17], the concordance of the experts' validity judgments was sufficient with $V_j \leq 0.25$.

The mean square deviation of the factor importance was determined as follows:

$$g_j = \sqrt{\frac{\sum_{i=1}^{N_E} (m_j - m_{ij})^2}{N_E - 1}}, \text{ for } N_E \ \leq \ 30 \tag{3a}$$

$$g_j = \sqrt{\frac{\sum_{i=1}^{N_E} (m_j - m_{ij})^2}{N_E}}, \text{ for } N_E \ > \ 30 \tag{3b}$$

The local priority m_j of the jth factor was determined as follows:

$$m_j j = \left(\sum_{i=1}^{N_E} m_{ij}\right) / N_E \tag{4}$$

2.3. ETA Analysis

The event tree assessing the main criteria for the development of generation II bioethanol production from various energy sources in Poland was performed to provide simplification of the expert analysis output data as described previously [17].

2.4. Game Theory

To determine the optimum strategy for the production of 2nd-generation bioethanol in varying economic and social conditions, the elements of game theory were applied as described previously [20] with several modifications. A range of considered states from unfavorable Y_2 through to current Y_3 to favorable Y_4 were distinguished. To ensure full orthogonality of the interval under consideration, it was extended by 21.5% of the assumed size of the interval, from average to very unfavorable (Y_1) and very favorable conditions (Y_5). The individual possible strategies were analyzed in terms of the production costs, and the optimum strategy was selected by the use of two groups of individual choice criteria. In the first group, the analysis was carried out with the probability of the occurrence of the economic and social environmental conditions. The first group included two criteria: Maximum average win and minimum average risk. The second group, with an unknown probability of occurrence of states of economic and social environment, included three criteria: Maximum pessimism, minimum risk, and pessimism-optimism.

With the maximum average win criterion, the optimal was identified by the minimal sum of the $M(S_i, Y_j)$ values:

$$S_{i\ opt} = \sum_{j=1}^{d} P_j M(S_i, Y_j) \to min \tag{5}$$

where d is the number of possible situations faced by the producer of 2nd-generation bioethanol (raw material acquisition costs, EU subsidies for raw material production, subsidies from the Polish budget for raw material production, taxation of raw material production) and P_j is the probability of occurrence of $\sum_{j=1}^{d} P_j$ given situations.

To use the minimum average risk criterion, the production cost matrix was transformed into a risk matrix (Table 1). For this purpose, the difference between the minimum possible value of $M_{min}(S_i, Y_j)$ in the j-th column and all its other values is determined using the S strategy for the same conditions, that is, when Y_j = const:

$$R(S_i, Y_j) = M(S_i, Y_j) - M_{min}(S_i, Y_j) \tag{6}$$

where $R(S_i, Y_j)$— is the risk-loss from a possibly incorrectly adopted strategy, $R(S_i, Y_j) \geq 0$.

Table 1. The possible cost risk matrix for the production of 2nd generation bioethanol. Y_1–Y_5 corresponds to strategies from very unfavorable (Y_1) to very favorable (Y_5) production conditions.

The Strategy Adopted	**Possible Situations**				
	$\mathbf{Y_1}$	$\mathbf{Y_2}$	$\mathbf{Y_3}$	$\mathbf{Y_4}$	$\mathbf{Y_5}$
S_1	$R(S_1,Y_{S1})$	$R(S_1,Y_{S1})$	$R(S_1,Y_{S1})$	$R(S_1,Y_{S1})$	$R(S_1,Y_{S1})$
S_2	$R(S_2,Y_{S2})$	$R(S_2,Y_{S2})$	$R(S_2,Y_{S2})$	$R(S_2,Y_{S2})$	$R(S_2,Y_{S2})$
S_3	$R(S_3,Y_{S3})$	$R(S_3,Y_{S3})$	$R(S_3,Y_{S3})$	$R(S_3,Y_{S3})$	$R(S_3,Y_{S3})$
S_4	$R(S_4,Y_{S4})$	$R(S_4,Y_{S4})$	$R(S_4,Y_{S4})$	$R(S_4,Y_{S4})$	$R(S,Y_{S4})$

The optimum production 2nd generation bioethanol strategy was selected using the criterium of the sum of values in the individual rows striving towards the minimum:

$$S_{i\ opt} = \sum_{j=1}^{d} P_j R(S_i, Y_j) \to min \tag{7}$$

In the situation of the unknown probability of a given situation, Laplace's insufficient basis principle was applied, where all possible situations are assumed with equal probability. In this situation, the probability of each situation occurrence was given by the general number d with the modifications of the optimal strategy criteria:

$$P = 1/\mathrm{d} = \mathrm{const} \tag{8a}$$

$$S_{i\ opt} = \sum_{j=1}^{d} M(S_i, Y_j) \to min \tag{8b}$$

$$S_{i\ opt} = \sum_{j=1}^{d} R(S_i, Y_j) \to min \tag{8c}$$

Wald's criterion of maximum pessimism was applied to provide the strategy adjustment with a minimum win criterium. Therefore, the optimal strategy was correlated with the identification of the $M(S_i, R_{sj})$ minimum value followed by the determination from each case of the maximum value:

$$S_{i\ opt} = \min_i \max_j M(S_i, R_{Sj}) \tag{9}$$

Sevige's minimum risk criterion was applied to provide the maximum risk factor analysis. For that purpose, all of the identified risk factors were analyzed by the maximum risk value $R(S_i, Y_{sj})$, and the optimum production strategy was based on the factor with the minimum risk criterion:

$$S_{i\ opt} = \min_i \max_j R(S_i, Y_{Sj}) \tag{10}$$

Gurvic's "pessimism-optimism" criterion was also applied to select the product strategy with the optimal relation between extreme pessimism and reckless risk (optimism):

$$S_{i\ opt} = \min_i [\kappa \max_j M(S_i, Y_j) + (1-\kappa)\min_j M(S_i, Y_j)] \tag{11}$$

where κ is the coefficient indicating the maximum pessimism or optimism criterion.

The factor κ was determined by the expert-mathematical method with a value of 0.60, indicating that 60% of the strategy was pessimistic and 40% was optimistic.

2.5. 2nd-Generation Bioethanol Cost Production Estimation in Poland

The costs of production of 2nd-generation bioethanol consisted of fixed costs and variable costs. For all costs calculation, a EUR/PLN ratio of 4.8 was used (currency ratios based on 1 November 2022).

Fixed costs consisted of production line purchasing and production hall renting costs. The costs of purchasing a production line included the purchase of individual elements of the production line.

Converting the total amount of expenditure incurred on the number of liters produced during the year, the unit production cost of 1 L of 2ndgeneration spirit fuel (k_p) was calculated as follows:

$$k_p = \frac{K_c}{V_{eh} H_r} \tag{12}$$

where:

K_c is the total cost [EUR/year].
V_{eh} is the quantity of ethanol produced per hour [L/h].
H_r is the number of working hours of the technological line per year [h/year].

3. Results and Discussion

3.1. Installation for the Production of Second-Generation Spirit Fuel

Bioethanol can be made from a variety of renewable materials rich in carbohydrates that are hydrolyzed into fermentable sugars and converted into ethanol. For the production of bioethanol, primarily three types of raw materials are used: Starch crops such as sugarcane, maize, and other similar crops (first-generation bioethanol), lignocellulosic biomass (second-generation bioethanol), and microalgae technology (third-generation bioethanol). Bioethanol production from lignocellulosic biomass is a complex and time-consuming process [13]. The first step of the process is based on the conversion of lignocellulose to sugars from biomass. Raw material (i.e., wood chips) is transported and pretreated in an acid medium (first step of hydrolysis) to release lignin from the lignocellulosic complex (Figure 1). Then lignin is purified and once again hydrolyzed with acid (second step of hydrolysis) to release the sugars (mostly simple sugars such as glucose and fructose). After purification, the sugar phase is transported to fermentation and ethanol dehydration

(Figure 2). All of the presented technological steps require specified product and co-product management with all other resources required for production (labor, machinery, utilities, and chemicals). Therefore, the efficiency of the entire biofuel production process strongly depends on the installation of the selected equipment.

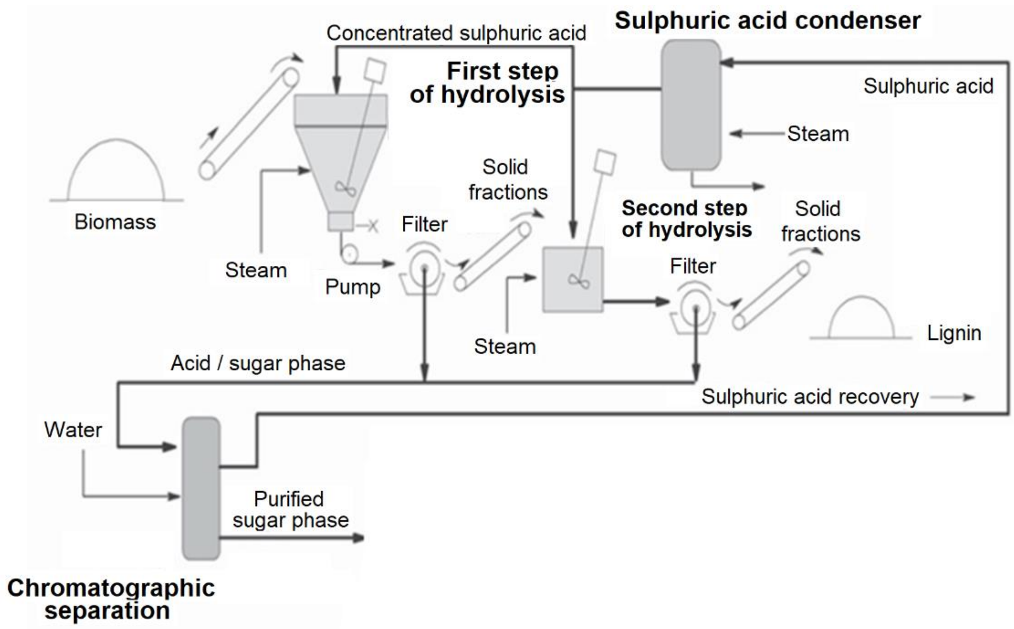

Figure 1. Scheme of the installation of conversion of lignocellulose into sugars [21].

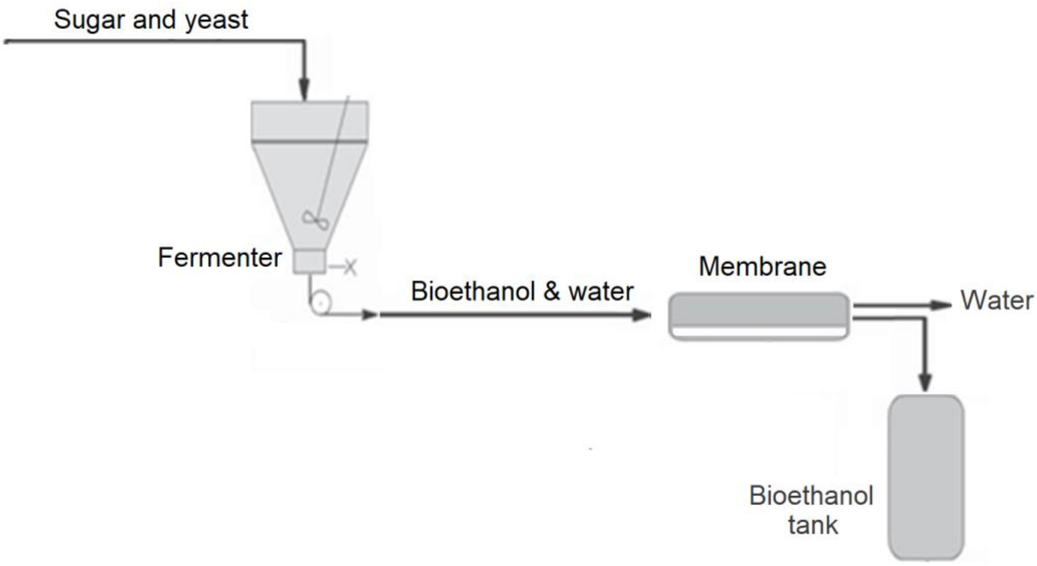

Figure 2. The proposed installation of the second stage of bioethanol fermentation and separation.

At the beginning of the production process, biomass such as lignocellulose is gradually dosed into a container with sulphuric acid for hydrolysis in the tank. In the presented installation, hydrolysis is carried out in two stages to provide a sugar medium of high purity. The lignin and sugars released in hydrolysis in solid form are sedimented and separated from the acid/sugar solution. In addition to hydrolyzed sugars, the mixture also contains sulphuric acid used in the hydrolysis process, which must be removed via chromatographic separation before further processing. This results in a purified carbohydrate mixture, which can be moved to the fermentation tank (Figure 2).

Manufactured from lignocellulose, hexoses and pentoses are dosed in the fermenter with yeasts. Then, after a certain fermentation time, a solution of bioethanol and water is obtained. This solution is then passed through the membrane module to separate bioethanol. Due to its solubility and diffusion, ethanol can pass through the membrane. This results in pure bioethanol and water.

3.2. Economic and Social Aspects of Second-Generation Biofuel Production in Poland

Increasing environmental protection requirements in Poland and the EU make it necessary to look for new possibilities for engine fuel production. One fuel meeting environmental safety conditions could be second-generation bioethanol produced from waste materials, i.e., lignocellulose, straw, maize grasses, or catch crops. Factors determining the bioethanol production efficacy include economic and social aspects, as well as the selection of the optimum production strategy. To evaluate the most important factors that can affect the possibilities of bioethanol production in Poland, the expert approach has been applied. Based on the methodology proposed by Yevlanov et al. [19], the minimum number of required experts was determined at 41. To provide a set of data with the highest potential statistical significance, a group of 96 experts was selected based on criteria discussed in detail in the literature [18]. The experts who participated in the survey were the management staff of companies specializing in the production of alternative energy sources in Poland, as well as faculty members from Polish universities working in applied biochemical engineering and energy engineering. The selected experts have either practical experience or have conducted broad studies on renewable spirit fuel production. In the group of factors affecting the possibilities of second-generation bioethanol production in Poland, experts distinguished well-known and structured economic factors, such as the costs of raw material purchase and direct production factors (production line purchase, labor, cost of electricity, and water). Interestingly, a wide group of legal, social, and human factors was also identified (Figure 3).

Based on an expert-based method, the costs of raw material purchase and direct production factors were distinguished as the most important factors determining the production of second-generation bioethanol in Poland. In the present paper, we analyzed the economic possibilities of bioethanol production from different raw materials such as wood, straw from cereal and other plants (rape, buckwheat), corn stems, grasses, and straw from catch crops. We also provided the concept of the installation of the second stage of bioethanol production with the calculation of bioethanol unit production cost analysis. In the group of social factors affecting second-generation bioethanol production, experts distinguished wide groups of legal, environmental, and human factors. Legal factors primarily included different sources of RES activity funding, including EU and Polish subsidies for production facilities, as well as tax aspects. Environmental factors included the availability of raw materials in a given region and the regional authorities' environmental regulations on possible production site locations. Nevertheless, human factors were also of great importance for bioethanol production. In this group, the possibilities of highly qualified workers' employment and environmental awareness of the society in a given region can be limiting factors for bioethanol production. The presented group of factors that can affect spirit fuel production was mostly in line with previous studies presented in the literature [10,22]. Despite the broad characteristics of various factors affecting the production of bioethanol in Poland [2,23], the available scientific literature lacks methods that would enable an extensive analysis of the various factors determining the production strategy. Therefore, based on a thorough analysis of all identified factors, which can vary from extremely unfavorable to extremely favorable, the identification of the most important factors influencing the possibilities of bioethanol production becomes a particularly important aspect of biofuel production in Poland.

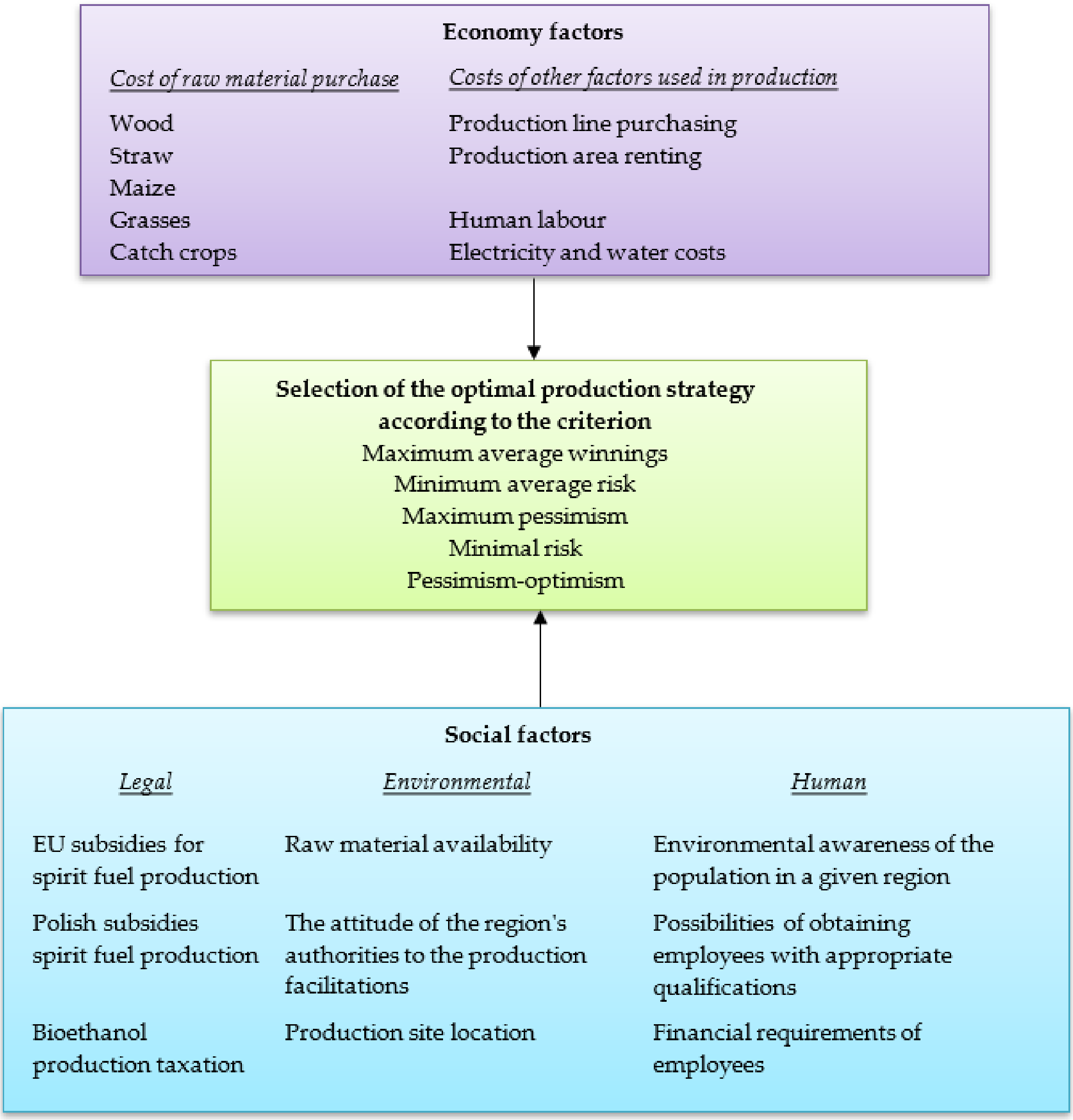

Figure 3. The set of economic and social factors influencing the selection of the most appropriate strategy for second-generation bioethanol production in Poland.

3.3. Prioritizing the Factors Influencing the Economic Effectiveness of Second-Generation Bioethanol Production in Poland

As presented in the literature [24–26], an ultimate indicator of a correctly adopted spirit fuel production strategy may be the minimum energy unit manufacturing cost, which requires the right balance of production factors in a changing economic and social environment. However, the mix of various economic, social, and political factors influencing the development of second-generation bioethanol production in Poland represents a heterogenous group of elements that can significantly complicate the identification of the most cost-effective production strategy. To provide a mathematical method enabling analysis of the identified incoherent group of factors, we applied the expert mathematical method. This tool enables investigating diverse factors, and the results obtained by this method differ slightly from other methods in the range of 6–8% [16,17]. To provide simplification of the expert analysis resulting in more structured and reliable output data, the idea of event tree analysis (ETA) was applied (Figure 4).

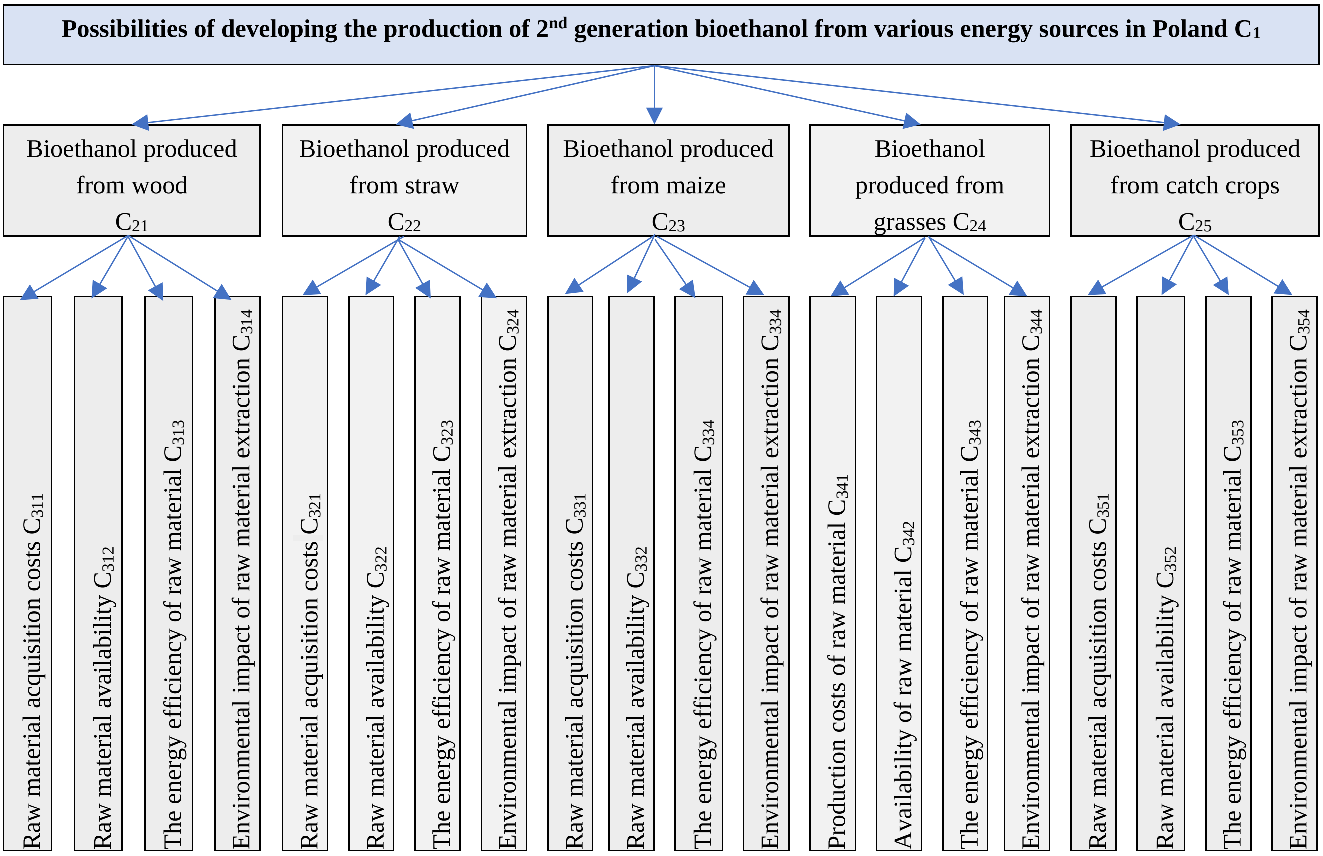

Figure 4. Input elements for event tree analysis (ETA) assessing the main criteria (*C*) of the development of generation II bioethanol production from various energy sources in Poland. The presented tree shows a top-down, inductive procedure structuring the bioethanol production possibilities from different raw materials. C_1—initial event of bioethanol production possibilities; C_{2X}—level of factors assessing the various substrates for bioethanol production; C_{3X}—level of factors assessing the cost, technical, and environmental aspects of bioethanol production from a given raw material.

In the ETA analysis, the importance of 5 level II factors (C_2) and 20 level III factors (C_3), determining the possibility of bioethanol production in Poland (C_1), were estimated. The level II factors included the option of fuel production from different organic materials, including wood, straw, maize, grass, and catch crops (Figure 4, Table 2). The level III factors assessed the cost, technical, and environmental aspects of second-generation bioethanol production in Poland. Data obtained from an expert survey was used to identify the most important factors based on the so-called "local' priority criterion. Local priorities were obtained by the sum of points given by experts and extrapolation to the value of 100. This approach enabled the identification of the share of each factor in the structure of the given group. This approach enabled the identification of the "importance" of level II factors in all sets of elements rated by the experts by the value of local priority m_j (Table 2).

As presented in Table 2, the most important factor determining the possibilities of developing the production of second-generation bioethanol in Poland is the availability of raw materials from the forestry and wood processing industries. Their share in the significance hierarchy in bioethanol production represents a value of 41 (41%), and it is almost twice as significant as the next most probable feedstock (maize) with a share of 21 points (21%). According to experts' assay, the least likely second-generation bioethanol production could be realized from catch crops, which account for only 7 points (7%). The presented concordance coefficient with the value of 0.624 enabled the quantitative assessment of experts' agreement and met the applied compliance criterion in expert method analysis as presented previously in the literature [27].

Table 2. Assessment of the importance of level II factors conditioning the development of second-generation bioethanol production in Poland.

Factor	Description	Value of Local Priority m_j	Coefficient of Variation V_j
C_{21}	Bioethanol production from wood	41	0.14
C_{22}	Bioethanol production from straw	14	0.11
C_{23}	Production of bioethanol from maize	21	0.17
C_{24}	Production of bioethanol from grasses	17	0.19
C_{25}	Bioethanol production from catch crops	7	0.14
	Concordance ratio	0.624	
	Criterion χ^2	29.79	

To identify more detailed elements that can affect the level II (C_2) factors, which, as a consequence, may also have an indirect impact on second-generation bioethanol production in Poland, the systemic priorities values of level III factors (C_3) were also determined (Figure 5). For that purpose, for each identified II level (C_2) factor, four III (C_3) level subfactors were distinguished (Figure 1) expressing the potential role of the II level (C_2) group and indirectly on the opportunities for the energy production process. In the level III (C_3) factors, the availability and purchasing costs of raw materials and the economic aspects of possible EU and Polish government subsidies and tax rates of production held in Poland were identified (Figure 5). For level III factors (C_3), the system priorities were calculated as a product of the local priorities from the lowest branch in the event tree to the level located at the top of the tree, with the standardization condition based on the sum of system priorities at a given level equal to 100. The largest share in the second-generation bioethanol production costs from all the analyzed raw materials was represented by the costs of raw materials acquisition, whose values vary from 28.0 to 52.0 points (local priority values). Contrarily, the possible production taxation possessed the lowest impact on estimates, with values ranging from 13.0 to 17.0 points. This factor also revealed the lowest impact on production efficacy in the system priority approach, from 1.1 to 16.0 points for the taxation of catch crops and wood acquisition, respectively.

Following the factor prioritization methodology, the elements affecting bioethanol process production were divided into four ranges of significance ("weights"), that is, high, higher than average, average, and lower than average (Table 3). The size of the priorities system varied from 1.10 to 16.00 points, with the average value of one factor to 5.00 points (100:20 = 5.00). By dividing the total range of the system priorities size into four groups and including 5.00 points as the average size, the implementation significance ranges can be assessed as follows: 1—high (12.25–16.00), 2—higher than average (8.49–12.24), 3—average (4.73–8.48), 4—lower than average (1.10–4.72). To determine the significance of the influence of each group on the achievement of the main objective, all the factors considered were grouped according to ranges of the size of the system priorities (Table 3).

Among level III factors, the purchasing cost of raw material from wood (C_{311}) was found to have the highest significance (Table 3). Therefore, this element represents the factor of the greatest possible influence on the economic efficiency of second-generation bioethanol production in Poland. Piwowar A. and Dzikuć M. reported that between 2015 and 2019, the main feedstock for bioethanol production in Poland was maize [23]. However, as presented previously by Kheybari et al. [28], agricultural waste including wood appears to be competitive from an economic and environmental point of view, primarily due to their high hemicellulose content and adequate amounts of lignin to balance energy demands during bioethanol production. Other materials, such as grass or maize, may not be economically attractive primarily due to lignin deficiency, which cannot meet the energy needs of the spirit fuel production process. As presented in a report analyzing the energy RES transition in Poland [29], the availability of waste wood raw materials is constantly growing. Wieruszewski et al. [30] indicated that the average volume of wood assortment harvested each year between 2018 and 2020 reached 12 million m^3, which corresponds to approximately 25% of the total wood harvested annually. Polish sawmills produce approximately 8 million m^3 of wood stocks annually for the production of wood materials and energy biomass, which accounts for approximately 20% of the total production of this raw material. For this reason, the use of wood waste for bioethanol production in Poland seems particularly interesting.

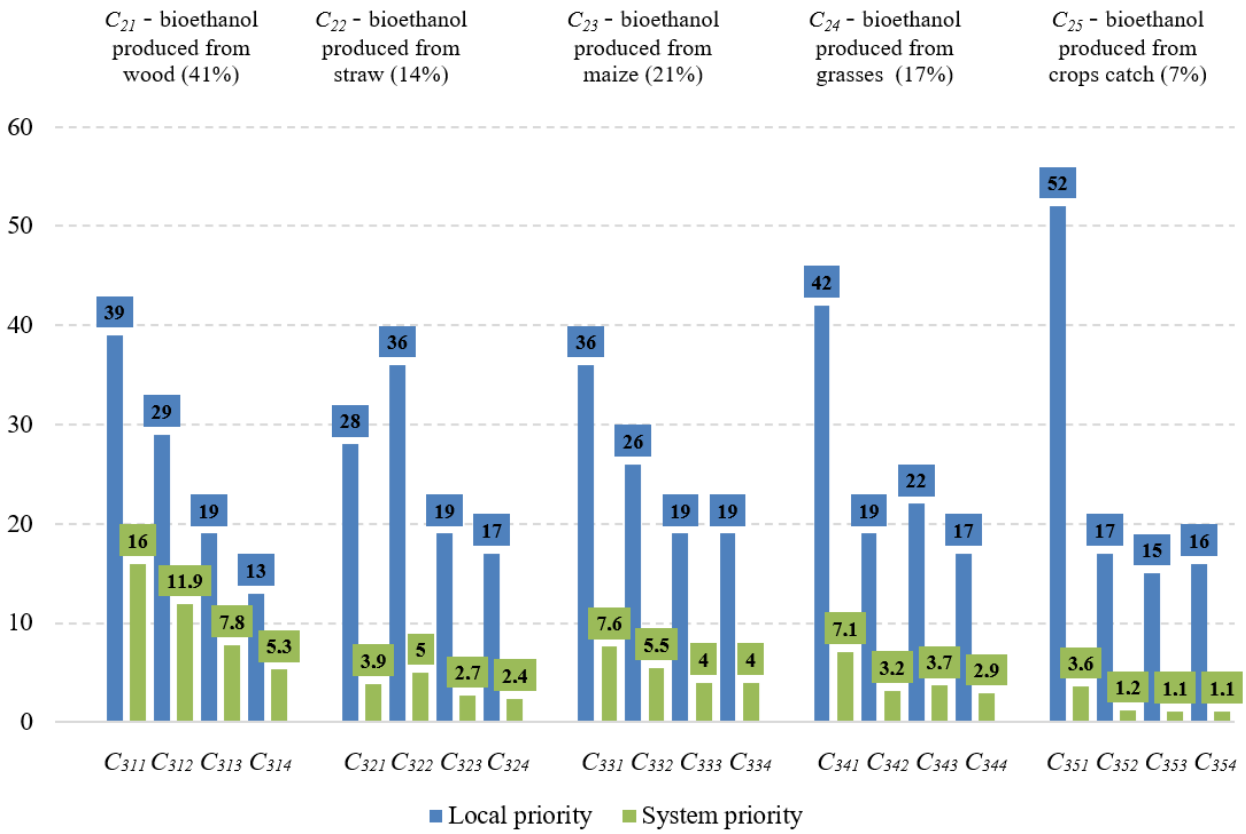

Figure 5. Assessment of the significance of level III factors conditioning the development of second-generation bioethanol production in Poland. Local priorities were determined, characterizing their significance in the given study group in level III factors (shown in blue bars). For each factor, system priority values were determined, which denoted their share in the hierarchy of significance of the main objective (shown in the green bars). The system priority value was calculated by multiplying the value of the local priority at a given level of the factor by the value of the local priority of the higher-level factor located in the given branch of the event tree.

Table 3. Significance rank of level III factors.

Range No.	Range Limits	Identified Factor	"Priority Weighting" of the Range	System Priority Average Value of a Given Objective in the Range
	%		%	%
1	12.25–16.00	C_{311}	16.0	16.0
2	8.49–12.24	C_{312}	11.9	11.9
3	4.73–8.48	C_{314}, C_{313}, C_{322}, C_{331}, C_{332}, C_{341}	38.3	6.8
4	1.10–4.72	C_{321}, C_{323}, C_{324}, C_{333}, C_{334}, C_{342}, C_{343}, C_{344}, C_{351}, C_{352}, C_{353}, C_{354}	33.8	2.81

The second distinguished group included one factor (C_{312}) regarding possible EU subsidies for raw material acquisition, which may also be regarded as a relatively significant factor affecting bioethanol production in Poland. The EU program "Infrastructure and Environment", established for 2016–2020, included subsidies for the production of biofuels. Within the framework of competition No. 1/PO IiS/9.5/2009, PLN 66.9 million was distributed to the beneficiary for this purpose, with the total cost of the winning project amounting to PLN 135.3 million [31]. Subsidies for renewable energy sources are also implemented for companies and farms. This includes investing in building new facilities and increasing the capacity of units that generate electricity and heat from biomass. Co-financing was provided by the European Regional Development Fund within the framework of Priority Axis V. All these activities were important from the point of view of Poland's climate policy and the development strategy of a CO_2-neutral economy [23]. In 2022, The European Commission approved another investment framework for subsidies worth more than EUR 380 million for 168 new projects under the LIFE program, representing a 27% increase over the previous program's figures. EU funding under LIFE will mobilize this investment of over EUR 562 million in projects targeting nature, the environment, climate action, and the clean energy transition. Actions will take place in almost all EU Member States. Therefore, the next tranche of grant funding may significantly increase the interest of local companies and international entities in investing in the construction of installations for the production of bioethanol.

In the third group, six factors, namely, C_{314}, C_{313}, C_{322}, C_{331}, C_{332}, and C_{341}, were identified. This different group included factors of waste material production taxation, as well as Polish subsidies for the purchase of different raw materials (wood, straw, maize, and grass). In line with previous reports [23], the biofuel taxation law regulations represent a significant aspect that may affect the development of spirit fuel production in Poland. The Minister of Finance Decree of 23 December 2003 on Excise Tax was issued to facilitate the production and blending of biofuel fuels. The profitability of using biofuels comes from low excise rates to support farmers' income, environmental protection, job creation, and fuel safety. Therefore, in Poland, liquid biofuels are less expensive than fuel oils with excise duty. Poland's renewable energy transport policy focuses on biofuels. Under the Energy Policy Review, Poland has targeted the increase to a 10% renewable energy share in transport by 2020 and 14% by 2030, whereas the real percentage share in 2020 was 6.6% [32]. Similar to many EU Members, Poland's main policy mechanism for achieving its RES targets is the biofuel blending obligation. It requires all companies that manufacture or import transport fuels to minimize their share of biofuels according to the energy content of their annual fuel turnover for all modes of transport. Companies that reach 85% of the required mix ratio are eligible to pay a replacement fee in exchange for fully achieving the target. Biofuels are taxed at the same rate as blended fuels. Therefore, Poland aims to maximize local production of biofuels as part of its goal of promoting domestic energy sources. Bioethanol production in 2020 was approximately 0.3 Mt, compared to 0.2 Mt in 2015, and the capacity was approximately 0.7 Mt. Biodiesel production was approximately 0.9 Mt, compared to 0.75 Mt in 2015, with a production capacity of approximately 1.4 Mt., which covers most of the domestically produced Polish biofuel needs.

Twelve factors were included in the last group, whose "system priority weight" of the whole range is quite significant, but the range significance resulted solely from the large number of factors included in this range. The average value of the fourth range significance factor was only 2.81 points, implying no major effect on the economic effects of the production of second-generation bioethanol in Poland.

3.4. Game Theory as an Optimal Tool in the Selection of an Optimum Production Strategy for Second-Generation Bioethanol in Poland

The most rational direction for solving the problem of economic efficiency of the production of second-generation bioethanol was the selection of an optimum strategy for its production. As a result of expert mathematical analysis, the economic efficiency of the production of bioethanol may be primarily affected by the cost of acquisition of raw materials and the amounts of the EU subsidies for the production of raw materials. To analyze the most cost-effective production strategies in the incoherent economic and social environment, the game theory was applied. Three main production scenarios have been highlighted from unfavorable Y_2 through to average Y_3 and favorable Y_4. To ensure the full orthogonality of the considered interval, it was additionally extended by 21.5% to very unfavorable Y_1 and very favorable Y_5 states. The production costs of second-generation bioethanol from different raw materials were calculated in all distinguished scenarios from very pessimistic (Y_1) to very optimistic (Y_5).

The pessimistic and optimistic variants were determined through the expert mathematical method (Table 4), with the index of the increase in the production cost for the pessimistic cases and the decrease in this index for the optimistic variants in comparison with the basic case.

Table 4. Production strategies of second-generation bioethanol from selected raw materials in Poland in diversified cases of the economic and social environment. The possible situations related to the production of second-generation biofuels are presented with the likelihood of the occurrence of a relevant condition in the economic and social environment [%]. For the production of second-generation bioethanol from raw material with the highest significance in the expert mathematical method (wood), all of the important production costs are presented in detail for the individual components determining the size of these costs and the index of increase or decrease for the final costs. For the remaining raw material cases, only the final cost index of this production is presented in this table for simplicity.

Factors Influencing the Cost of Producing 1 L. of Bioethanol	$\mathbf{Y_1}$	$\mathbf{Y_2}$	$\mathbf{Y_3}$	$\mathbf{Y_4}$	$\mathbf{Y_5}$
Bioethanol production from wood					
Raw material acquisition costs	1.35	1.22	1.00	0.86	0.77
EU subsidies for raw material acquisition	1.00	1.00	1.00	0.92	0.89
Poland's subsidies for raw material acquisition	1.00	1.00	1.00	0.97	0.94
Taxation of biofuel production	1.11	1.05	1.00	1.00	1.00
Final costs	1.50	1.28	1.00	0.77	0.64
Bioethanol production from straw					
Final costs	1.69	1.56	1.00	0.76	0.66
Production of bioethanol from maize					
Final costs	1.62	1.52	1.00	0.61	0.52
Production of bioethanol from grasses					
Final costs	1.56	1.46	1.00	0.63	0.46
Bioethanol production from catch crops					
Final costs	1.61	1.52	1.00	0.43	0.33
Likelihood of the option [%]	2	14	68	14	2

Based on the index of an increase or decrease in the cost of production of second-generation bioethanol in Poland (Table 4), the costs of production of this fuel have been determined for individual raw materials and possible conditions of the economic and social environment that the producers of second-generation bioethanol may face in Poland (Table 5).

To determine the optimum economic efficiency of the production of second-generation bioethanol from the raw materials analyzed in Poland, in consideration of a diversified economic and social environment, ranging from extremely favorable to extremely unfavorable, five individual selection criteria were used, i.e., maximum mean reward, minimum mean risk, maximum pessimism, minimum risk, and pessimism-optimism. For this purpose, the unit costs of bioethanol production were transformed by the methodology of the individual choice theory into unit cost indices for the three criteria under consideration and risk size indices for the two remaining criteria (Figure 6).

Table 5. Unit production costs of second-generation bioethanol in various cases of the economic and social environment in Poland [EUR/L]. The production costs of second-generation bioethanol, depending on the type of raw material used and the case of the economic and social environment, may range from 0.08 EUR/L to 0.41 EUR/L with production costs. When using wood as the raw material, costs range from extremely optimistic to extremely pessimistic from 0.10 EUR/L to 0.23 EUR/L; for straw, 0.16–0.32 EUR/L; maize, 0.11–0.36 EUR/L; grass, 0.11–0.38 EUR/L; and catch crops, 0.08–0.41 EUR/L, respectively.

Type of Raw Material	Y_1	Y_2	Y_3	Y_4	Y_5
Wood	0.23	0.19	0.15	0.12	0.10
Straw	0.32	0.31	0.24	0.18	0.16
Maize	0.36	0.33	0.22	0.13	0.11
Grasses	0.38	0.36	0.24	0.15	0.11
Catch crops	0.41	0.39	0.25	0.11	0.08

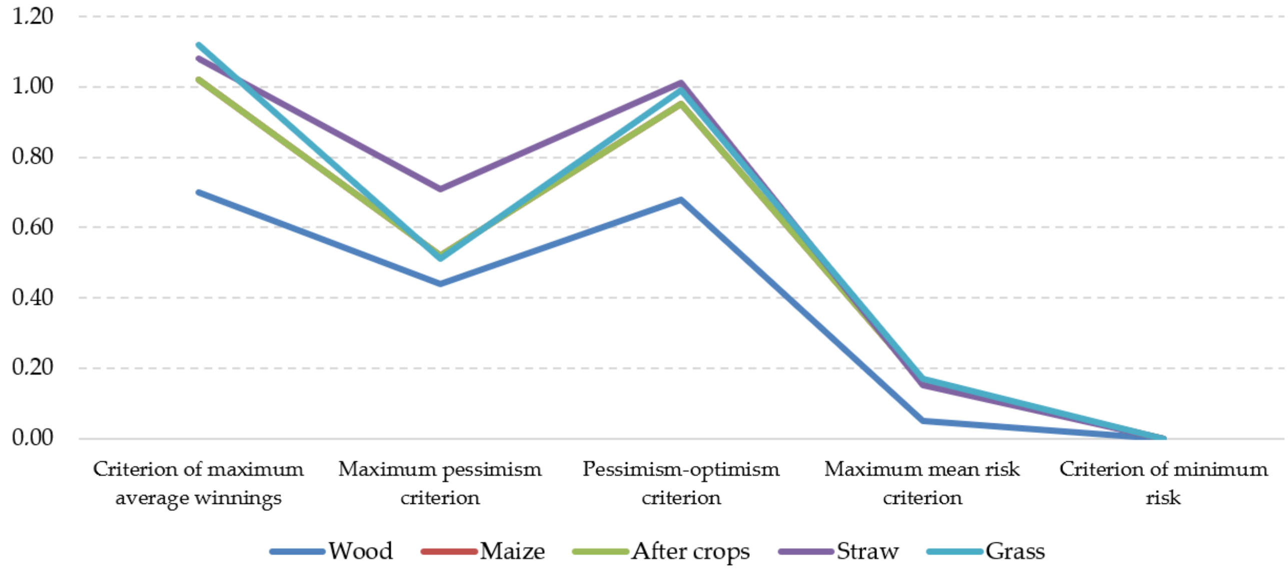

Figure 6. Possibilities of production of second-generation bioethanol in Poland according to individual choice criteria.

The optimum strategy of bioethanol production in Poland was adopted as the one with the largest number of indications in the individual criteria with the minimum identified production costs or minimum risk of increase in production costs depending on changes in the economic and social environment. After the comparison of individual strategies, the final strategy of bioethanol production should be based on the minimal possible production costs and minimal possible risk of production costs increase. The data presented in Figure 6 indicate that the production of second-generation bioethanol in Poland from wood waste represents the optimum production scenario. According to three main choice criteria, i.e., the criterion of maximum win, the criterion of maximum risk, and the criterion of optimism-pessimism, the possible bioethanol unit production costs represent the lowest value among all analyzed raw materials. Furthermore, according to the fourth criterion—maximum average risk—the production of second-generation bioethanol seems to be optimal. According to the fifth criterion, in the changing economic and social environments analyzed, the production of this fuel is equivalent to that of all the raw materials analyzed. The production of bioethanol from other feedstocks such as maize, catch crops, straw, and grasses is very similar in terms of the possibility of changes in the costs of their production, as well as the size of the risk of these changes, according to all five criteria of individual choice.

3.5. Second-Generation Bioethanol Cost Production Estimation in Poland—Study Case

A case study of bioethanol cost production in Poland was adopted both in technical preferences regarding the installation design (presented in Section 3.1) and economic parameters of fixed and variable costs, of which the simulation is presented below. Based on the proposed installation scheme, the production line with a capacity of 315 L of spirits per hour was used to analyze the costs of spirits fuel production. As an optimal raw material for the production strategy, the wood chips were selected, based on the prepared expert mathematical method with elements of game theory.

Production line. The proposed production line for bioethanol production included the following elements: A chipper, belt conveyor, tank with a stirrer, pump, drum filter, chromatographic separator, fermenter, membrane module, pipes, sulphuric acid condenser, tank for the finished product, and scales. The individual elements of the production line for the production of second-generation spirit fuel together with their number and price were selected by the analysis of commercial offers of suppliers operating in the Polish market (Table 6).

Table 6. Components of the production line necessary for second stage of bioethanol production.

Element	**Qty**	**Price**
	pcs.	**EUR**
Wood chipper	1	23,474.0
Arkama belt conveyor	3	14,084.5
2000 L tank with stirrer from Łysoń company	3	28,169.0
Digital mixing membrane pump by Grundfos	2	4,225.4
Drum filter by Drumi	2	11,737.1
Chromatographic separator HPLC by Foxy	1	11,737.1
Fermenter 1000 L	1	70,422.5
Membrane module by Koch	1	5,868.5
30 cm pipe by Sanibud	140 m.	79.5
Evaporator by Buchi	1	2582.2
Tank 450,000 L	1	70,422.5
Built-in scales with assembly	1	21,596.2
Total costs		264,398.8

The total cost of the production line for the production of second-generation bioethanol amounts to EUR 264,399 (Table 6). For the proposed installation, depreciation costs can be determined assuming the number of years of use of the production line. To depreciate fixed assets, we assumed a 20-year period of their use, which means that the annual depreciation costs will amount to EUR 13,220. It is worth mentioning that the purchase price of the primary equipment was obtained from local equipment suppliers. However, if the suppliers and proposed equipment type did not match, the estimated costs of the proposed technological components may be different. Data presented in Table 6 indicate the favorable level of production installation costs. The studies previously reported in the literature show that estimated installation investment can vary from 340,000 up to over 57,200,000 EUR, depending on the production equipment capacities and advancement of line automation [33,34]. Nevertheless, we envisage that the bioethanol industry practice concentrates on decreasing the investment outlays by multiplying the total installation purchase by a minimum of three times, which allows for obtaining a total value investment almost 50% lower [33]. Thus, there is still space for further optimization of the installation purchase expenditures of the proposed technological line for second-generation bioethanol production.

Cost of rent and security of production area. To calculate the cost of renting the premises, the necessary technological space has been identified and characterized into four distinguished production zones: (1) Pre-treatment, where the wood chipper and raw material storage will be located; (2) hydrolysis, where a tank with a stirrer, pump, drum filter, tank with a stirrer, pump, drum filter, chromatograph, tank with a stirrer, and centrifuge will be; (3) fermentation: Fermentation tanks and membrane module; and (4) warehouse for finished products, with a tank with the finished product. In the pre-treatment area, space for the chipper and a stock of raw material is needed. Assuming wood deliveries are made regularly every week, a weekly storage place for the stock should be determined. According to the demand of the production line, 1500 kg of wood is used within 1 h, while the weekly demand, including 20% of the stock, is 152,000 kg. The necessary storage area for the weekly storage of such a quantity of wood is $S_1 = 40\ m^2$. The second zone must include three tanks with an agitator, two pumps, two drum filters, a chromatograph, and a centrifuge. Summing up the necessary areas for the installation of the above-mentioned machines, we obtain the area of 24 m^2, and upon adding the area required for paths for employees of 10 m^2 to this, we obtain the total area of the second zone of 34 m^2. In zone three, space should be provided for a fermenter and a membrane module to concentrate the ethanol solution. The total area of this zone, including the added area for technical paths, is 37.25 m^2. The fourth zone is the storage area. It was assumed that the quantity of bioethanol produced in a month would be 226,800 L with the necessary storage area of 100 m^2. By summing up the areas of all zones, the total production and storage area is 240 m^2. For technological space, the average monthly rental cost in Poland amounts to 660 EUR per month, which will amount to ca. 8000 EUR/year. The production of spirit fuel in Poland is subject to excise tax. To be able to store and produce such material, it is necessary to obtain a permit for a tax warehouse. Concerning the specific legal requirements and Polish tax policy, the average annual costs of monitoring can be settled at 11,265 EUR with the total cost of renting a production hall of 19,155 EUR/year. The analysis of fixed production costs of bioethanol based on published data shows that the spatial organization of the production of second-generation bioethanol, together with the costs of purchasing production equipment and auxiliary materials, is a variable issue, depending on the geographical and geopolitical location of the production site [15]. In line with previously reported bioethanol production models, our assumptions are based on official statistical reports of the cost of raw materials and energy published by local government institutions, as well as personal communication with suppliers of production solutions [35]. For this reason, the analysis of various geographical conditions of bioethanol production can be a very variable element, and the analysis of its variance can be an interesting aspect of further research.

Variable costs. In the proposed installation for second-generation bioethanol production, variable costs include the costs of raw materials, costs of purchasing water and sulphuric acid, labor costs, and costs of electricity. Cost of materials. To determine the costs of all necessary raw materials, the aforementioned costs have to be calculated: (1) The amount of wood, which will be based on the technological demand for lignin-cellulose content (the content of lignin-cellulose in wood is approximately 95%, which differs for various waste biomass); (2) the purchase cost of sulphuric acid, which is a one-off expense because it is recovered in the production process; (3) technological medium cost (water). Lignin. Lignin is not subject to hydrolysis and is therefore disposed of into the environment during processing. Only wood with cellulose and hemicellulose content of approximately 75% can be used for fermentation. Cellulose. The hydrolysis process has to be recalculated separately for cellulose and hemicellulose because, during hydrolysis, each substance is converted into different sugars. In the case of cellulose, it hydrolyses by converting it into glucose. The efficiency of the hydrolysis process must be taken into account. During single hydrolysis, an efficiency of approximately 67% can be achieved. When hydrolysis occurs twice, the yield is increased to approximately 89% [9]). By recalculating the capacity, it is possible to determine the amounts of the obtained components capable of further fermentation. For ease of use, all calculations will be calculated for the conversion of 1 kg of wood. The amount of glucose produced from 1 kg of wood is 0.445 kg. It can also be assumed that this is the amount of hexose produced, because glucose, having six carbon atoms in its molecule, belongs to this group of sugars. Hemicellulose. In the case of hemicellulose, it hydrolyses into pentose and hexose sugars. Each hydrolysis should be considered separately since pentoses and hexoses have different molecular masses [13]. Hemicellulose consists of pentosanes (approximately 60%) and hexosanes (40%). The total amount of hexose obtained should be calculated by summing up the amount of glucose obtained from cellulose and pentoses from pentosanes from 1 kg of wood to 0.565 kg. The total amount of ethanol obtained from 1 kg of wood is 0.33 kg. Since the easiest method is to calculate the cost of fuel per unit of volume, i.e., in liters, the amount obtained should be converted taking into account the density of the product. Thanks to the final thickening stage, ethanol with a concentration of approximately 99% can be achieved. At this concentration, the density of ethanol is 0.79243 g/cm^3, which is 0.42 L.

Material flow during the production process. Analyzing the selected installation and hydrolysis reaction rate makes it possible to assume an input material flow of 500 L/h. Taking into account the bulk density of wood, it is possible to calculate the amount of input material for 750 kg/h, which results in an annual demand of 6,480,000 kg of wood, and its annual cost is EUR 228,100. The same methodology was used to calculate the costs of other raw materials (Table 7).

Table 7. Costs of purchasing raw materials for the production of second-generation bioethanol in Poland.

Row Material	Unit Price [EUR/kg]	Cellulose Production [kg/1 kg of Raw Material]	Production of Ethanol from 1 kg of Row Material [kg]	Raw Material Purchasing Cost [EUR/year]
Wood	0.04	0.565	0.33	228,000.0
Straw	0.10	0.560	0.29	477,000.0
Corn stalks	0.09	0.520	0.28	426,000.0
Hay	0.12	0.550	0.31	497,000.0

The costs of purchasing raw materials for the production of second-generation bioethanol range from 228,170 EUR to 496,900 EUR (Table 5). The presented empirical ethanol production effectiveness ranged from 0.28 to 0.33 kg/kg of raw material used, which represents values similar to those previously reported in the literature [36,37]. According to the analysis of literature data, the production of ethanol from wood waste may be one of the most cost-effective production solutions, despite the greatest difficulties with the hydrolysis of the input material [38,39].

Our findings from the cost analysis supported by the selection of production conditions via game theory confirmed that an appropriately high ratio of lignin-cellulose with the lowest purchasing price from analyzed materials represents the most cost-efficient raw material from second-generation bioethanol in Poland. The most effective ethanol production unit was obtained from wood chips (0.33 kg/kg of wood used) with the total annual row material purchasing price that can be positively compared to previously reported studies on bioethanol production costs from different materials [40]. Water, as a technological medium, is necessary both in the hydrolysis process and in the HPLC chromatography as an eluent. To calculate the amount of water required, the amount of water needed for hydrolysis of cellulose and hemicellulose 1036.8 tonnes/year should be added up, which, at the price of 0.6 EUR per tonne, gives a total of 632 EUR/year.

Waste wood is a valued resource that may be used either for material recycling or energy production, depending on the quality grade. The waste wood is available in large volumes as wood residue chips (from untreated wood residues, recycled wood, and off-cuts), forest chips (from forested areas), short rotation forestry chips (from energy crops), and sawing residue chips (from sawmill residues) [41]. The rising cost of waste material disposal and the growing consciousness of the environment also contribute to the increasing importance of waste wood recycling. In Poland, the average purchase price per kilogram of wood is approximately 0.1 EUR/kg [29]. In the case of tonnage purchases, the purchase price can even be reduced to 0.04 EUR/kg (this price of wood was used for further calculations). Converting this quantity into liters results in 0.1 EUR/L of raw material.

Labor cost. In the presented technological line for second-generation bioethanol production, the very process of production is automatic, so an employee is not needed for every position. Since the product can operate for 24 h, shift work should be added. Considering that the day is 24 h old, the working time of a quality control specialist should be converted into three shifts of eight hours each. In the case of a technologist, two shifts of eight hours will suffice. To summarize, four quality control specialists and three technologists should be recruited. In Table 8, the total monthly subsistence costs of the staff are presented. Thus, the monthly labor costs of people amount to EUR 9160, while annual labor costs amount to EUR 110,000 (detailed data are presented in Table 8).

Table 8. Labor costs of people [EUR/month]. Average monthly gross salaries are based on annual calculations of the Polish Central Statistical Office 2022 [42].

Worker	Monthly Gross Salary EUR	Number of Workers	The Total Cost of Labor EUR/month
Quality control specialist	940	4	3760
Technologist	1200	3	3600
Production manager	1800	1	1800
	Total cost		9160

Electricity costs. Electricity in the production line of second-generation spirit fuels is necessary to drive working elements and heat or cool down individual machines. Electricity will also be needed to illuminate the production premises and as a source of energy in control equipment. It is estimated that, on average, machines and equipment will consume 65 kWh of energy per hour, which represents 569,400 kWh of energy annually. The current price of 1 kWh of energy for medium-sized enterprises is 0.11 EUR/kWh, so the annual costs of electricity consumption will amount to 61,485 EUR/year.

The annual costs of second-generation bioethanol production in Poland. Annual production costs of second-generation spirit fuel, assuming production of 315 L/h, amount to ca. 433,150 EUR/year (Table 9). In the structure of these costs, fixed costs constitute 7.47%, while variable costs constitute 92.53%. In the structure of variable costs, the highest item is the cost of raw material (used wood) at 52.82%, which is more than twice as high as labor costs.

The production costs of 1 L of second-generation ethanol were determined based on the production line capacity of 315 L/h, while the annual operating time was 8600 h.

$$k_p = \frac{K_c}{V_{eh} H_r} = \frac{43,152.3}{315 \times 8600} = 0.16 \frac{\text{EUR}}{1} \tag{13}$$

The presented unit production cost of 1 L of second-generation spirit fuel is EUR 0.16. The use of wood chips obtained from forestry or post-production waste products allowed the production of 0.33kg/kg of raw wood chips with a unit production cost of 0.16 EUR/L g when using the production line capacity of 315 L/h, which represents lower production costs than previously reported in the literature. As presented by Randelli et al., the costs per liter of bioethanol production can vary from 0.24 for sugarcanes to 0.57 for sugar beets [43]. Tran and Yanagida proposed the unit cost of bioethanol produced from banana grass with a minimum value of 0.18 USD/L [44], which is similar to but still above the value proposed for production in Poland. At this point, it should be noted that the assumptions used in the calculations are based on average prices for wood, water, and electricity in 2021 in Poland. In the case of changes in the average prices of the variable cost elements, the unit cost of production of 1 L of bioethanol will change proportionally; however, the methodology presented above will still be a universal tool allowing quick estimation of the adjusted unit cost of production. Thus, the proposed work entails an advance toward the production of hemicellulose-based ethanol from wood chips. The presented methodology allows for the identification of the most favorable production conditions from various raw materials and presents a universal tool for estimating the cost of bioethanol production from various sources.

Table 9. Annual production costs of second-generation bioethanol from wood chips.

Costs	Ingredients Costs	Annual Production Costs EUR/year	Share in Total Costs %
Fixed costs	Amortization	13 220,0	3,1%
	Production space rental costs	19 154,9	4,4%
Sum of fixed costs		32 374,9	7,5%
Variable costs	Cost of wood	228 169,0	52,8%
	Labor cost	109 859,2	25,4%
	Water consumption cost	632,4	0,2%
	Electricity consumption cost	61 484,5	14,2%
Sum of variable costs		400 777,4	92,5%
Annual total production costs		433 152,3	100%

4. Conclusions

In the present study, an attempt was made to determine the cost-effectiveness of second-generation bioethanol from different raw materials. This fuel can be produced from wood waste from public or private forests, as well as from wood chips from energy willow or wood waste from the wood industry. The analysis carried out with the use of the expert mathematical method indicated that the most important factor that will determine the possibility of development of the production of second-generation bioethanol in Poland will be the availability of raw material from forestry waste or post-production waste of the wood processing industry. The share of this raw material in the hierarchy of significance of other raw materials that may be used for the production of second-generation bioethanol is 41 points (41%). This share is almost twice as high as the next most probable feedstock, maize, which has a share of 21 points (21%). According to experts, the least probable production of second-generation bioethanol is from catch crops, whose share in this ranking is only 7 points (7%). The optimum strategy for the production of second-generation bioethanol in Poland, in terms of the minimization of its production costs in a changing economic and social environment, from extremely unfavorable to extremely favorable, with the use of individual selection criteria, is the production of bioethanol from wood acquired from forests or its residues from the wood processing industry. The production of this fuel from the other raw materials analyzed is much less favorable in the production conditions under consideration; however, all four of these raw materials generate very similar costs for the production of second-generation bioethanol in Poland in the analyzed economic and social environment. Annual costs of production of second-generation spirit fuel with a production line capacity of 315 L/h amount to 433,152 EUR/year. The largest share in the structure of these costs is raw material costs, which constitute 52.82%, while the next items in the structure of these costs are labor costs at 25.36%. Therefore, a great deal of attention should be paid to the prices of the purchased raw material and optimizing labor costs. Unit costs of production of second-generation spirit fuel amount to 0.16 EUR/L, as calculated by the authors. As can be seen from the calculations presented above, these are not high costs, but they do not include various types of taxes that are imposed on this type of motor fuel and determine the final price of these fuels. Despite these factors, the presented production technology indicates significant competitive advantages in renewable energy sources utilization and cost-effectiveness during bioethanol production. Furthermore, a less energy- and labor-demanding process such as the one proposed, mainly achieved by the implementation of technological medium recovery and recirculation, reduces the production cost and results in higher production efficiency, and therefore has a significant effect on the overall process economy.

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