

Properties of substitute motor fuels produced from ethanol in biorefineries

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The article presents the definition of bioindustry, in particular biorefinery. The technology for obtaining synthetic fuel EtG (Ethanol to Gasoline) in a plant using bioethanol from food waste was presented. The physicochemical properties of EtG fuel were presented. EtG fuel stands out due to its limited content of benzene and sulfur and a low content of mechanical impurities and heavy metals. EtG fuel can be considered a replacement fuel for motor gasoline. The results of exhaust emissions tests from vehicles with spark-ignition engines in the WLTC test on a hot and cold engine were presented. It was found that EtG fuel is characterized by lower specific distance emissions of CO, NO_x and CH₄ and slightly higher specific distance emissions of NMHC when starting a cold engine compared to gasoline, while the specific distance emission of CO₂ for both fuels were very similar

Key words: *biorefinery, substitute motor fuels, bioethanol, ethanol to gasoline*

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1. Introduction

Due to the increasingly intense expectation to develop rationalization of the use of available energy carriers and raw materials to meet the needs of societies while ensuring the needs of the environment, new production methods are being sought. This role is played by the so-called bioindustry. An integrated bioindustry is an industry that uses a spectrum of techniques to obtain products such as chemicals, bio-based fuels, food, feed ingredients, biomaterials, and usable energy, taking into account the three pillars of sustainability: environment, economy, and society.

There are many possibilities for using types of biologically derived raw materials [1–4, 6–9, 13–17, 19–23, 25].

The article [1] reviews the current state of knowledge about algae biofuel as a renewable energy source.

Article [2] describes current challenges and opportunities to sustainably increase biomass production and highlights future technologies to further improve the production of biofuels directly from sunlight. It was postulated that in order to objectively assess the environmental impact of the use of fuels of biological origin, it is necessary to conduct LCA tests.

Publications [3, 25] present a comprehensive review of the catalytic conversion of bioethanol to hydrocarbons – gasoline components. A great potential of this technology was found.

The studies [4, 22, 23] present the Global Biorefinery Status Report (GBRSR), published by the IEA Bioenergy Task 42 Biorefinery. The report provides an overview of the latest developments in biorefinery. The report compiles data and information reported by representatives of partner countries and member states in the National Reports of Task 42 Biorefinery.

The publication [7] contains systematic information on the biorefinery system as a basic element of sustainable civilization development.

Articles [6, 14, 16, 17] are dedicated to future technologies aimed at further improving the production of fuels of biological origin directly from sunlight – the so-called "synthetic biology". Particularly, great hopes are associated with

the use of microorganisms for this purpose. The current progress in hybrid technologies (biomass production, wastewater treatment, reduction of greenhouse gas emissions) enables the effective production of first-class products, such as, above all, renewable fuels.

Article [21] provides an overview of techniques developed to valorize biomass for the production of platform chemicals in a biorefinery and the status of commercialization. Biomass is treated as a way to constantly deplete limited fossil resources, the use of which is attributed to an adverse impact on the environment.

The article [8] analyzed the problems of biorefinery systems according to the criteria: technology, raw materials, and products. Attention was paid to the possibility of obtaining products with versatile uses in biorefineries, e.g. not only renewable fuels, but also animal feed.

The study [13] presents an existing biorefinery in Venice, created as a result of the transformation of a conventional oil refinery in which HVO fuel (Hydrotreated Vegetable Oil) is produced. The article also presents the parameters of this new biofuel and compares them with the parameters of other fuels used to power compression-ignition engines, such as FAME (Fatty Acid Methyl Esters) and diesel oil, and discusses the prospects for the development of HVO fuels in Europe.

The publication [20] presents the balance of fuel consumption in the United States of America. It has been found that in the last few decades, the consumption of transport fuels corresponds to about 1/3 of all energy consumed, of which about 90% comes from fossil sources, which is a serious ecological problem.

The paper [19] presents basic information on the metabolic engineering of microorganisms for the production of fourth-generation biofuels. The fourth-generation fuel production technology is presented as a fundamental pro-ecological contrast to earlier technologies.

Monograph [9] is dedicated to the use of methane fuels to power the internal combustion engines of city buses. The work presents a systematic classification of methane fuels, distinguishing renewable fuels produced from biogas.

The article [15] highlighted the great possibilities of using bioethanol as an oxygen component for conventional gasoline to power spark-ignition engines. It was found that in modern spark-ignition engines, it is possible to use gasoline with the addition of ethanol up to 30% V/V as a fuel treated as a substitute fuel, thus not requiring changes in the design, materials used, and control algorithms of combustion engines.

The use of biofuels of biological origin is the subject of many publications [2, 9–12, 15, 18, 26]. In most cases, significant ecological benefits related to pollutant emissions were found.

The publication [9] describes the results of research on pollutant emissions from spark-ignition engines powered by methane fuels intended to power city buses. The tests were performed on an engine dynamometer in static and dynamic homologation tests. A significant reduction in emissions of carbon monoxide, hydrocarbons and nitrogen oxides was found, and – obviously in relation to compression-ignition engines originally used to power city buses – a particularly significant reduction in particulate matter emissions.

Paper [10] presents the results of research on the combustion process in a compression-ignition engine powered by diesel oil and methyl esters of rapeseed oil with summer and winter additives. The aim of the research was to assess whether, due to the properties of the combustion process, it is justified to treat rapeseed oil methyl esters as substitute fuels for diesel oil. It was found that the tested biological fuels meet these requirements, especially fuel with summer additives.

In publication [11], the emission of pollutants from a compression-ignition engine used in a passenger car was examined in driving tests. The sensitivity of pollutant emissions to the concentration of rapeseed oil methyl esters in the mixture with diesel oil was tested. A significant reduction in road emissions of carbon monoxide, hydrocarbons and, especially, particulate matter was found thanks to the use of rapeseed oil methyl esters.

The publication [12] presents the results of tests on pollutant emissions from combustion engines powered by bioethanol fuels: E95 for compression-ignition engines and E85 for spark-ignition engines. It was found that the use of bioethanol fuels compared to conventional fuels reduces emissions of carbon monoxide, hydrocarbons and nitrogen oxides, and in the case of compression-ignition engines – an additional significant reduction in particulate matter emissions.

The study [15] examined the emission of pollutants from internal combustion engines powered by mixtures of gasoline and ethanol in driving tests starting with a cold engine. A beneficial effect of the use of ethanol on pollutant emissions when starting a cold engine was found.

The publication [18] examines the emission of pollutants from compression-ignition engines powered by mixtures of diesel oil with esters of biological oils and esters of biological oils and bioethanol. Confirming the beneficial effect of bio-additives on the emission of pollutants harmful to the health and life of living organisms, the authors focus mainly on reducing fossil carbon dioxide emissions.

Paper [2] presents the results of tests on a spark ignition engine powered by gasoline with a mixture of biological additives. The tests were performed on an engine dynamometer in static conditions. The beneficial effect of the use of oxygen additives on pollutant emissions has been confirmed.

Publication [26] presents the results of empirical research and tests of the developed mathematical model of a marine engine powered by a mixture of diesel oil and n-butanol. Benefits in terms of pollutant emissions were found when using biological additives to power the engine. The results of empirical research confirmed the adequacy of the developed mathematical model.

Perspectives of advanced biofuels development, including using ethanol as a raw material, were described in Global biorefinery status report 2022 by IEA Bioenergy [4, 22].

One of the products of the bio-industry used to power internal combustion engines is fuel called EtG (Ethanol to Gasoline), which is a substitute fuel for gasoline for spark ignition engines.

The results of empirical research on the use of biological additives to conventional fuels confirm the benefits in terms of the emission of pollutants harmful to the health and life of living organisms and – which is obvious – a reduction in bituminous carbon dioxide emissions.

There are relatively few publications on the use of biologically derived fuels as substitute fuels to power internal combustion engines. Such fuel for spark-ignition engines is EtG fuel, which is a hydrocarbon fuel made from bioethanol. For these reasons, this study deals with comparative studies of pollutant emissions from the engine of a passenger car fuelled with commercial gasoline and EtG synthetic fuel.

2. EtG fuel (Ethanol to Gasoline)

EtG is a fuel produced from renewable sources, which has functional properties corresponding to those of motor gasoline. EtG fuel meets the quality requirements specified in the Regulation of the Minister of Economy of December 17, 2010 and can be added to gasoline as a biocomponent intended for the fuels used in spark-ignition engines.

The most important advantages of producing and using EtG fuel are as follows:

- EtG fuel is produced from renewable sources. The biomass used in the bioethanol production process comes from waste raw materials (i.a. waste bread). The production and use of EtG fuel enables the achievement of the National Indicative Target and the National Reduction Target in gasoline fuels at the level provided for by EU directives for 2020–2030 or even higher. EtG fuel therefore meets the criteria of sustainable development.
- The EtG fuel production process does not require a large amount of energy from external sources. This is facilitated by the possibility of using raw (unpurified) alcohol in the production process of EtG fuel. The low energy consumption of the EtG fuel production process results in reduced greenhouse gas emissions. Table 1 shows the parameters of the EtG fuel.

Table 1. Parameters of EtG fuel

Parameter	Unit	Result
Density at the temperature 15°C	kg/m ³	761.1
Appearance	–	bright and transparent
Vapour pressure (dry vapour pressure equivalent)	kPa	57.0
N-paraffins	% V/V	11.44
I-paraffins	% V/V	32.59
Olefins	% V/V	1.95
Naphthenes	% V/V	7.60
Aromatic hydrocarbons	% V/V	41.84
Polycyclic hydrocarbons	% V/V	0.31
Not specified	% V/V	4.27
Oxygen derivatives	% V/V	0.00
Oxygen	% m/m	0.00
Benzene	% V/V	0.30

3. Research methodology

Empirical tests of the effects of using EtG fuel were carried out on a chassis dynamometer in accordance with the WLTP type 3 [5, 24].

The research equipment used in the tests met the formal requirements of the approval procedures.

The object of the research was a passenger car – a Hyundai i30 with a spark-ignition engine (Euro 6AP level). The vehicle was fuelled by motor gasoline and EtG fuel. Tests were performed to start a cold and hot engine.

4. Results of empirical research

The specific distance emissions of CO, NMHC, CH₄, NO_x, CO₂, and operational fuel consumption are presented in Fig. 1–12.

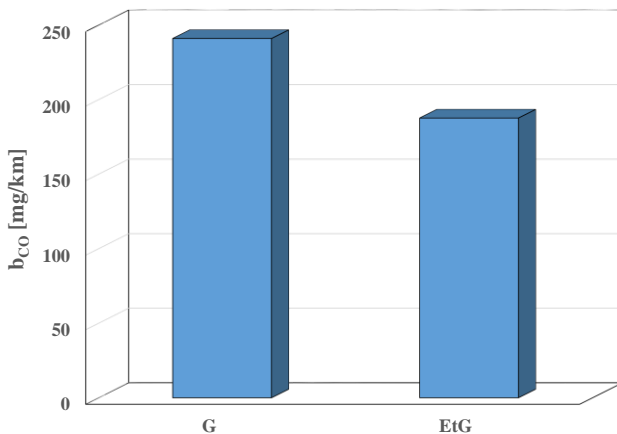


Fig. 1. The CO specific distance emission – b_{CO} when the vehicle is fuelled with gasoline – G and EtG for cold start

Specific distance emission of CO in the cold start is lower for EtG (187.7 mg/km) than for motor gasoline (241 mg/km). The difference in road carbon monoxide emissions is over 50 mg/km (Fig. 1).

The situation is similar for starting a hot engine: when powered by petrol, specific distance emissions of CO is over 73.4 mg/km, and when powered by EtG fuel – about 46.6 mg/km. The absolute difference is over 26 mg/km, but the relative difference is larger when the engine is hot (Fig. 2).

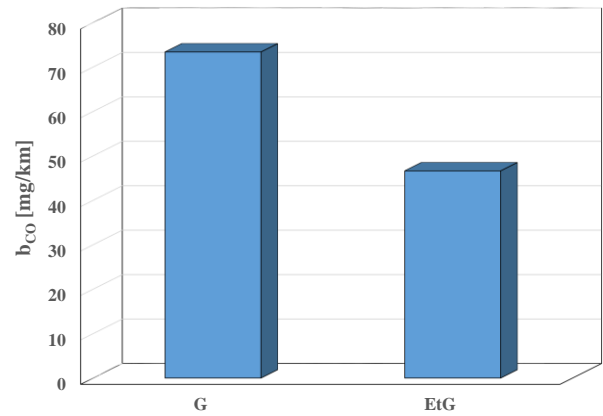


Fig. 2. The CO specific distance emission – b_{CO} when the vehicle is fuelled with gasoline – G and EtG for hot start

The impact of the thermal condition of the engine at start-up on carbon monoxide emissions is very significant.

In the case of emissions of organic compounds, the emissions of non-methane hydrocarbons and methane are examined.

For NMHC specific distance emissions in the cold start test (29.6 mg/km) are higher when the engine is fuelled with EtG fuel (39.0 mg/km). The difference is significant – almost 10 mg/km (Fig. 3).

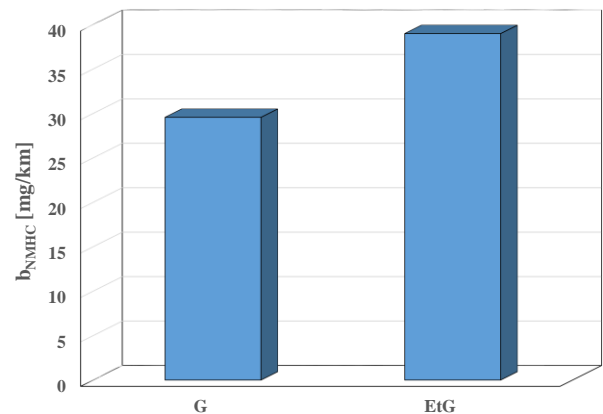


Fig. 3. The NMHC specific distance emission – b_{NMHC} in the WLTC test when the vehicle is fuelled with gasoline – G and EtG for cold start

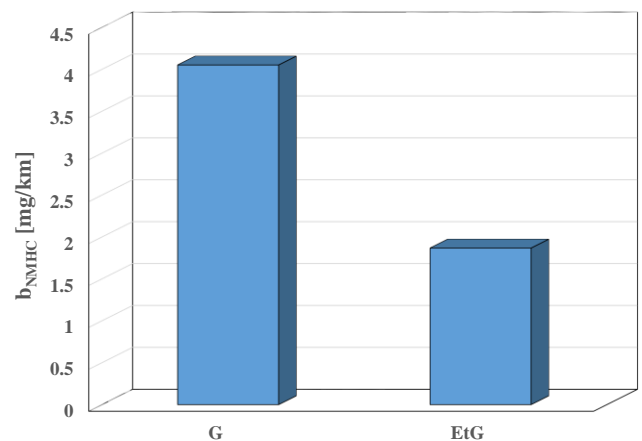


Fig. 4. The NMHC specific distance emission – b_{NMHC} when the vehicle is fuelled with gasoline – G and EtG for hot start

It is different for the hot start of the engine – the specific distance emission of non-methane hydrocarbons for motor gasoline is 4.1 mg/km, and EtG fuel is 1.9 mg/km. In this case the difference is over 2 mg/km (Fig. 4). The thermal condition of the engine during its start-up has a very large influence on the test results, more than in the event of carbon monoxide emissions. The thermal condition of the engine during its start-up in the event of EtG fuel has a particularly remarkable influence on the test result.

Specific distance emissions of CH₄ in the cold engine start test (6.2 mg/km) are much lower for EtG fuel (2.2 mg/km). The difference is approximately 4 mg/km (Fig. 5).

The dissimilarity in specific distance emission of CH₄ in the test with a hot engine start is even greater. For motor gasoline, this emission is almost 4.5 mg/km, and for EtG fuel – about 0.2 mg/km (Fig. 6).

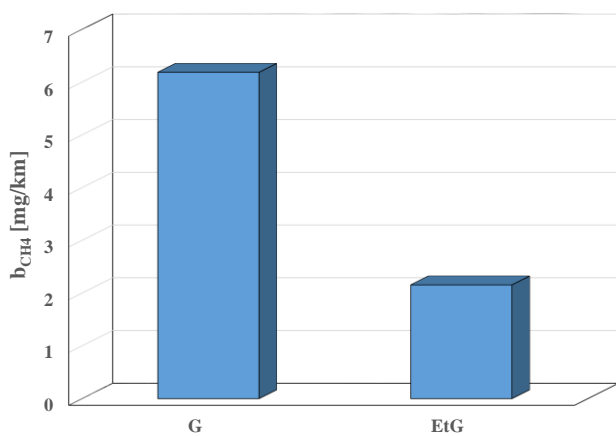


Fig. 5. The CH₄ specific distance emission – b_{CH_4} when the vehicle is fuelled with gasoline – G and EtG for cold start.

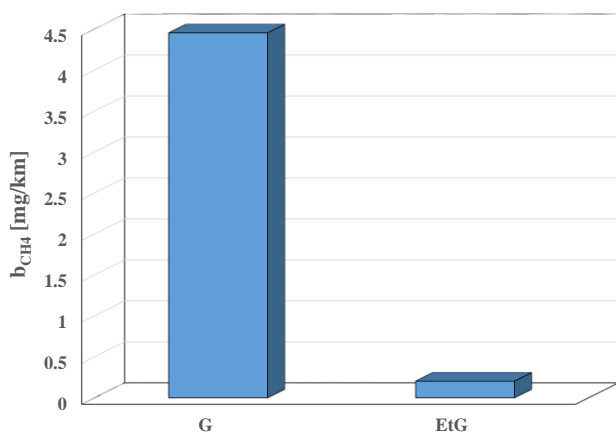


Fig. 6. The CH₄ specific distance emission of methane – b_{CH_4} when the vehicle is fuelled with gasoline – G and EtG for hot start

The influence of the thermal condition of the engine during its start-up is much greater for specific distance emission of CH₄ when the engine is fuelled with EtG fuel. In general, the influence of the thermal condition of the engine during its start-up on specific distance emission of organic compounds is greater for non-methane hydrocarbons than for methane.

The specific distance emission of NO_x in the cold start test is about 1.5 mg/km higher for motor gasoline (13.1 mg/km) than for EtG fuel (11.7 mg/km), so the difference is small (Fig. 7).

The difference in specific distance emission of NO_x during hot start-up is even smaller – this difference can be assessed as insignificant: 5.2 mg/km for motor gasoline and 5.0 mg/km for EtG fuel (Fig. 8).

The influence of the thermal condition of the engine at start-up on specific distance emission of nitrogen oxides is much smaller than in the event of CO, especially biocompounds.

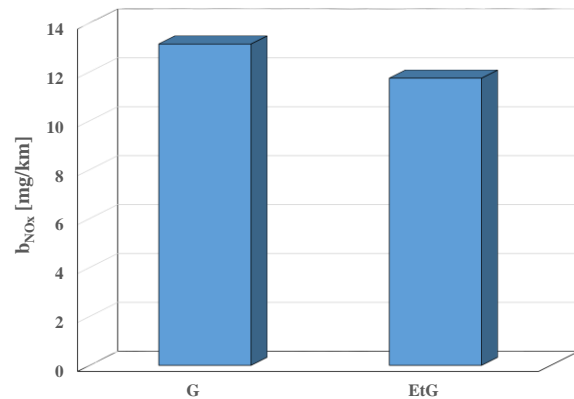


Fig. 7. The NO_x specific distance emission of nitrogen oxides – b_{NO_x} when the vehicle is fuelled with gasoline – G and EtG for cold start

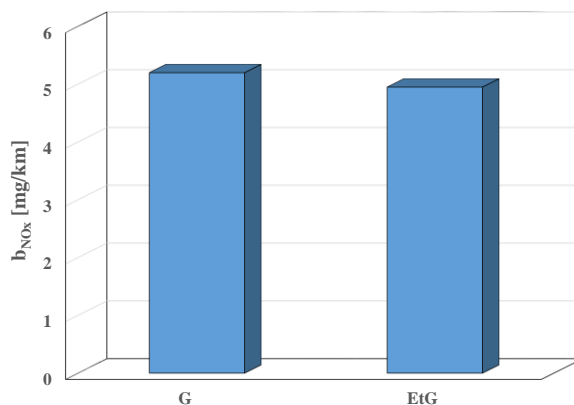


Fig. 8. The NO_x specific distance emission – b_{NO_x} when the vehicle is fuelled with gasoline – G and EtG for hot start

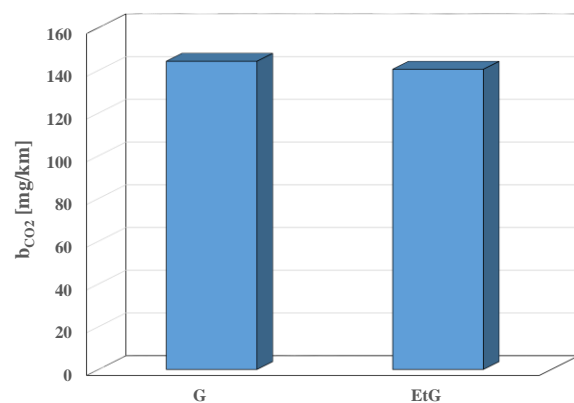


Fig. 9. The CO₂ specific distance emission – b_{CO_2} when the vehicle is fuelled with gasoline – G and EtG for cold start

The specific distance emission of CO₂ when starting a cold engine is slightly higher for motor gasoline (Fig. 9).

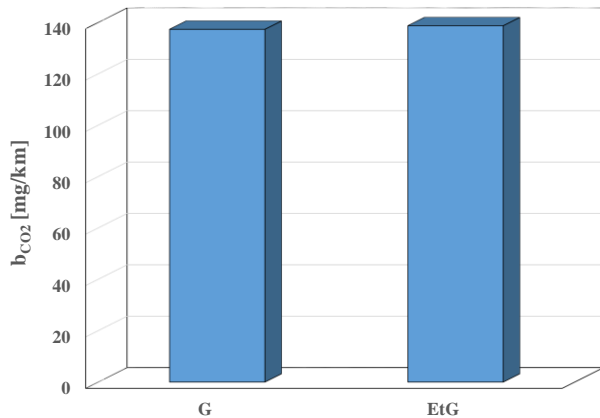


Fig. 10. The CO₂ specific distance emission of carbon dioxide – b_{CO2} in the WLTC test when the vehicle is fuelled with gasoline – G and EtG for hot start

In the case of a hot start-up, it can be estimated that the specific distance emission of CO₂ is similar for both tested fuels (Fig. 10).

The engine’s thermal condition at the start of the engine has a very small influence on the specific distance of CO₂ emission.

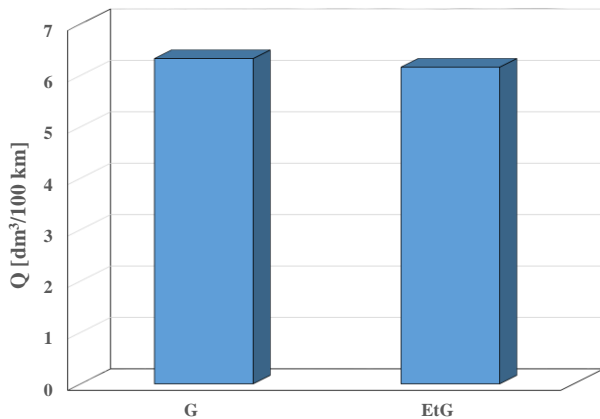


Fig. 11. The operational fuel consumption – Q when the vehicle is fuelled with gasoline – G and EtG for cold start

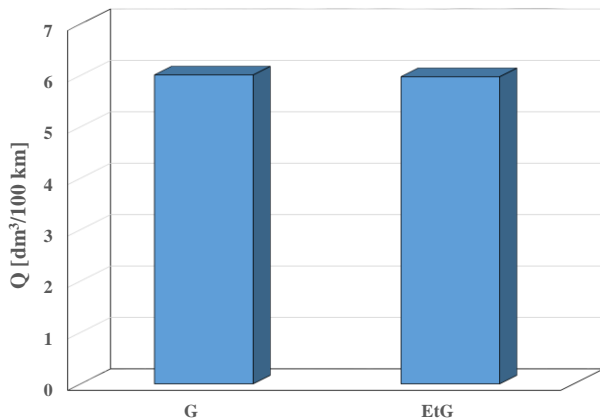


Fig. 12. The operational fuel consumption – Q when the vehicle is fuelled with gasoline – G and EtG for hot start

The dependence for operational fuel consumption is practically identical to those for specific distance emission of CO₂ (Fig. 11, 12).

The relative decrease of the value of physical quantity "w" for the use of EtG fuel in relation to the value for the use of gasoline is defined as follows:

$$\delta = -2 \cdot \frac{w_{EtG} - w_G}{w_{EtG} + w_G} \quad (1)$$

Based on the empirical research conducted, the conclusions are as follows:

- The use of EtG fuel causes a relative reduction in specific distance emissions of the following pollutants for cold start compared to the use of motor gasoline:
 - carbon monoxide 24.9%
 - methane 96.6%
 - nitrogen oxides 11.2%
 - carbon dioxide 2.6%
 - and operational fuel consumption 2.7%.
- The use of EtG fuel causes a relative increase in specific distance emission of NMHC for hot start compared to the use of gasoline by 27.5%.
- The use of EtG fuel causes a relative reduction in specific distance emissions of the following pollutants for hot start compared to the use of gasoline:
 - carbon monoxide 44.6%
 - non-methane hydrocarbons 73.8%
 - methane 182.5%
 - nitrogen oxides 4.9%
 - carbon dioxide –1.0%
 - and operational fuel consumption 0.6%.
- The use of EtG fuel causes a slight relative increase in specific distance emission of CO₂ with hot start-up compared to the use of gasoline by approximately 1%.
- The greatest impact on pollutant emissions is caused a cold engine start for NMHC, CH₄, CO, and NO_x. The relative change in specific distance emissions is for:
 - non-methane hydrocarbons for EtG fuel about 180%
 - non-methane hydrocarbons for gasoline about 150%
 - methane for EtG fuel over 170%
 - for carbon monoxide for both fuels over 100%
 - for nitrogen oxides for both fuels almost 100%.

In general, it can be stated that the use of bioethanol fuel instead of gasoline to power a spark ignition engine brings ecological benefits in terms of emissions of pollutants harmful to health and fossil carbon dioxide emissions.

5. Summary

In the summary of the article, the conclusions are as follows:

- The production of non-petroleum fuels in biorefineries is an important element of energy safety. There is also an important aspect of protecting natural resources.
- An important benefit is that biorefinery fuels are produced from waste products that pose a serious threat to the environment.
- The production of fuels in biorefineries is characterized by low energy consumption – this is an economic bene-

- fit, and it also results in a reduction in greenhouse gas emissions.
4. In general, it can be stated that the use of EtG instead of gasoline to power a spark ignition engine brings ecological benefits in terms of pollutants and fossil carbon dioxide emissions.
 5. EtG fuel is characterized by extremely low content of benzene, sulfur, and nitrogen, mechanical impurities, and the content of heavy metals is below the limit of the test method determination. This has significant environmental impacts related to eutrophication and acidification.
 6. EtG fuel is not the only product of the biorefinery installation. This process also produces biopropane and bio-

butane, which can be used as biocomponents or self-contained biofuels.

Further directions of planned research on the properties of ethanol fuels include:

- tests in real vehicle driving conditions, including: in RDE tests,
- tests in model vehicle traffic conditions, significantly different in nature, typical for driving: in traffic jams, in cities outside traffic jams, on roads outside cities and on highways and expressways,
- tests in various engine operating states, both static and dynamic.

Nomenclature

b	specific distance emission
CH ₄	methane
CO	carbon monoxide
CO ₂	carbon dioxide
EtG	Ethanol to Gasoline
NMHC	non-methane hydrocarbons
NO _x	nitrogen oxides

Q	operational fuel consumption
w	value of physical quantity
WLTC	Worldwide harmonized Light vehicles Test Cycle
WLTP	Worldwide harmonized Light vehicles Test Procedure
δ	relative reduction

Bibliography

- [1] Alam F, Mobin S, Chowdhury H. Third generation biofuel from algae. *Procedia Engineer*. 2015;105:763-768. <https://doi.org/10.1016/j.proeng.2015.05.068>
- [2] Andrych-Zalewska M, Sitnik L, Sroka Z, Mihaylov V. Fuel with a higher content of bio components in greenhouse effect aspects. *Combustion Engines*. 2023;192(1):36-42. <https://doi.org/10.19206/CE-147741>
- [3] Anekwe IMS, Isa YM, Oboirien B. Bioethanol as a potential eco-friendlier feedstock for catalytic production of fuels and petrochemicals. *J Chem Technol Biot*. 2023;98:2077-2094. <https://doi.org/10.1002/jctb.7399>
- [4] Annevelink B, Chavez LG, van Ree R, Gursel IV. Global biorefinery status report 2022. In *IEA Bioenergy: Task 42 Biorefining in a Circular Economy*. IEA Bioenergy. <https://www.ieabioenergy.com/wp-content/uploads/2022/09/IEA-Bioenergy-Task-42-Global-biorefinery-status-report-2022-220712.pdf> (accessed on 24.08.2023).
- [5] Annex XXI to Commission Regulation (EU) 2017/1151 as last amended by Commission Regulation (EU) 2018/1832. <https://www.legislation.gov.uk/eur/2018/1832/adopted>
- [6] Aro EM. From first generation biofuels to advanced solar biofuels. *Ambio*. 2016;45:24-31. <https://doi.org/10.1007/s13280-015-0730-0>
- [7] Biernat K, Grzelak P. Biorefinery systems as an element of sustainable development, biofuels – status and perspective. *InTech*. 2015. <https://doi.org/10.5772/60448>
- [8] Cherubini F, Jungmeier G, Wellisch M, Willke T, Skiadas I, Van Ree R et al. Toward a common classification approach for biorefinery systems. *Biofuel Bioprod Bior*. 2009;3(5): 534-546. <https://doi.org/10.1002/bbb.172>
- [9] Chłopek Z, Gis W, Menes E, Waśkiewicz J. The study of the use biomethane to the supply city buses in Poland. *Motor Transport Institute*. Warszawa 2013.
- [10] Chłopek Z, Jagiełło S, Juwa S, Zakrzewska D. Examination of the combustion process in a compression ignition engine fuelled with diesel oil and rape methyl esters. *The Archives of Automotive Engineering – Archiwum Motoryzacji*. 2017;76(2):17-35. <https://doi.org/10.14669/AM.VOL.76.ART1>
- [11] Chłopek Z, Grzelak P, Zakrzewska D. Evaluation of the influence of car engine power supply with rapeseed oil esters on emission of pollutants in dynamic conditions. *Machine Dynamics Research*. 2018;47(4):55-71.
- [12] Chłopek Z. Ecological aspects of using bioethanol fuel to power combustion engines. *Ekspluat Niezawodn*. 2007;35: 65-69. <https://archive.ein.org.pl/2007-03>
- [13] Grzelak PL, Żółtowski A. Environmental assessment of the exploitation of diesel engines powered by biofuels. *Combustion Engines*. 2020;180(1):31-35. <https://doi.org/10.19206/CE-2020-105>
- [14] Ho S-H, Ye X, Hasunuma T, Chang J-S, Kondo A. Perspectives on engineering strategies for improving biofuel production from microalgae: A critical review. *Biotechnol Adv*. 2014;32(8):1448-1459. <https://doi.org/10.1016/j.biotechadv.2014.09.002>
- [15] Iodice P, Langella G, Amoresano A. Ethanol in gasoline fuel blends: Effect on fuel consumption and engine out emissions of SI engines in cold operating conditions. *Appl Therm Eng*. 2018;130:1081-1089. <https://doi.org/10.1016/j.applthermaleng.2017.11.090>
- [16] Jungmeier G, Hingsamer M, van Ree R. Biofuel-driven biorefineries. A selection of the most promising biorefinery concepts to produce large volumes of road transportation biofuels by 2025. *IEA Bioenergy – Task 42 Biorefinery*, February 2013. <https://task42.ieabioenergy.com/publications/biofuel-driven-biorefineries/>
- [17] Maity JP, Bundschuh J, Chen C-Y, Bhattacharya P. Microalgae for third generation biofuel production, mitigation of greenhouse gas emissions and wastewater treatment: present and future perspectives: a mini review. *Energy*. 2014;78: 104-113. <https://doi.org/10.1016/j.energy.2014.04.003>

- [18] Mofijur M, Rasul MG, Hyde J, Azad AK, Mamat R, Bhuiya MMK. Role of biofuel and their binary (diesel-biodiesel) and ternary (ethanol-biodiesel-diesel) blends on internal combustion. *Renew Sust Energy Rev.* 2016;53:265-278. <https://doi.org/10.1016/j.rser.2015.08.046>
- [19] Moravvej Z, Makarem MA, Rahimpur MR. The fourth generation of biofuel (Chapter 20). *Second and Third Generation of Feedstocks. The Evolution of Biofuels.* 2019;557-597. <https://doi.org/10.1016/B978-0-12-815162-4.00020-3>
- [20] Rosentrater KA. Production and use of evolving corn-based fuel ethanol coproducts in the U.S. *Biofuels – Status and Perspective.* InTech. 2015. <https://doi.org/10.5772/59951>
- [21] Takkellapati S, Li T, Gonzalez MA. An overview of biorefinery-derived platform chemicals from a cellulose and hemicellulose biorefinery. *Clean Technol Envir.* 2018;20:1615-1630. <https://doi.org/10.1007/s10098-018-1568-5>
- [22] Van Dyk S, Su J, McMillan JD, Saddles JN. Drop-in biofuels: The key role that co-processing will play in its production. IEA Bioenergy. Task 39. 2019. <https://www.ieabioenergy.com/wp-content/uploads/2019/09/Task-39-Drop-in-Biofuels-Full-Report-January-2019.pdf> (accessed on 15.12.2022).
- [23] Van Ree R, Annevelink E. Status Report Biorefinery 2007. November 2007. <http://www.wur.nl> (accessed on 31.10.2022).
- [24] Worldwide emissions standards passenger cars and light duty vehicles. Delphi. Innovation for the real world. 2022/2023.
- [25] Xiang H, Xin R, Prasongthum N, Natewong P, Sooknai T, Wang J et al. Catalytic conversion of bioethanol to value-added chemicals and fuels: a review. *Resour Chem Mater.* 2022;1(1):47-68. <https://doi.org/10.1016/j.recm.2021.12.002>
- [26] Zacharewicz M, Kniaziewicz T. Model tests of a marine diesel engine powered by a fuel-alcohol mixture. *Combustion Engines.* 2022;189(2):83-88. <https://doi.org/10.19206/CE-143486>

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