

Fuel with a higher content of bio components in greenhouse effect aspects

ARTICLE INFO

Transport is an energy-intensive sector of the economy and it is important where energy comes from and how it is used – now and in the future. The presented research results seem to encourage further work, despite the fact that the work had the character of basic research. The results were achieved in idealized conditions by the fact that the internal combustion engine was tested in static conditions on the test bench and the fuels contained components with strictly defined parameters. These conditions are different from everyday life. However, the obtained results seem to be valuable as they lead to conclusions regarding biofuels, and these conclusions are not directly formulated and published in the literature on the subject. The general conclusion from the research carried out is that the introduction of the so-called biofuels can contribute not to the reduction of CO₂ emissions, but to its faster balancing in the environment. This balancing can be achieved but at the cost of increased fuel consumption. This increase in fuel consumption would probably not occur if the "bio" components in the fuel were synthetic hydrocarbons obtained from biomass. However, proving it requires wider studies, including LCA. Data for this LCA, especially about a fuel consumption, may be coming from long term operation of vehicles.

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1. Introduction

The global problem is the concentration of CO₂ in the atmosphere which lead to the greenhouse effect. The general problem is that the concentration of CO₂ in the ambient air is too high and is constantly increasing. This trend must be reversed. A number of quick measures should be taken to reduce the amount of CO₂, which in many cases is associated with the simultaneous reduction of emissions of CO₂ and other compounds – mainly harmful to health. Therefore, reducing CO₂ emissions has many benefits. Road transport is one of a major contributor to CO₂ emissions. As a consequence, the car industry is forced to reduce it [1, 27].

And this means (as is commonly believed) that the problem of CO₂ emissions from transport could be solved immediately if the energy used today and in the future comes from renewable sources [1, 28].

But the world's problem is not CO₂ emissions, but the increasing concentration of CO₂ in the atmosphere, leading to the acceleration of the greenhouse effect. It seems that understanding this problem is not obvious. Confirmation of this observation results from the analysis of various forecasts for the development of transport and energy sources for its supply. For example in Fig. 1 shows historical and forecast energy consumption for the United States by 2050 [1].

But the world's these projections (Fig. 1) show that by 2050 the demand for petroleum fuels will change by approx. 10%, but after the initial decline (until 2035) there will be another increase in demand, which will result in a total decrease of this demand from 2020 to 2050 only by approx. 7.5%. According to this forecast, the minimum demand for petroleum fuels will occur around 2036 and this demand will be similar to what it was in 2008.

The forecasts (for USA) also show that the maximum share of biofuels (approx. 4%) is achieved now, and will

practically not change by 2050 (but today the bio-components concentration in fuels, in EU for example, there is up to 10%).

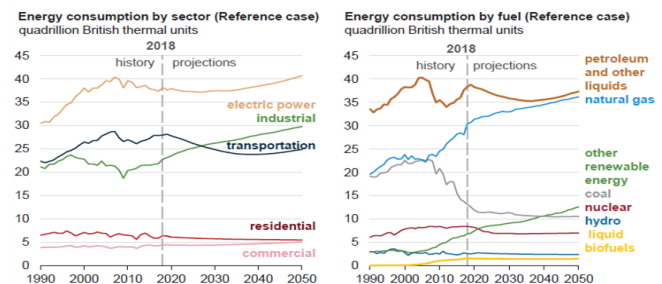


Fig. 1. Historical and projection models of energy and fuel consumption by economy sector in the USA [1]

The forecast of the total consumption of crude oil and other fluids and biofuels shows that the share of biofuels in the fuel blend first will increase (until around 2035) and then decrease. It seems that the increase in the share of bio components is rather unexpected. There is an "old school" opinion (example [2]), that "The share of renewable transport fuels is minimal and most of those supplied to date (biodiesel) do more harm than good". Other point of view is that up to 2030, advanced biofuels will not make a sizeable contribution and will be constrained in the medium term by land availability for achieving of "renewable power" to produce this kinds of fuels.

One could agree with this and similar opinions, were it not for the fact that the raw material for the production of bio components is not only biomass from industrial plants. The real raw material for the production of bio components on a large scale is municipal solid waste (MSW), of which there is an excess of which around the world will increase [3].

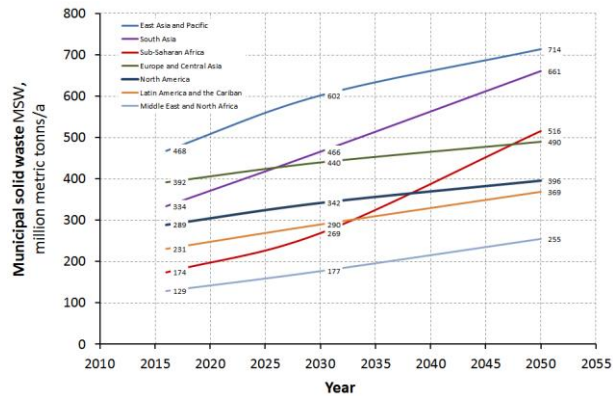


Fig. 2. Municipal waste now and in forecasts (data from [3])

Municipal solid waste (MSW) can be transformed to many fuel components (or fuel). Nowadays a popular technology is achieving from MSW a butanol [4–5]. This technology is relatively simple therefore the find more and more interest. Municipal solid waste can also be converted into synthetic gas (syngas) [6–8], and then into synthetic hydrocarbons that can be used as fuel or fuel components.

Regarding today's practice, there are three basic ways to reduce CO₂ as follows [9].

- The use of alcohols (first of all the ethanol) and their mixtures with petrol (in Europe, for example, the B10 petrol has a 10% ethanol by volume in petrol) [10].
- The use of fatty acids esters (methyl or ethyl esters) of vegetable oils and their mixtures with diesel fuel (nowadays B7 in EU has 7% FAME by volume in commercial diesel fuel) [11–14].
- The use of synthetic hydrocarbons produced from synthesis gas coming from biomass and their mixtures with standard hydrocarbons [15–17].

The article presents another method of obtaining fuel from bio components. For this purpose, a mixture of light and heavy alcohols was used as an additive to fuels for a spark ignition (SI) engine. On the use of alcohols, as fuel components, exist a many papers e.g. [18, 19] but in this work we wanted to conduct research with multi-component fuels, but such that each component had precisely defined composition and properties. Therefore, we used isooctane as the base. Research with the use of isooctane, as a fuel base, has been described in various publications, and the characteristic is, for example.

In [20] studies were conducted to evaluate the effect of mixing iso-octane with ethanol on ignition delay times (IDT). The results showed that the IDT of ethanol/isooctane mixtures decreased with the ethanol ratio and pressure, and decreased with increasing temperature. It has been shown that a large number of active OH groups generated by the added ethanol shorten the IDT of the fuel blend.

In [21] three test fuels were used in the study, namely isooctane, ethanol and n-butanol. The macroscopic spray characteristics and the droplet size distribution of the sprayed liquid were measured. The results showed that properties such as surface tension, fuel density and viscosity, saturation temperature, and latent heat of vaporization play a very important role in the penetration of the fuel plume. Isooctane showed the shortest penetration lengths

while butanol showed the longest penetration length. Alcohol sprays consisted of larger diameter droplets.

In [22] the main purpose of this study is to understand the effect of fuel properties on atomization. This was quantified by the length of the liquid penetration and the spray angles. The stream shape was determined for fuel mixtures containing isooctane, hexane and ethanol. The results showed that the addition of ethanol or hexane to isooctane can promote vigorous boiling. The ethanol blend sprays showed sharper boiling compared to the hexane blend sprays. Shorter liquid penetration and better liquid-ethanol dispersion were observed. Compared to the isooctane spray, the droplet size decreased steadily with increasing hexane content. Sprays with ethanol mixtures showed a different trend [22].

In [23] were investigated the size and velocity of the liquid droplets upon impact against the wall. The spray was fed with methanol, ethanol, isooctane, toluene reference fuels (TRF) and gasoline. The results show that in the case of free atomization of methanol, ethanol and TRF, the droplet velocity is lower and the droplet size is larger compared to gasoline fuel. Falling droplets are larger and reflected droplets are smaller compared to free spray droplets. The droplet diameters of ethanol fuel are smaller, and the crushing effect upon hitting a wall is better than that of isooctane fuel.

In [24] the authors concluded that, the petroleum-derived gasoline is the most commonly used fuel for propelling vehicles (especially passenger cars). Its substitutes are sought. Until now, single components or binary mixtures (n-heptane/isooctane) were usually used as substitutes for gasoline in investigations. In the last decade, however, there has been rapid progress in the creation and use of ternary mixtures (n-heptane/isooctane/toluene), as well as multi-component mixtures with hydrocarbons having carbon numbers of C4–C10. The concept of using oxidized components (ethanol, butanol, MTBE, etc.) accelerated research into such compositions. The conclusion is that despite the progress in research into the combustion of alternative fuels for gasoline, there are still serious gaps in knowledge on this subject.

Alcohol components such as butanol and ethanol are considered alternatives to conventional gasoline due to their lower emissions and their renewable nature [25]. This article explores the spray structures and atomization of butanol, ethanol and isooctane. The results clearly show two phases of the stream development; initial (phase 1) and main (phase 2). The developed phase cone angles for butanol and ethanol are consistently stable, while isooctane exhibits relatively large fluctuations. The highest value of the cone angle is observed for ethanol, while butanol shows the lowest. Higher injection pressure leads to a smaller cone angle for any fuel. In phase 2, All three components exhibit consistently smaller droplet sizes in phase 2 compared to phase 1. The higher injection pressure helps isooctane to reduce the droplet size while allowing butanol and ethanol to produce a more uniform stream.

An empirical model of ignition retardation for fuel mixtures of n-heptane, toluene, ethanol and isooctane was developed in [26]. This model has been successfully validated based on the published experimental data on ignition retar-

ation, two-component, three-component and quaternary fuel blends with the above-mentioned components.

2. Research methodology

The main aim of the research, for this article topics, was to clarify whether the addition of bio components must be accompanied by an increase in fuel consumption and whether adding such additives makes sense due to the greenhouse effect.

The article presents research on the use of three-component fuels. The isooctane was mixed with the two alcohols, light (ethanol) and heavy (n-butanol). All three components have a strictly defined chemical composition and properties. Their mixture does not contain any additives improving the fuel. This is a rare situation in research. Typically, tests are performed using a hydrocarbon fuel as the base. This base usually cannot be strictly defined chemically. This makes it much more difficult to evaluate the results obtained.

The main properties of the ingredients used in the tested here fuel mixtures can be found on the websites.

The composition of the mixtures was made in accordance with the mathematical design of the experiment. The variables in the study are the shares of mixture components, which add up to 100%. Experimental design such as Simplex-Lattice and Simplex-Centroid were used.

Assessed was the impact of :

- x_1 – isooctane (EC: 208-759-1) concentration
- x_2 – ethanol (EC: 200-578-6) concentration
- x_3 – butanol (EC: 200-751-6) concentration

as independent variables of mixture components.

The engine was tested on the standard test bench (equipment with standard devices for dynamic fuel consumption and emission measurement.

For each blends, the universal characteristics of the engine were determined (torque and power as function of engine speed in rpm).

On basis of this data was next the minimum of brake specific fuel consumption (BSFC_{min}) for each blends calculated.

It is unexpected that the BSFC_{min} position for each blend, in relation to the torque, changes slightly, while in relation to rpm it changes within quite wide limits. There will be a further discussion on the reason for such phenomena. If the minimum of BSFC for each blend is known, then it will be possible to find which blend provides the lowest BSFC. This question can be answered with relevant use of a mathematical model. Such model be found (as result of owner investigations), and here is presented as:

$$BSFC_{min} = 235.75 x_1 + 334.5 x_2 + 291 x_3 + 130 x_2 x_3 \quad (1)$$

$$x_1 + x_2 + x_3 = 1 \quad (2)$$

For this model the correlation coefficient equals to $R^2 = 0.9678$.

By searching for minimum of the function (1) can be found

$$x_1 = 1, x_2 = 0, x_3 = 0 \quad (3)$$

From formula (1) it shows that the lowest specific fuel consumption is achieved by supplying the engine with

isooctane. The addition of any alcohol or simultaneously of both alcohols to this fuel, leads to an increase in BSFC.

3. Tests results and discussion

The presented data (based on the data from the works [27, 28]) were somewhat surprising. The addition of low energy components was expected to increase the specific fuel consumption. These expectations were confirmed. However, it was not expected that the increase would be as radical as, for example, in the case of the 3V mixture, when the increase in BSFC_{min} by almost 37% was recorded. This result is different confirmed by the literature data. For example in [29] The experiment was conducted in a spark ignition engine to investigate the effects of gasoline components on fuel consumption, combustion and emissions. Isooctane was chosen as the base fuel. Short-chain, medium-chain and long-chain alkanes, ethers and aromas were appropriately blended with isooctane. The results show that the aromas contribute to fuel economy. 20% toluene (C₇H₈) mixed with isooctane shows a relatively lower BSFC. Short chain alkanes (C_nH_{2n+2}) show great potential for improving fuel economy, e.g. a blend of 20% n-pentane mixed with isooctane. In contrast, 20% methyl tert-butyl ether (C₅H₁₂O) mixed with isooctane shows a higher BSFC value. Therefore blending with hydrocarbons shows lower BSFC and with oxygen content components lead to higher BSFC.

In [30] are described a comparative analysis of the combustion process, emissions and performance of the PFI SI engine fueled with mixtures of methanol, ethanol and butanol with gasoline. Gasoline and butanol blends showed lower BSFC for higher LHV.

The effect of blending of gasoline with butanol isomers on the combustion and emission characteristics of the PFI SI engine was investigated and described also in [31]. The mixtures accounted for 70% of the volume gasoline and 30% vol. butanol isomers (N30, S30, I30 and T30). Compared to gasoline, all butanol isomeric mixtures have higher cylinder pressure. and the T30 has a higher specific fuel consumption (BSFC).

Acetone-butanol-ethanol (ABE) is an intermediate in the fermentation process for the production of bio-butanol [32]. This product is considered to be a promising alternative fuel. Pure gasoline and ABE blends have been prepared, ranging from 0% to 80% vol. ABE. ABE blending showed an increase in (BSFC); while measurements of exhaust gas temperature and nitrogen oxide emissions show that ABE burns at a lower peak temperature (which is less important due to the widespread use of three-way catalysts in SI engines.

One such alternative fuel may be gasoline-alcohol blends. The work [33] analyzes the operation of the S.I. with variable compression ratio. The mixtures tested in this study were butanol and ethanol in proportions of 10, 20, 30 and 40 percent in gasoline. The thermal efficiency of the brake and the specific fuel consumption (BSFC) were compared for the composed mixtures and for different compression ratios and loads. It was found that the Brake Thermal Efficiency was observed to increase and the BSFC to decrease. The results show that the engine runs smoothly up to 40 percent of the component content, and at this content, its maximum efficiency was found.

It is relatively difficult to draw clear conclusions from this short presentation of the results. Undoubtedly, any mixture of combustible components, if only they can be made into a liquid that can be burned in the engine, changes all combustion parameters, emissions and performance. The only question is whether there is any common denominator of these activities and whether conclusions can be drawn from such studies that will be a guide to the development of fuels useful for achieving the intended goals, e.g. pro-ecological. At what cost (eg increase or decrease of fuel consumption) this will be achieved. This paper is an attempt to answer the presented problems.

Even more interesting values were obtained by analyzing the unit energy consumption in each gram of fuel.

Because the tested fuels consisted of chemicals with strictly defined properties, it was possible to determine calorific value for each blend. Since $BSFC_{min}$ values are known, it was still possible to determine the values of the minimum of specific energy consumption – $BSEC_{min}$. These values are given respectively. This also gives the percentage deviation $BSEC_{min}$ at engine running with each tested fuel in relation to isooctane supplying.

Data on $BSFC_{min}$ and $BSEC_{min}$ are additionally shown in Fig. 3.

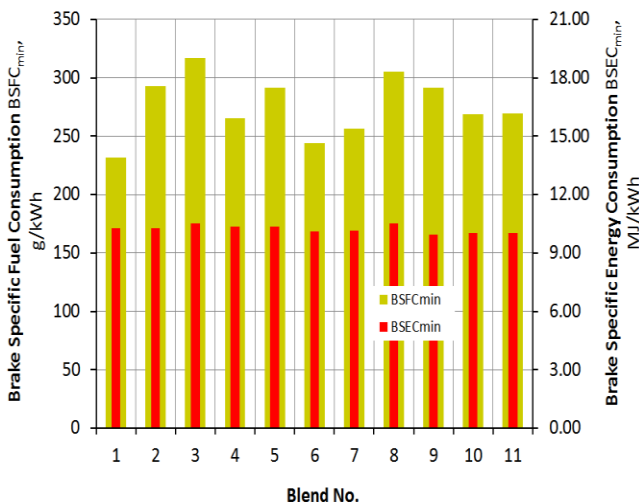


Fig. 3. $BSFC_{min}$ (higher bars – in yellow) and $BSEC_{min}$ (lower bars – red) vs. mixtures

The presented data shows that regardless of the fuel composition, the amount of energy consumed by the engine is quasi constant. It is obvious that with each $BSFC_{min}$ the engine had almost identical torque (Fig. 6). This torque was achieved at various engine speeds. Burning any type of fuel is a chemical reaction. If there are many reactants, each burns at a different rate – which in the case of an internal combustion engine means practically different speeds. Hence the deviations of this speed with $BSFC$ minima from the data on the deviation of $BSEC$ minimum when feeding the engine with tested fuels in relation to its supply with isooctane, it shows that these deviations ($D BSEC$) – do not exceed a few percent, which can be considered as being within the measurement error (up to 5%). If the composition of blends and the corresponding $BSFC_{min}$ value are

taken into account, the resulting data can be represented as shown in Fig. 4.

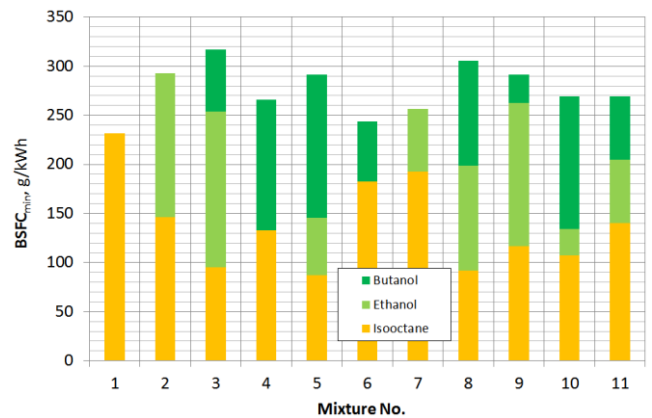


Fig. 4. $BSFC_{min}$ by each blends

One of the main goal of this study was showing the influence of bio-components contained in engine fuel, on the possibility of the greenhouse effect reduction. All the mixtures, used in the tests, contained carbon and hydrogen, and moreover those with alcohol(s) content also oxygen. In CO_2 emissions, only the carbon content is important, independent of its sources, but for greenhouse effect lowering, the source of carbon in CO_2 (renewable or non-renewable), is primary important.

Assuming that the alcohols come from renewable sources and the isooctane comes from crude oil, that is, from non-renewable sources, the use of alcohol additives should reduce the greenhouse effect (with CO_2 as the main influencing factor). Since, as already mentioned, chemically pure components with specific properties were used for the tests, the mass of carbon in each mixture can be calculated. Such calculations were made and the results are shown in Fig. 5.

If one compares $BSEC$ (Fig. 4) with the content of carbon and hydrogen plus oxygen in fuels (Fig. 6), it can be seen that there is a convergence between $BSEC$ and C_{TOTAL} and at the same time there is no relationship between $BSEC$ and $H_2 + O_2$.

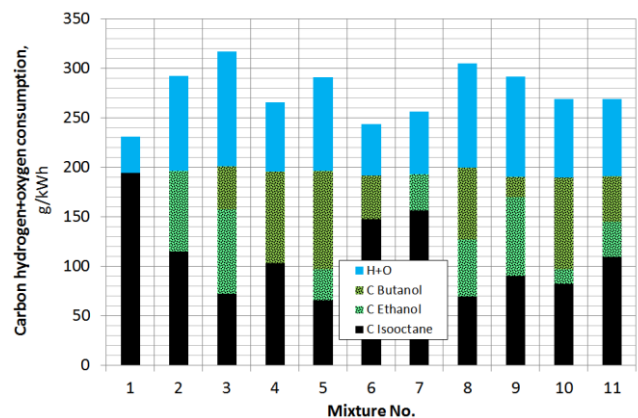


Fig. 5. $BSFC_{min}$ with carbon contents and it's overcoming depends of blends composition

After simple calculations, the relationship is obtained $BSEC_{min} = f(C_{TOTAL})$ as

$$BSEC_{min} = 0.50317 + 0.04993 C_{TOTAL} \quad (4)$$

with the correlation coefficient $R^2 = 0.96313$. While $BSEC_{min} = f(H + O)$ is given by the equation

$$BSEC_{min} = 9.99160 + 0.00294 (H + O) \quad (5)$$

with the correlation coefficient $R^2 = 0.13505$ so there is no correlation.

Therefore, the above remark is preliminary confirmed.

It is noteworthy that independent of the origin of carbon in the fuel, its total mass, in individual blends, does not differ significantly. However, the content of carbon from non-renewable and renewable resources is clearly different. These proportions on a mass basis, taking into account $BSFC_{min}$ are important.

These masses obviously refer to BSFC i.e. they are expressed in g/kWh. It was assumed (by every j-th blend; j = 1 to 11)

$$C_{TOTAL(j)} = C_{Isooctane(j)} + C_{Ethanol(j)} + C_{Butanol(j)} \quad (7)$$

It is already known (on the basis of the research results presented here) that with the increase in the share of components from renewable sources (alcohols), the BSFC also increases, but the share of bio-carbon also increases – which should generally relieve the environment.

The question is whether there are any regularities in the discussed changes. A preliminary analysis of this problem can be made on the basis of the research data collected here.

Using the obtained data in, the change in $BSFC_{min}$ can be determined if carbon from non-renewable sources is replaced with “bio carbon”. If

$$C_{BIO(j)} = [C_{Ethanol(j)} + C_{Butanol(j)}] / C_{TOTAL(j)} \quad (8)$$

it can be concluded that the minus of the $C_{BIO(j)}$ is an indicator of this replacement.

The data are graphically presented in Fig. 6.

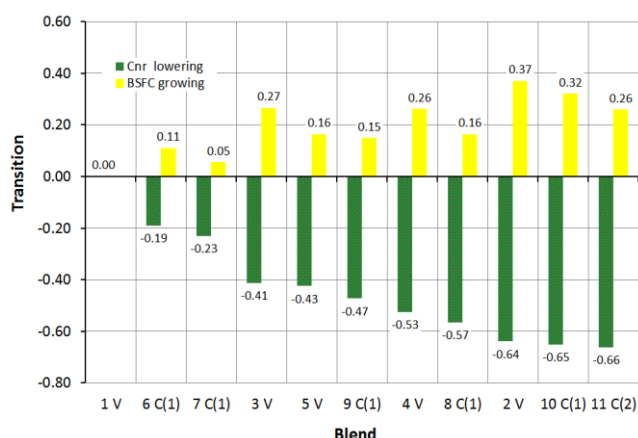


Fig. 6. Carbon from non-renewable sources content lowering and $BSFC_{min}$ grooving

Replacing non-renewable carbon with “bio carbon” leads to an increase in fuel consumption (in this case $BSFC_{min}$). This increase in fuel consumption does not de-

pend only on the carbon resources. As it can be see, other factors are also important

It should be remembered that the engine powered by each of the blends operated normally and reached the "factory" parameters. The obtained results indicate that it is even possible to significantly reduce CO_2 emissions, however, this is always associated with an increase in fuel consumption. There are no linear relationships. Although CO_2 emissions are proportional to carbon consumption. The molar mass of carbon is 12 g and the molar mass of CO_2 is 44 g. Assuming that CO_2 generated from carbon from renewable resources will be completely utilized in the environment, replacing carbon with “bio carbon” seems reasonable, and the mass effect of CO_2 balance may be significant. Replacement by more than 60% of nonrenewable carbon can be achieved with an increase in $BSFC_{min}$ from 26% (blend 11C(2)) to 37% (blend 2V). On the other hand, replacement by "only" 19% (blend 6C(1)), causes an increase in $BSFC_{min}$ by 11% but in turn a greater reduction of 23% (blend 7C(1)) causes an increase in $BSFC_{min}$ by only 5%. A similar lack of regularity can be demonstrated with indirect limits on carbon replacement between 40% and 60%.

4. Summary

The paper shows a possible way to reduce CO_2 generated by road transport by preparing, testing and using of fuels with a higher content of bio-components. High CO_2 concentration in the air is a global problem, and because road transport has here a share of about 17%, therefore the reduction of CO_2 emissions in this economy sector is important. One of the ways, and certainly one of the fastest to implement, is the use of bio-components in fuels. Since the technology of preparing fuel blends seems relatively simple, as well the obtaining of components – from renewable sources such as municipal waste available is, it was decided to carry out research with the aim to clarity of possibility of use a of bio components in bigger amount (volumetric over 10%).

Eleven fuel mixtures were prepared, of which one was the isooctane as reference fuel, six mixtures were two-component and four were three-component.

By testing the spark ignition engine, the minimum specific fuel consumption ($BSFC_{min}$) was determined for each blend, as well as the corresponding values of torque and engine speed.

Although the calorific values of each mixture are different, the location of $BSFC_{min}$ relative to the torque is almost identical, but differ in the engine speed (rpm).

Regardless of the $BSFC_{min}$ location on the operating characteristics, the engine consumes a similar amount of energy, which prompted the authors to introduce a specific energy consumption indicator – $BSEC_{min}$.

Also is shown that the energy “consumption” depends mainly of carbon content in fuel. Other ingredients such hydrogen are from second importance. The explanation of this phenomenon requires further research. However, it can be hypothesized that the energy needed to break down (analyze) the fuel molecules is covered from the synthesis (oxidation) of hydrogen to water, so that the net energy comes from the oxidation of carbon.

Replacing carbon in fuel with "bio carbon" may, as a consequence, lead to the balancing of CO_2 in the environment, but

it leads to an increase in specific fuel consumption. However, these relationships are not of a regular linear nature.

The general conclusion from the research carried out is that the introduction of the so-called biofuels can contribute not to the reduction of CO₂ emissions, but to its faster balancing in the environment. All of this can be achieved but at the cost of increased fuel consumption. This increase in fuel consumption would probably not occur if the "bio" components in the fuel were synthetic hydrocarbons obtained from biomass. However, proving this requires more extensive research, including LCA, because obtaining synthetic hydrocarbons requires additional energy (and the question arises what kind of resources will this energy come from).

5. Recommendation

Transport is one of the most energy-consuming sectors of the economy. Its role is constantly growing. Therefore, it is important where the energy used in transport comes from and how it is used – both now and in the future. It is particularly important in terms of ensuring the possibility of storing energy on board vehicles, e.g. in the form of liquid fuels. Here, in turn, it is important to start the circulation of individual elements that make up fuels in nature and to close the one-way directions for example, flow of carbon from the lithosphere to the atmosphere, which consequently

must result in an increase in its concentration (e.g. in CO₂) in the latter.

The simplest solution to the problem seemed to be the use of biofuels containing carbon, hydrogen and oxygen. Especially that there is an opinion that oxygen (usually one atom in a biofuel molecule for several carbon atoms and often at least twice as many hydrogen atoms) may play any role here.

In fact, different conclusions can be drawn from the research presented here. In the process of burning, a molecule of a biofuel must first be analyzed (to atoms), which then are synthesized into new compounds (mainly CO₂ and H₂O).

The more complicated the fuels are, the more energy is needed to analyze them. This energy is further recovered during the synthesis, but the net yield depends directly only on the carbon content of the fuel. On the other hand, the more complicated the fuel composition, the more its consumption (and therefore also the price of transport work) increases.

However, it is also worth taking into account that the results presented here were achieved under idealized conditions. These conditions are different from everyday life [34, 35]. Of course, global trends in the development of drive systems must be taken into account, and research must be carried out in the light of regulations on emissions, fuels, lubricants and test methods [36]. Hence, further work in the presented direction is necessary.

Nomenclature

CO ₂	carbon dioxide	TRF	toluene reference fuels
LCA	life cycles assessment	BSFC	brake specific fuel consumption
UE	European Union	LHV	lower heating value
MSW	municipal solid waste	ABE	acetone-butanol-ethanol
IDT	ignition delay times	PFI SI	port fuel injected spark ignition

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Monika Andrych-Zalewska, DEng. – Faculty of Mechanical Engineering, Wroclaw University of Science and Technology.
e-mail: monika.andrych@pwr.edu.pl



Prof. Lech Sitnik, DSc., DEng. – Faculty of Mechanical Engineering, Wroclaw University of Science and Technology.
e-mail: lech.sitnik@pwr.edu.pl



Prof. Zbigniew Sroka, DSc., DEng. – Faculty of Mechanical Engineering, Wroclaw University of Science and Technology.
e-mail: zbigniew.sroka@pwr.edu.pl



Veselin Mihaylov, DSc., DEng. – Department of Technical Engineering, Technical University of Varna.
e-mail: v_mihaylov@tu-varna.bg

