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COMPREHENSIVE ENVIRONMENTAL IMPACT ASSESSMENT OF THE PROCESS OF PREPARATION OF BIOETHANOL FUELS OF THE FIRST AND SECOND GENERATION

KOMPLEKSOWA OCENA ODDZIAŁYWANIA NA ŚRODOWISKO PROCESU PRZYGOTOWANIA PALIW BIOETANOLOWYCH PIERWSZEJ I DRUGIEJ GENERACJI*

The paper provides some information regarding comprehensive evaluation of the environmental hazard caused by the operation of automotive vehicles with internal combustion (IC) engines powered by bioethanol fuel. It presents the assumptions made for the life cycle assessment (LCA) of the environmental impact of fuel, carried out according to the Well-to-Wheel (WtW) method, where the fuel preparation stage, including the acquisition of raw materials as well as the production, transport, and distribution processes, and the vehicle operation stage are taken into account. The technologies and raw materials used to make bioethanol of the first and second generation have been presented and compared with each other. Results of research on greenhouse gas (GHG) emissions and non-renewable energy input in the process of preparation of bioethanol fuels of the first and second generation have been analysed. Nine versions of the production process, differing from each other in the process methods used and the types of the biomass processed, have been examined.

***Keywords**: bioethanol, Well-to-Wheel analysis, pollutant emission, fuel production technology.*

W pracy przedstawiono informacje na temat kompleksowej oceny zagrożenia środowiska przez eksploatację pojazdów samochodowych z silnikami spalinowymi zasilanymi paliwem bioetanolowym. Przedstawiono założenia analizy ekologicznej cyklu istnienia paliwa według metody Well–to–Wheel, uwzględniającej etap przygotowania paliwa, składający się z pozyskiwania surowców, wytwarzania, transportu i dystrybucji, oraz etap użytkowania pojazdów. Zaprezentowano i porównano technologie oraz surowce stosowane w wytwarzaniu bioetanolu pierwszej i drugiej generacji. Przeanalizowano wyniki badań emisji gazów cieplarnianych oraz zużycia energii ze źródeł nieodnawialnych w procesie przygotowania paliw bioetanolowych pierwszej i drugiej generacji. Rozważono dziewięć wariantów przebiegu procesu wytwarzania, różniących się zastosowaną technologią i rodzajem przetwarzanej biomasy.

***Słowa kluczowe**: bioetanol, analiza Well–to–Wheel, emisja zanieczyszczeń, technologia wytwarzania paliw.*

1. Introduction

Ongoing growth in the production of fuels from renewable sources, where bioethanol is particularly important as a fuel made on the largest scale [15], has been observed for many years. This trend has chiefly resulted from the striving for energy security of individual countries and from environmental protection issues, as the powering of internal combustion (IC) engines with fuels of biological origin (biofuels) may not only improve the environmental performance of such engines but also reduce the environmental loading with pollutants at the fuel production stage.

The former of the above two reasons for increasing interest in biofuels is related to the need that the world economy should be made independent of crude oil supplies because of limited fossil fuel resources and a danger connected with the fact that the power raw materials needed by a large part of the world are concentrated in a small group of countries, which in many cases are politically unstable at that. As regards the energy security, the availability and prices of fuels are of particularly great importance because of the mass use of IC engines. The situation where these factors strongly depend on the moods prevailing in the world markets is highly unfavourable. Therefore, it seems reasonable to pursue a policy of diversification of energy sources based on fuels made from biomass, which, in the form of agricultural products and waste, is much more easily available for many countries than crude oil.

Environmental protection problems make another, equally important reason for increasingly common tackling of the issue of biofuels. Public interest in the problems of harmful environmental impact of IC engines, or of motorisation in general, is very often limited to the consideration of anthropogenic reasons for global climate changes, and sometimes to mere balancing of the emission of greenhouse gases (GHG), especially fossil carbon dioxide. Meanwhile, the most important and simultaneously the most painfully felt effect of the use of IC engines is the immediate danger arising from the emission of pollutants that are harmful to health of the local population. The areas of large urban agglomerations, where high intensity of vehicle traffic and unfavourable conditions of dissemination of exhaust gases result in high levels of pollutant immissions, make an extreme example.

The increasing interest in the use of renewable energy carriers creates the need to compare them with each other for the optimum solution to be chosen. Regardless of economic factors, a matter of overriding importance is the evaluation of environmental properties of specific biofuel types. Efforts are made at the same time to minimise the impact of such

(*) Tekst artykułu w polskiej wersji językowej dostępny w elektronicznym wydaniu kwartalnika na stronie ***www.ein.org.pl*** fuels on the environment and the local population, with this impact being understood in a complex way instead of being limited to its single aspect only. Such an approach means the gaining of qualitative and quantitative knowledge of the environmental risks related to the fuel at every stage of its life cycle. So far, the methods most frequently used are limited to pollutant emission measurements carried out in laboratory conditions, on chassis dynamometers (for complete vehicles) or on engine test beds (for engines only), with tests of various kinds, both static and dynamic, being run. Normally, the tests provided in type-approval procedures are used, but this, in principle, does not give grounds for the formulation of conclusions about the engine performance in actual service conditions. Tests of this kind make it possible to carry out only comparative analyses of fuel consumption and pollutant emission effects, but the formulation of judgments on the inventorying of pollutant emissions and energy inputs is inacceptable at all. Therefore, a tool is needed that would enable evaluation of the whole fuel preparation process, covering not only the final pollutant emissions from a vehicle being in service but also the acquisition of raw materials needed for the fuel production as well as the transport and distribution of the fuel as a finished product. Such a tool is the "Well-to-Wheel" method, the name of which (often abbreviated as WtW) might be interpreted as "from the source (of an energy carrier) to the wheel (of a vehicle)". It is a particular case of the application of the Life Cycle Assessment (LCA) method [12, 16] to motor fuels.

The topic of the discussion presented herein is comprehensive evaluation of the pollutant emissions and energy inputs connected with the process of preparation of bioethanol of the first and second generation. The vehicle operation stage has been excluded from the scope of the discussion; this is because the knowledge of environmental properties of fuels with respect to the pollutant emissions during vehicle operation is much better than that related to the fuel preparation stage. The environmental benefits resulting from the powering of IC engines with bioethanol fuels, such as very big reduction of particulate matter and carbon monoxide emissions, significant reduction of the emissions of nitrogen oxides and hydrocarbons (including polycyclic aromatic hydrocarbons), very good biodegradability and possibility to reduce the emission of fossil carbon dioxide because of renewability of raw materials (the use of pure bioethanol result in zero emission of fossil carbon dioxide) are generally known [1 – 4, 14, 19]. While the effects of any changes possible to be introduced at the vehicle operation stage are usually quite small, much more benefits may be expected from the optimisation of the processes of production and distribution of energy carriers. In the case of bioethanol production, the use of cellulose waste in place of the traditionally used sugarcane and maize may result in a significant reduction of the environmental loading.

2. Assumptions made for the Well-to-Wheel analysis of environmental hazard

The Well-to-Wheel method may be defined as a quantitative and qualitative analysis of the possible environmental impact of the processes connected with the whole conventional life cycle of a fuel. This cycle is divided into two stages. The first one is the fuel preparation stage, which covers the acquisition of raw materials for energy carriers, fuel production, transport of the fuel as a finished product, and fuel distribution. In English, this stage is referred to as "Well-to-Tank" (abbreviated as WtT), which has the meaning "from the source (of an energy carrier) to the tank (i.e. the fuel tank of a vehicle)". The second stage is related to the vehicle operation and its English name is "Tank-to-Wheel" (abbreviated as TtW); it should be interpreted as "from the tank (i.e. the fuel tank of a vehicle) to the wheel (of the vehicle)" [5 – 7, 19]. A schematic diagram of the Well-to-Wheel analysis has been graphically presented in Fig. 1, with the energy losses at specific parts of the process having been additionally shown.

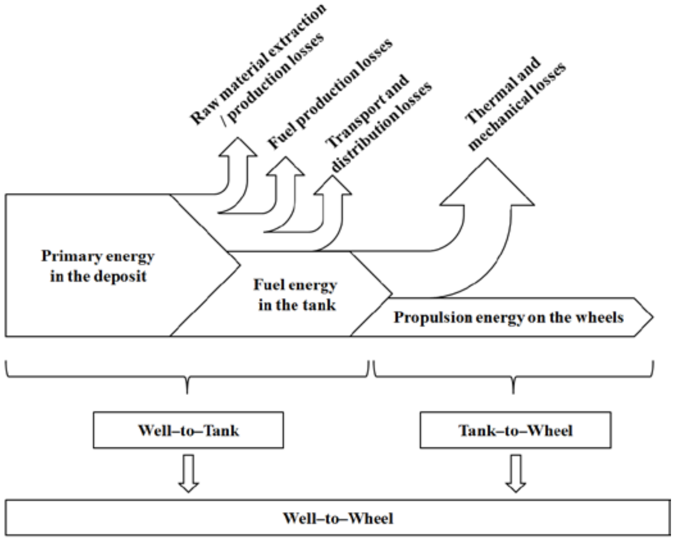

Fig. 1. Schematic diagram of individual stages of the Well-to-Wheel analysis

The Well-to-Wheel analysis is used to define and quantify the environmental loading resulting from the method of realisation of individual processes at every life cycle stage and then to evaluate this impact. These purposes are pursued by dividing successive stages into single processes (the whole scope of the analysis constitutes a "product system", i.e. a "fuel system" in this case), for which sets of input data (e.g. energy inputs, raw materials) and output data (e.g. products, intermediate products, waste, pollutant emissions) are determined. Thus, a material and energy balance is compiled, which is referred to as Life Cycle Inventory (LCI) [12, 16]. The necessary quantitative data are sourced in most cases from the economy sector and from the government administration bodies engaged in environmental protection. The analysis of this type produces highly valued results as it enables not only global assessment of the whole life cycle of a fuel but also separate evaluation of individual processes being parts of the life cycle.

The LCI analysis makes it possible to determine the values of cumulative pollutant emissions as obtained from the material balance, and cumulative energy inputs as obtained from the energy balance, in relation to a "functional unit" [12], e.g. 1 km of the distance covered by a vehicle or 1 MJ of energy contained in fuel.

The energy balance makes a basis for determining the amount of energy needed for the preparation of the fuel quantity consumed by the vehicle to travel a road section of unit length (expressed in [MJ/km] or [MJ/mi]) or the ratio of the fuel preparation energy to the energy contained in finished fuel (expressed in [MJ/MJ]) [6, 7, 19, 20].

The most popular environmental impact indicator is the total greenhouse gas (GHG) emission taken for the whole fuel life cycle. Specific gas emissions, with appropriate weights, are summed up to obtain the equivalent carbon dioxide emission (according to Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources):

$$m_{CO_2 eq} = \sum m_x \cdot w_x \qquad (1)$$

where: m_x – emission of substance "x";
w_x – potential share of substance "x" in the development of the greenhouse effect.

For selected substances, the "w_x" values are:

- Carbon dioxide – 1;
- Methane – 23;
- Dinitrogen monoxide – 296.

The emission of greenhouse gases is specified as mass emission of carbon dioxide equivalent, i.e. the mass of carbon dioxide equivalent in relation to the distance travelled by this vehicle (expressed in [g/km] or [g/mi]), or as an energy-related indicator of the emission of carbon dioxide equivalent, i.e. the mass of carbon dioxide equivalent corresponding to a fuel amount carrying 1 MJ of energy (expressed in [g/MJ]) [5 – 7, 19, 20].

The information obtained from the inventorying of pollutant emissions and energy inputs may be used for making comparisons between various fuel types; however, it cannot produce a full picture of the environmental impact of a specific fuel. Therefore, other indicators should additionally be taken into account where, based on results of the balance of inputs and outputs of individual processes, the said processes are considered accountable for specific environmental risks ("impact categories"), such as eutrophication, acidification, noise, vibrations, smog, electromagnetic radiation, dust, land-use change, depletion of the fossil fuel, mineral raw material, and water resources, climate changes, ozone layer depletion, etc. [12, 16]. Calculations of the impact of the fuel life cycle in the categories as mentioned above are made with the use of Life Cycle Impact Assessment (LCIA) methods, which include e.g. CML 2002, Eco-indicator 99, EDIP, EPS2000, Impact 2002+, LIME, LUCAS, MEEup, ReCiPe, Swiss Ecological Scarcity method, TRACI, or USEtox [9, 12, 16]. An unquestionable good point of these methods is a possibility to show a direct dependence between a process under consideration and the elements of the ecosystem affected by the process. On the other hand, much controversy is aroused by the subjectivity in the assessment proposed by individual methods, which leads to significant differences in the results obtained, even if identical input data are used.

In the European conditions, a popular Life Cycle Impact Assessment method is Eco-indicator 99 [5, 9, 12, 16]. It presents the environmental impact with the use of an "eco-indicator," in which environmental impact assessments in the following three damage categories are combined together:

- Damage to human health;
- Damage to ecosystem quality;
- Damage to resources.

The damage to human health is expressed in this method by the DALY indicator (Disability-Adjusted Life Year), which is a unit of measure of the impact of ill-health on the human being in terms of both the life time lost because of premature death (mortality) and the time lived in the state of disability (morbidity). This indicator is commonly used in health economy to define the state of health of a specific population, e.g. by the World Health Organization (WHO). In the Eco-indicator 99 method, models have been developed where respiratory diseases, tumours, climate change effects, ozone layer depletion (causing such diseases as cutaneous carcinoma or cataract), and harmful impact of ionising radiation have been taken into account and where the quantities measured include exposure to pollutants and pollutant immissions.

The damage to ecosystem quality is determined as the percentage of the species that vanish in a specific area due to the environmental impact of vehicles (i.e. the fuel production processes in the case under consideration). Here, such factors are taken into account as water and soil acidification and eutrophication, land-use change (e.g. deforestation), and "ecotoxicity", defined as the percentage of all the species present in the environment within a certain area and within a specific time interval and living under toxic stress (Potentially Affected Fraction or PAF).

In the third damage category, the resource depletion is assessed in terms of the quality of the remaining raw material resources, including petroleum-derivative fuels. It is determined as the increase in the energy to be spent for the extraction of 1 Mg of the raw material (expressed in [MJ/Mg]). In some cases, the scale of extraction of other chemical elements and compounds is considered.

In its final form, the eco-indicator is a figure that is the sum of the figures obtained for the three damage categories and weighted as appropriate.

A different approach has been adopted at the Swiss Ecological Scarcity method [5, 8], sometimes referred to as Ecoscarcity or UBP'06 (from German "*Umweltbelastungspunkte*") method. As it is in the case of the Eco-indicator 99 method, a few areas of the environmental impact of the product or process under investigation (e.g. the operation of an automotive vehicle) are taken into account. In this method, chiefly the pollutant emissions (with such factors as acidification and eutrophication, ozone layer depletion, etc.) and the use of natural raw materials are taken into account. The unique nature of this method lies in the determining of the difference between the current environmental loading in a specific area, i.e. "current flow," and the maximum acceptable loading defined by the existing legislative guidelines or political goals, referred to as "critical flow." The terms of "current flow" and "critical flow" have not been formalised yet; therefore, they should be understood as physical quantities that define the environmental impact of civilisation, e.g. pollutant immissions, mass emission, or specific brake emission of pollutants from internal combustion engines. According to the Swiss method, the result of the environmental impact assessment is presented in the form of an "eco-factor," the unit of which has been defined as the "eco-point" (EP) divided by the unit of measure of the polluting effect under consideration (for the GHG emissions, the eco-factor units would be [EP/g]). The eco-factor is calculated from the following formula [8]:

$$eco-factor = K \cdot \frac{1 \cdot EP}{F_n}\left(\frac{F}{F_k}\right)^2 \cdot c \qquad (2)$$

where: K – coefficient of relative harmfulness of the specific polluting effect;
F – current flow;
F_n – normalised flow;
F_k – critical flow;
c – constant.

Hence, the eco-factor may be defined as a measure of the potential environmental hazard imposed by a specific polluting effect. Its value rises with growing excess of the current emission or consumption of natural raw materials over the limits allowed. The coefficient of relative harmfulness of the polluting effect under consideration, present in the formula, is to adjust the calculation result by differentiating substances that exert more or less harmful environmental impact (as it is in the case of greenhouse gases). The current flow value is usually taken from the most recent statistical data available that concern the specific area.

The main good points of the Swiss Ecological Scarcity method are simplicity of calculations and direct relationship with the political targets and legislative limits that should be met in a specific area or country. This is the main difference between this method and the methods that are oriented at absolute evaluation of environmental damage (such as the Eco-indicator 99 method). On the other hand, however, the eco-factor values may only be determined for the substances for which any legislative limits or political targets actually exist.

In recapitulation of the discussion presented in this section and concerning the methods of comprehensive evaluation of motor fuels, two opposing trends can be identified. On the one hand, the scope of the Well-to-Wheel analysis should be as wide as possible, so that all the impact types are taken into account and their full environmental consequences are determined. On the other hand, however, the scope of the investigation should be unequivocally defined by introducing certain limitations and making specific assumptions for the comprehensive evaluation to be generally possible. In consequence, the obtaining of objective results is extremely difficult and the generalisation of conclusions may often lead to erroneous interpretation. Nevertheless, in the necessity of comprehensive evaluation of motor fuels and in consideration of the limitations presented, the use of the Well-to-Wheel method seems to be a reasonable solution.

3. Methods of production of bioethanol of the first and second generation

An unquestionable good point of bioethanol fuels is the possibility of obtaining such fuels from a wide range of raw materials. Based on the origin of the biomass used for the production, it has been agreed to divide biomethanol into the following "generations" [1, 14, 17, 18]:

- Biomethanol of the first generation, obtained from the raw materials that may be used in the food industry, e.g. maize, potato, rye, sugarcane, sugar beet, rice, and sweet sorghum; such materials contain monosaccharides (glucose, fructose), disaccharides (sucrose, lactose), or polysaccharides (starch);
- Biomethanol of the second generation, obtained from biomass rich in lignocellulose and from waste and by-products of the processing industry; the most important substrates include wood, grass, cane, straw, wood waste of the pulp and paper industry, cereal stover, maize cobs, waste of the milling and oil manufacture industries, used building timber, paper mill discards, municipal waste (dry part of the mass), molasses (by-product of sugar factories, rich in sucrose), and whey (lactose-containing waste of the milk processing industry).

At present, the world's most popular bioethanol production method is alcoholic fermentation with the use of microorganisms, chiefly yeast (*Saccharomyces cerevisiae*). In general, the biomethanol production process may be presented as consisting of three stages [11, 18]. The first one, referred to as saccharification, is the feedstock preparation process. It consists in preliminary hydrolysis to convert polysaccharides into monosaccharides. The second stage is the fermentation proper, which takes place in water environment under catalytic influence of the enzymes generated by the yeast. This process may be run periodically or continuously; the latter method is more efficient but requires a more complicated process system. The fermentation process is followed by the final stage, at which alcohol is separated by distillation. Thus, hydrated bioethanol is obtained, with about 5% water content. For the water content to be removed and, thus, anhydrous bioethanol (of more than 99% purity) to be obtained, a dewatering process should additionally be applied.

The most important differences between the processes of production of bioethanol of the first and second generation can be seen at the substrate preparation stage. The molasses and whey do not contain polysaccharides; therefore, they do not require any hydrolysis process to be carried out and they may be directly subjected to fermentation. The starch, which constitutes a reserve material in plants, is easily hydrolysed under the influence of enzymatic preparations. Lignocellulose as a structural material of plant cells is more resistant to the action of hydrolysing agents. It is a complex of three polymers, i.e. cellulose, hemicelluloses, and lignin of various chemical compositions bonded together with covalent and hydrogen bonds [10, 17, 18]. In this case, preliminary treatment of the feedstock is necessary to separate cellulose and hemicellulose from lignin, which is a macromolecular aromatic compound with no saccharide contents and, as such, does not undergo fermentation. In this process, acid hydrolysis, chiefly with the use of sulphuric acid, or enzymatic hydrolysis is employed. The latter method makes it possible to achieve high process efficiency and is now being developed, with the development work being aimed at a reduction in the high enzyme acquisition cost [10, 17, 18].

4. Environmental impact assessment of the process of preparation of bioethanol of the first and second generation

In this paper, selected results of evaluation of the environmental loading caused by the stage of preparation (Well-to-Tank stage) of bioethanol of the first and second generation have been presented and compared with each other. The numerical data have been taken from Swiss sources [11, 20] and they are predominantly related to the bioethanol production methods employed in that country, except for the bioethanol production from sugarcane (in Brazil), maize (in the USA), sweet sorghum (in China), and rye (in general European conditions). The scope of the analysis covers the activities related to plant growing, biomass conversion into alcohol in a production facility, transportation of bioethanol to filling stations, and distribution of the fuel to end-users. Nine versions of the production process, differing from each other in the types of the biomass processed and in the corresponding process methods used, which are now practically worldwide used and are reasonably cost-effective, have been examined. Three examples represent biofuels of the second generation, obtained from wood, grass, and whey. Additionally, corresponding results obtained for gasoline have been provided for comparison. The following symbols have been adopted:

- EtOH–Wo – bioethanol obtained from wood;
- EtOH–Gr – bioethanol obtained from grass;
- EtOH–Wh – bioethanol obtained from whey;
- EtOH–SB – bioethanol obtained from sugar beet;
- EtOH–SC – bioethanol obtained from sugarcane;
- EtOH–SS – bioethanol obtained from sweet sorghum;
- EtOH–MC – bioethanol obtained from maize;
- EtOH–Po – bioethanol obtained from potato;
- EtOH–Ry – bioethanol obtained from rice;
- G – gasoline.

The Well-to-Tank analysis has been based on inventorying the set of input and output data concerning the materials and energy that are involved in a specific process and exert an impact on the environment [20]. If a bioethanol production process results in the generation of by-products such as electricity, Dried Distillers Grains with Solubles (DDGS), or sugarcane bagasse then the allocation of emissions and energy inputs is based on estimated market prices of such products (it is proportional to the respective prices) [13]. However, other factors, of economic and social nature, have not been taken into account. Only the direct environmental impact (material and energy balance) has been calculated, with the side effects having been ignored (while e.g. the cultivation of plants for ethanol production on an area previously used for the growing of plants for food production purposes results sometimes in the necessity to import some food products from abroad, which entails additional transport activities). For the bioethanol made in Brazil, China, and the USA, the cost of transportation of finished fuel to Europe has been taken into account.

Results of calculations of the total amount of energy obtained from non-renewable sources and necessary to prepare bioethanol and gasoline carrying 1 MJ of energy (at the WtT stage) have been shown in Fig. 2.

The input of energy obtained from non-renewable sources and used for the bioethanol production in all the versions examined is significantly lower than the consumption of energy used for the production of gasoline. The highest figures, ranging from 0.9 to 1 MJ/MJ, have been recorded for the making of bioethanol from maize, potato, and rye. In the other cases, the level of 0.5 MJ/MJ has not been exceeded. The relatively high consumption of non-renewable energy at the production of bioethanol from maize in the American conditions results from significant quantities of fossil fuels used for the operation of agricultural machinery; for the bioethanol obtained from potato and rye, the high energy consumption is caused by low eco-

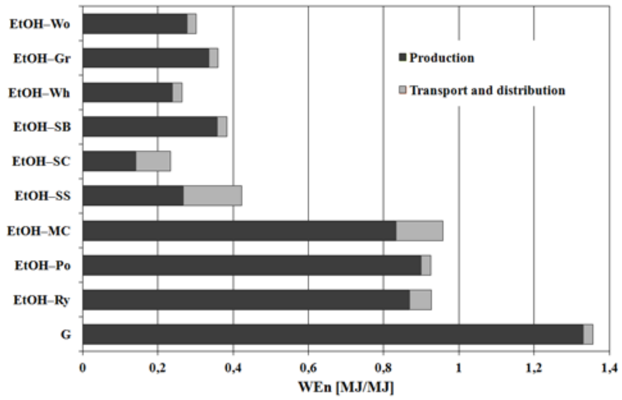

Fig. 2. Total amount of non-renewable energy used to prepare fuel of 1 MJ energy content

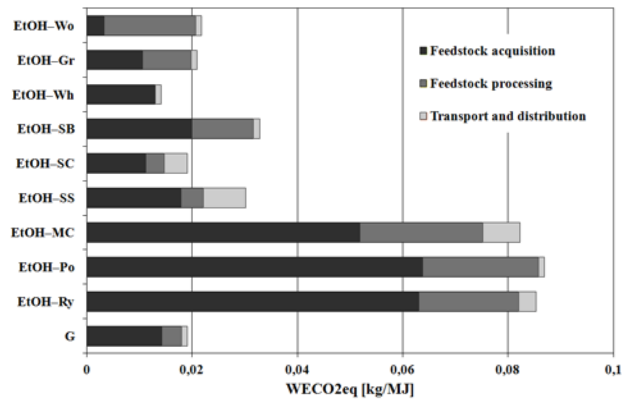

Fig. 3. Energy-related GHG emission indicator determined for the stage of preparation of the fuels under consideration

nomic value of the by-products and low rye yield per a unit area. The lowest consumption of energy obtained from non-renewable sources has been recorded for the preparation of bioethanol from sugarcane, which has resulted from high plant yield per a unit area thanks to good weather conditions in Brazil and, simultaneously, from the fact that a significant part of the energy needed for the production process has been sourced from the combustion of bagasse, which is a by-product of sugarcane processing. The low consumption of non-renewable energy at the production of sweet sorghum may be explained in a similar way; however, the amount of energy needed to transport finished fuel from China to Europe is higher than that in the case of Brazil. The very good result recorded for the production of bioethanol from whey (below 0.3 MJ/MJ) is explainable by the fact that, according to the allocation principles, bioethanol is accountable for as little as 20% of the energy input of the whole process while the predominating part is assigned to the by-products of high protein contents. The consumption of non-renewable energy for bioethanol production from wood and grass fell within the range of (0.3 ÷ 0.4) MJ/MJ and only slightly exceeded that recorded for bioethanol obtained from sugarcane, which is cultivated in the warm climate areas of Brazil with employing the well-developed mass production methods. In comparison with the European technologies (where potato, rye, and sugar beet are used) and with the Chinese and American solutions, bioethanol of the second generation offers a possibility of significant reduction in the consumption of energy obtained from non-renewable sources.

Results of the GHG emission balance in the form of an energy-related emission indicator determined for the bioethanol and gasoline preparation (WtT) stage have been presented in Fig. 3. The following three sub-stages have been singled out: feedstock acquisition (plant cultivation or crude oil extraction), fuel production, and fuel transport inclusive of distribution at filling stations. As it can be seen, a decisive role is played in most cases by the agricultural production. Local production of fuel in the country where the fuel is to be actually used will result in a significant reduction of the transportation emissions. As it happened in the case of the findings concerning the consumption of non-renewable energy at the fuel preparation stage, the highest indicator values have been obtained for the bioethanol production from maize, potato, and rye and the lowest figures are associated with whey and sugarcane. Only for the two latter materials, the results obtained are close to, or better than, those determined for gasoline. Slightly higher values of the energy-related GHG emission indicator have been found for the bioethanol preparation from wood and grass, although the biomass sources used at the fuel production technologies under consideration were mixed and significantly diversified, as they included energy plantations, forests, meadows of various types (natural and intensively fertilised) and, to a smaller extent, wastes. If exclusively the use of waste biomass were taken into account, the GHG emission at the feedstock acquisition stage could be fully eliminated.

Figs. 4 and 5 show a comparison between results of the environmental impact assessment of the process of preparation of bioethanol fuels and gasoline, determined with the use of two methods, i.e. the Swiss Ecological Scarcity method and the Eco-indicator 99 method, and presented in the form of eco-factor and eco-indicator values, respectively. Each of the methods, in accordance with its own scale, assigns a specific score corresponding to the environmental loading that results from the preparation of a fuel amount consumed by a vehicle to travel a distance of 1 km. Among the bioethanol fuels, the least harmful environmental impact at the WtT stage is exerted by biofuels of the second generation, obtained from whey, wood, and grass. For the bioethanol obtained from Brazilian sugarcane, a significant environmental risk is posed by the pre-harvest field burning, which translates into higher values of the impact assessment indicators. The biofuel preparation processes of the worst environmental performance are those where potato, maize, or rye is used as the feedstock. The outstandingly high eco-indicator value obtained from the Eco-indicator 99 method for rye is connected with the significant, for European conditions, land use degree; the high score given by the Swiss Ecological Scarcity method to the use of potato as the feedstock stems from soil contamination with fertilisers and pesticides.

The environmental impact assessment characteristics of the fuels under consideration in the eco-factor vs. energy-related GHG emission indicator coordinate system have been presented in Fig. 6.

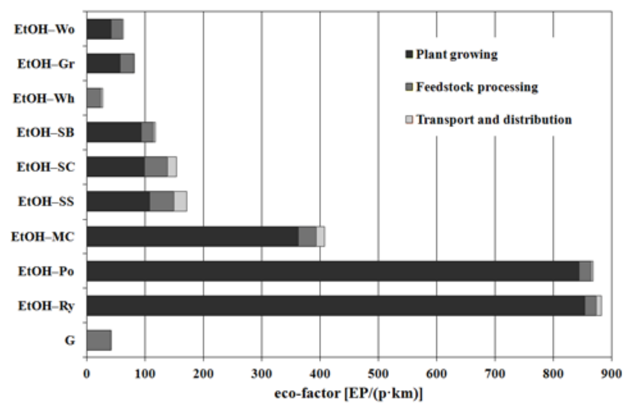

Fig. 4. Environmental impact assessment of the fuel preparation processes as obtained from the Swiss Ecological Scarcity method

The points corresponding to specific fuels provide information about the emission of greenhouse gases and about the comprehensive environmental impact assessment of the whole fuel preparation (WtT) process carried out to the Swiss Ecological Scarcity method. Bioethanol fuels of the first and second generation and gasoline have

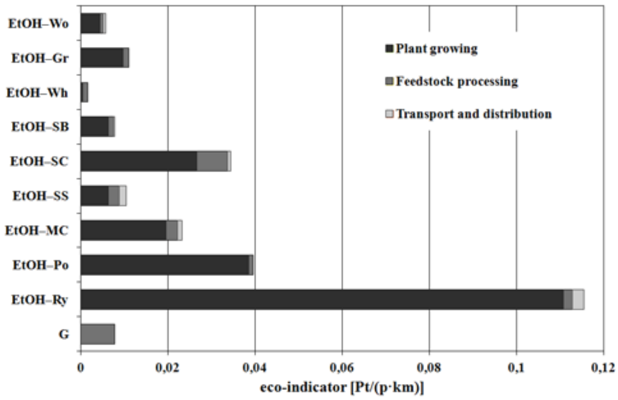

Fig. 5. Environmental impact assessment of the fuel preparation processes as obtained from the Eco-indicator 99 method

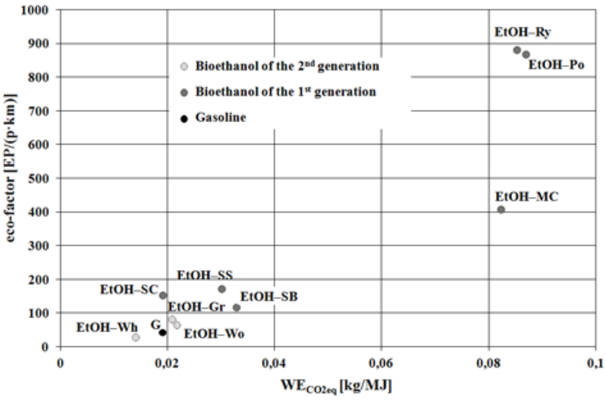

Fig. 6. Comparison between the energy-related GHG emission indicator and eco-factor values determined for the processes of preparation of the fuels under consideration

been indicated by green, red, and black colour, respectively. Based on an analysis of the research results, a statement may be made that for most of the bioethanol production options under consideration, the fuel preparation stage produces a higher environmental loading than that observed for gasoline. It should be stressed, however, that gasoline shows very unfavourable environmental properties at the fuel use (TtW) stage, especially a very high emission of fossil carbon dioxide [4 – 7, 19, 20]. As regards the bioethanol fuels, the technologies of making bioethanol of the second generation from whey, wood, and grass have been found to be the least harmful to the environment, in general terms.

5. Recapitulation

In connection with the fact that the use of fuels obtained from renewable energy sources becomes increasingly popular, a need arises to assess pollutant emissions and energy inputs in a comprehensive way, with taking into account not only the vehicle operation stage but also the whole fuel preparation process. Among the biofuels used now to power IC engines, bioethanol fuel takes the largest share in the world market [15]. This results from numerous ecological advantages of bioethanol, especially the possibility to reduce the emissions of pollutants harmful both to local populations and global ecosystem and the flexibility of bioethanol production technologies in respect of the raw materials used, such as edible plants with saccharide contents used for the production of biofuels of the first generation and lignocellulose and other wastes for the production of biofuels of the second generation.

Based on the discussion presented here, the following conclusions may be formulated on the comprehensive environmental impact assessment of the process of preparation of bioethanol fuels of the first and second generation:

1. For the assessment of pollutant emissions and energy inputs at the bioethanol preparation stage, the most important factor is the technology employed, especially the type of the biomass used as the feedstock.
2. The process of obtaining bioethanol of the second generation causes significantly lower environmental loading than it is in the case of bioethanol of the first generation. Additionally, zero pollutant emissions at the biomass acquisition stage may be achieved by exclusive use of waste raw materials sourced from e.g. the wood processing or paper industry rather than biomass acquired from the so-called energy plantations.
3. The technology of making biofuels of the second generation must be further developed and optimised towards the achieving of high process efficiency. A top priority task is the development of a method to reduce the costs of production of enzymatic preparations used at the lignocellulose hydrolysis process.
4. Thanks to the use of the Well-to-Wheel method, both qualitative and quantitative environmental impact assessment of the whole conventional life cycle of motor fuels is possible. Nevertheless, the assumptions and limitations imposed by the adopted scope of the analysis must be taken into account for the interpretation of the analysis results to be correct.
5. An important issue is the selection of comprehensive indicators of environmental loading, i.e. the selection of evaluation criteria. While the inventorying of pollutant emissions and energy inputs is based on simple principles of material and energy balancing, the existing life cycle impact assessment (LCIA) models show significant subjectivity.

The discussion presented supports the thesis that the use of bioethanol of the second generation makes it possible to gain clearly visible environmental benefits at the fuel production stage. Undoubtedly, the future of biofuels lies in the technologies of this kind, where waste raw materials and by-products are utilised.

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