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Assessment of the Environmental Impact of Using Methane Fuels to Supply Internal Combustion Engines

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Abstract: This research paper studied the environmental impact of using methane fuels for supplying internal combustion engines. Methane fuel types and the methods of their use in internal combustion engines were systematized. The knowledge regarding the environmental impact of using methane fuels for supplying internal combustion engines was analyzed. The authors studied the properties of various internal combustion engines used for different applications (specialized engines of power generators—Liebherr G9512 and MAN E3262 LE212, powered by biogas, engine for road and off-road vehicles—Cummins 6C8.3, in self-ignition, original version powered by diesel fuel, and its modified version—a spark-ignition engine powered by methane fuel) under various operating conditions in approval tests. The sensitivity of the engine properties, especially pollutant emissions, to its operating states were studied. In the case of a Cummins 6C8.3 modified engine, a significant reduction in the pollutant emission owing to the use of methane fuel, relative to the original self-ignition engine, was found. The emission of carbon oxide decreased by approximately 30%, hydrocarbons by approximately 70% and nitrogen oxide by approximately 50%, as well as a particulate matter emission was also eliminated. Specific brake emission of carbon oxide is the most sensitive to the operating states of the engine: 0.324 for a self-ignition engine and 0.264 for a spark-ignition engine, with the least sensitive being specific brake emission of nitrogen oxide: 0.121 for a self-ignition engine and 0.097 for a spark-ignition engine. The specific brake emission of carbon monoxide and hydrocarbons for stationary engines was higher in comparison with both versions of Cummins 6C8.3 engine. However, the emission of nitrogen oxide for stationary engines was lower than for Cummins engines.

Keywords: alternative fuels; methane fuels; biogas; biomethane; approval tests; emission of pollutants; sensitivity of engines

1. Introduction

The observed growth of the alternative fuel market is associated with priorities in the field of environmental protection and the tendency to implement the idea of sustainable development and circular economy in all branches of the economy. They are driven by global trends that have quantified targets for progressively reducing greenhouse gas emissions and energy intensity, as well as increasing the share of renewable energy sources and their use in transport [1,2]. Such idea additionally enables a partial independence on fossil fuels due to replacement of part of fossil fuels by alternative ones. For this reason, the development of engine fuels obtained from renewable sources is very important. There are many different types of compounds which can be used as a substitute for conventional fuels, e.g., bioethanol [3,4], dimethyl ether (DME) [5,6], fatty acid methyl ester (FAME) [7,8], methane [9,10] and hydrogen [11–13]. These compounds can be produced with the use of various methods and raw materials. Recently, methane fuels have become very popular and are promoted as low-emission fuels. These fuels include:

- Fuels from a fossil raw material—natural gas, purified to a standard required for various applications, i.e., as engine fuel—the name natural gas, the same as the raw material they originate from, has been adopted for this type of fuels.
- Biogas fuel—biogas cleaned of specific pollutants, primarily hydrogen sulfide, water and silicon compounds, excluding, i.e., carbon dioxide.
- Fuel obtained from biogas purified to a natural gas fuel standard—so-called biomethane.

Biogas is a product derived from biomass (a renewable energy source), produced in the course of a process of anaerobic organic substance decomposition, by a diverse population of microorganisms. The physical and chemical properties of biogas and its availability are the key reasons behind its application as an alternative engine fuel, reducing the dependence on fossil fuels and diversifying energy sources. It can be used for producing thermal or electrical energy or combined cycle energy production (CHP—combined heat and power) in cogeneration [14] or trigeneration [15] systems. After relevant purification to biomethane, it can be pumped into a natural gas distribution network or be used as an internal combustion engine fuel [16]. It is also possible to use biogas for producing syngas [17], which is a semi-finished product in the processes of producing, e.g., methanol [18], hydrogen [19] and in the BTL (biogas-to-liquid) process of hydrogen synthesis [20].

Biomethane and natural gas are used in [21–23]:

- Compressed form (compressed natural gas—CNG, and compressed biomethane —BCNG).
- Liquefied form (liquefied natural gas—LNG, and liquefied biomethane—BLNG).
- Adsorbed form (adsorbed natural gas—ANG, and adsorbed biomethane—BANG).

The feasibility of using methane fuels for powering internal combustion engines is determined by several parameters, where the most important ones include: chemical composition (methane concentration, pollutant content, etc.), resistance to knock combustion (determined based on the methane number and octane number), ignition and self-ignition temperatures, fuel stoichiometric constant, combustion rate of the fuel–air mix and energy value measured by the calorific value or the Wobbe index.

2. Directions of Research in the Field of Using Methane Fuels for Supplying Internal Combustion Engines

Based on the conducted overview of the available source literature, the authors concluded that due to the widespread availability of natural gas on the market, most of the conducted studies involved this type of methane fuel. The studies concerned, among others, the application of natural gas in the automotive industry, in particular:

- Impact of fuel on the performance of engines, in particular, the operating parameters of spark-ignition (SI) engines (torque, exhaust gas temperature, etc.), depending on the mixture composition and ignition advance angle, compared to the case of supplying self-ignition (CI) engines with conventional fuel—diesel fuel [24].
- Evaluation of fuel combustion in a spark-ignition engine or a self-ignition dual-fuel engine, with the addition of other gases, e.g., hydrogen [25].
- Impact of changing the fuel initiating mixture ignition, from diesel fuel to, e.g., biodiesel [26–28], biodiesel with ethanol [29,30] or diesel fuel with ethanol or with methanol [31–33].
- Emission of toxic components of exhaust gases [34–36] and the environmental impact throughout the entire life cycle of gaseous fuel (from raw material acquisition, through manufacturing, until its use within an engine [37,38]).
- Economic effects of fueling an engine with CNG [39,40].

Research papers on biomethane are significantly scarcer. This is due to the fact that in many countries, due to the lack of infrastructure for upgrading biogas to biomethane, this fuel is still unavailable. The conducted research work primarily concentrated on the impact of biomethane on the environment (the emission of particulates and gaseous substances, in particular), relative to fuel with natural gas [41,42]. Authors of [43] concluded that the use of methane fuels significantly reduces emissions compared to fossil fuels. The GHG emissions for gasoline, diesel fuel and LPG in the whole life cycle are estimated at 164, 156 and 141 g CO_2-eq/km, respectively (Figure 1). For biomethane, it is only from 33 to 66 g CO_2-eq/km (depending on the raw material used), and for natural gas, 124 g CO_2/km in the whole life cycle.

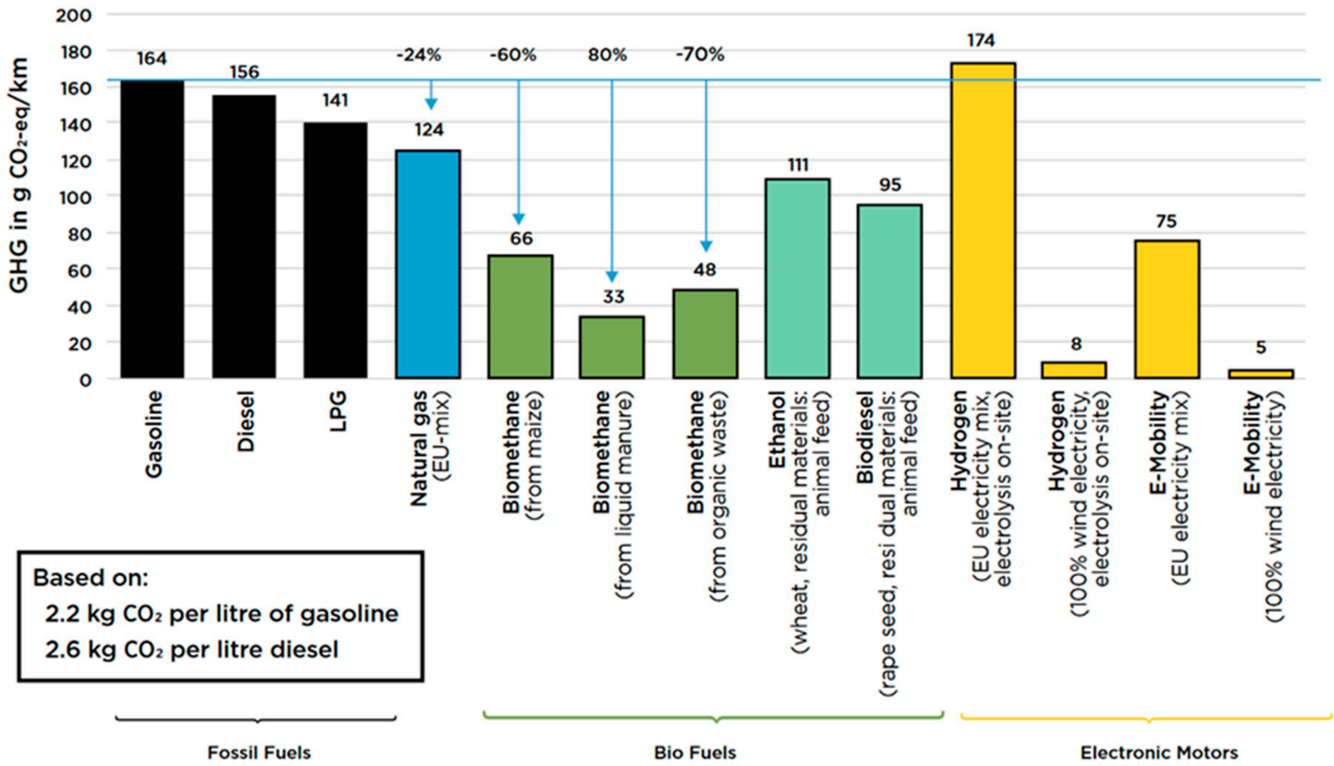

Figure 1. Comparison of GHG emissions from passenger cars fueled with different fuels [43].

The reduction of greenhouse gas emissions by biomethane fuel throughout the life cycle compared to the use of conventional fuels is due not only to the combustion process in the engine but also to the technology of its production [44,45]. The type of substrate used for methane fermentation has the greatest impact on the reduction of GHG emission in the whole life cycle. For biomethane produced from arable crops such as maize, greenhouse gas specific distance emission, expressed as CO_2-eq, is 66 g/km, of which more than 50% is attributed to cultivation (nitrogen fertilization) and harvesting of raw materials (fuel combustion), and 28% to the process of purification and upgrading of biogas to natural gas quality. Greenhouse gas emission, thanks to the use of biomethane produced from edible raw materials, can therefore be reduced by approximately 60% compared to gasoline [43]. The use of manure (waste material) as input for the production of biogas reduces greenhouse gas emission by approximately 80% compared to gasoline, and the use of biomethane from municipal waste reduces greenhouse gas emission by approximately 73% compared to fossil fuels. For biomethane from municipal waste, the standard assumption is that the emission factor expressed in CO_2-eq is 83.8 g/MJ, according to the Renewable Energy Directive (RED) [46]. This means a reduction in greenhouse gas emission per kilometer driven by around 70% compared to a petrol-powered passenger car. If, on the other hand, during the production of biomethane, the places of uncontrolled methane emission, such as the method of storing raw materials and digestate (storage in closed tanks) are delimited to a minimum, and the emissions associated with the process of methane fermentation of animal manure (slurry and manure) are taken into account, then we can talk about GHG emission in the entire life cycle close to zero or below this value.

Apart from research on the use of natural gas and biomethane for road vehicles, work is also carried out on its use for off-road vehicles [47,48]. Researchers study their application in the engines of: trucks [49–51], water vessels [52,53], traction locomotives [18,54] or tractors and agriculture machines (AGCO Valtra [55], Same Deutz-Fahr [56], New Holland [57] and others [58,59]).

The main factor determining the possibility of using biogas as a raw material for the production of various energy carriers is the high content of methane (over 60%). Table 1 presents the differences in the composition of raw biogas, biogas after purification (biomethane) and natural gas.

Table 1. Differences in the composition of raw biogas, biomethane and natural gas [60,61].

Gas Component.	Raw Biogas	Biomethane	Natural Gas
Methane, (%)	45–70	94.0–99.9	93–98
Carbon dioxide, (%)	25–45	0.1–4.0	1
Nitrogen, (%)	<3	<3	1
Oxygen, (%)	<2	<1	-
Hydrogen, (%)	<1	traces	-
Hydrogen sulfide, (ppm)	20–20,000	<10	-
Ammonia, (%)	traces	traces	-
Ethane, (%)	-	-	<3
Propane, (%)	-	-	<2
Siloxane, (%)	traces	-	-
Water, (%)	2–7	-	-

Owing to its chemical composition, as well as the need for refining, biogas is only used as a biogas fuel for producing electricity and/or thermal energy, i.e., to supply stationary self-ignition or spark-ignition engines, which are a component of a cogeneration plant [62]. These engines differ from vehicle engines in terms of design, adapted to constant operating conditions. The ongoing studies in the field of using biogas fuel to supply these engines concern, in particular, the impact of biogas composition on the performance of the engine [63–65] and the exhaust gas component emissions [66–70]. Moreover, the influence of the concentration of hydrogen added to biogas fuel on the ecological and energy parameters of an engine [71] and the application of ignition-initiating heavy fuel other than diesel fuel, e.g., biodiesel [72], were also studied.

Methane fuels, due to their chemical composition (carbon and hydrogen content), enable greater reduction of carbon dioxide emission relative to conventional fuels. Furthermore, since they are gaseous fuels, they enable the combustion of more homogeneous mixtures than in the case of liquid fuels. This allows limiting the emission of gaseous pollutants and particulates [73,74]. Owing to the decreased heat generated in the kinetic phase of combustion, emission of nitrogen oxides from an engine dual-fueled by natural gas and diesel fuel can be limited compared to an engine supplied with diesel fuel, depending on the composition of the fuel mixture, excess air coefficient and the adjustment of the fuel pilot dose injection angle [75,76]. Due to the lack of self-ignition ability in gaseous fuels, they are mostly used in spark-ignition engines. On the market are vehicles with modern gas-fuel engines, which are factory-adapted to run solely on gaseous fuel (so-called NGVs—Natural Gas Vehicles). In case of vehicles without a gas-fuel engine, they can be adapted to run on gaseous fuel by [18,75,77–80]:

- Adapting a gasoline-fueled spark-ignition engine to run on gaseous fuel (a relatively simple procedure involving the installation of an additional gas supply system, as well as controllers for the engine operating processes, especially the fuel dose).

- Converting a self-ignition engine to a spark-ignition engine—a costly and complicated engine modification, which involves replacing the injector with a spark plug, implementing a gas fuel ignition system, controllers for the engine operating processes (fuel mixture composition, fuel dose, ignition angle of advance, etc.), throttle in the suction system, the catalytic reactor in the outlet system and decreasing the compression ratio. The implemented modifications enable a vehicle to run only on gaseous fuel.
- Changing a self-ignition engine's supply system from single-fuel to dual-fuel (the engine will then be supplied with gaseous fuel and a pilot dose of heavy fuel, primarily diesel fuel).

In some cases, for example for large fleets of vehicles, the adaptation of currently used vehicles (with conventional self-ignition engines) to run on gaseous fuels is more economically justified than replacing the entire fleet with new vehicles equipped with gas engines. Conversion of a self-ignition engine into a spark-ignition engine is a solution which has been especially applied in buses and trucks. After modifications in ignition systems (installation of spark ignition equipment) and fuel injection, the vehicle can be bi-fueled (with methane fuel and gasoline) or fueled only with methane fuel. Studies on such engine modification can be found in the literature [81,82], where the performance of engine and harmful gas emissions were investigated. However, the studies conducted so far do not cover the topic of the sensitivity of the pollutant emission to the operating states of the engines, determined by the operating conditions of the device powered by the engine. The measure of the sensitivity of a physical quantity to engine operating states is the coefficient of variation (ratio of the mean standard deviation to the mean value) of that quantity for various engine operating states. By the operating states of engines in thermally stabilized conditions (heated engines), one should understand the engine speed and the value characterizing the load—most often the torque. The largest set of information on the emission of pollutants from combustion engines supplied with methane fuels concerns the approval test results. The operating states of internal combustion engines in the course of approval tests often vary greatly from their real operating conditions. For example, the operating states of combustion engines in city buses are characterized by significantly lower values of the average engine speed and load, and a higher share of idling time, than in the case of approval in static and dynamic tests [83,84]. Similarly, there are large differences between the actual operating states of combustion engines of construction machinery and the operating states defined in approval tests [85].

The authors have not found a comparison of empirical assignments of engines in different operating states corresponding to different conditions of engine application in the world's literature so far. Moreover, to the best of the authors' knowledge, the results of comparative studies of self-ignition engines converted to spark-ignition engines supplied with methane fuel, in various operating states, corresponding to actual operating conditions of these engines in vehicles and other applications, have not been reported elsewhere. For this reason, the authors conducted such tests and compared the obtained results. It was decided to investigate the sensitivity of operational properties to various states of engine operation, e.g., in motor vehicles and working machines. The functional properties of internal combustion engines for driving power generators in an agricultural biogas plant were also investigated. The authors decided to fill this research gap by empirically testing the engine, before and after such conversion, in four different tests. It allowed to assess the sensitivity of the engine properties, especially pollutant emissions, to its operating states. The significance of this lies in the fact that the conversion to methane fuel is usually performed for engines used in heavy-duty applications: buses, trucks, stationary machines and power generators that differ largely in operating conditions. The results presented in this paper broaden the knowledge of the real benefits of converting engines to run on methane fuels, precisely in specific applications, and not only under the conditions defined in the law.

3. Materials and Methods

3.1. Introduction to Experiments

The research was conducted with the use of the conventional fuel (diesel fuel) and two methane fuels with different methane content (natural gas and biogas containing approximately 97% and 60% of methane, respectively). It was planned to conduct empirical research on biogas and biomethane. Due to the lack of availability of biomethane in the Polish market, its fossil-based counterpart—natural gas—was used for the research. The results obtained for natural gas can be treated as representative for biomethane, because both fuels have similar physicochemical properties and are used interchangeably as engine fuel. Different content of methane in tested fuels enabled to evaluate the performance properties of these fuels. The research methodology used in the work is an original conception of the authors. The idea of this methodology is to study the properties of various internal combustion engines used for different applications (specialized engines of power generators, engines for road and off-road vehicles) under various operating conditions, including in the conditions of approval tests. Two cogeneration engines (Liebherr G9512 and MAN E3262 LE212) and one universal engine used in road and off-road vehicles as well as machines, aggregates, etc. (Cummins 6C8.3), were selected for approval tests. Research tests were carried out in two stages.

Empirical tests of internal combustion engines were performed in certified laboratories. The apparatus used met the requirements of: Directive 1999/96/EC of the European Parliament and of the Council of 13 December 1999, Regulation (EC) No. 715/2007 of the European Parliament and of the Council of 20 June 2007 and Regulation (EC) No. 692/2008 of the European Parliament and of the Council of 18 July 2008, and ISO 3046-1: 2002, ISO 3046-3: 2006, ISO 8178-3: 1994 and ISO 8178-10: 2002.

3.2. Stage One

In the first stage, comparative tests of the original Cummins 6C8.3 engine and the same engine after its conversion were performed. An original Cummins 6C8.3, turbocharged, 6-cylinder engine with a displacement volume of 8.3 dm^3 has a rated effective power of 153 kW and an engine speed of 1950 min^{-1}. The idle engine speed is 750 min^{-1}. The Cummins 6C8.3 engine is a self-ignition, diesel-fueled engine. In its modified versions, it was a spark-engine fueled with natural gas, set to run on a stoichiometric mixture. The conversion of the original diesel engine into a spark-ignition one included: change of the gas fuel supply system, change in the engine control system (concerning fuel mixture composition, fuel dose, ignition timing, etc.), installation of a spark-ignition system and use of a multi-functional catalytic reactor in the exhaust system. The Cummins 6C8.3 engine is originally intended for the drive of motor vehicles, and in the modified configuration for the drive of working machines. These are the engine operating conditions, characterized by a relatively low relative load (in relation to the maximum engine load).

The internal combustion engine was studied on a test bench (Figure 2) equipped, among others, with:

- An AFA-E 460/4,4-9 EU electric brake by AVL,
- A T10F digital torque and engine speed meter by HBM,
- A CEB II exhaust gas analyzer assembly by AVL,
- A system for measuring particulate emission comprised of a Smart Sammler SPC partial flow dilution tunnel by AVL and a MT5 microscale by Mettler Toledo,
- A 735-type system for measuring fuel consumption with a device for stabilizing fuel temperature by AVL,
- A Sensyflow P system for measuring air consumption.

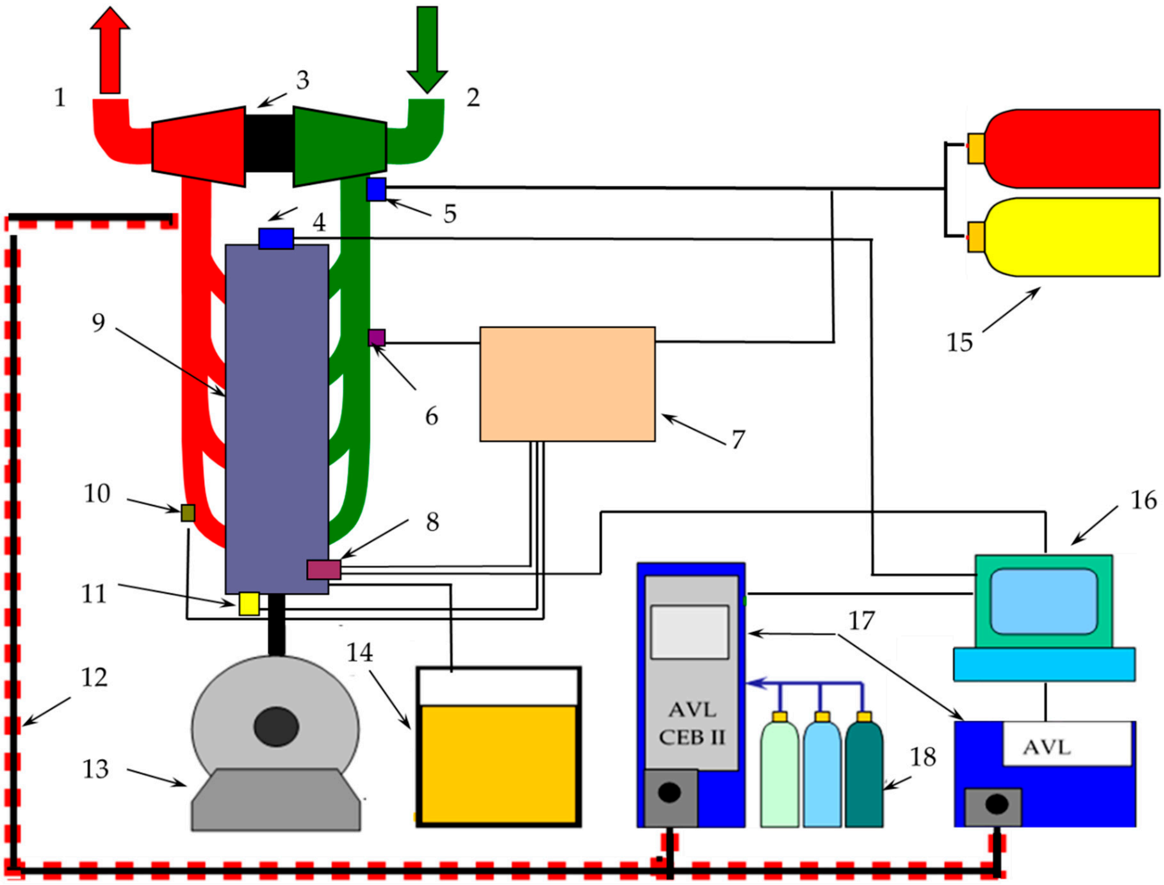

Figure 2. Scheme of the test bench, where: 1—exhaust outlet, 2—air inlet, 3—turbocharger, 4—crankshaft angle sensor, 5—gas fuel injector, 6—boost pressure sensor, 7—fuel electronic dosage control module, 8—cylinder pressure sensor, 9—engine, 10—thermocouple, 11—knocking combustion sensor, 12—heating pipes supplying exhaust gas to the analyzers, 13—AVL electric brake, 14—liquid fuel tank, 15—methane fuel tanks, 16—computer, 17—exhaust gas analyzers, 18—reference gases.

The instrumentations used for the tests complied with the requirements of Directive 97/68/EC. The tests of the natural gas-fueled engine and the self-ignition engine involved the determination of:

- External speed characteristics,
- Specific brake emission within test studies.

The test studies, which concerned the pollutant emission (carbon oxide—CO, hydrocarbons—HC, particulate matter—PM and nitrogen oxides—NO_x), corresponded to the static operating states of the engine. The basis test is the D2 test for studying the emission of pollutants from internal combustion engines used to drive power generators with variable load, as per the ISO 8178-4 standard [86]. For comparative purposes, the authors also conducted studies within other static tests [84,87]:

- ECE R 49.02—the so-called thirteen-phase test, in accordance with regulation No. ECE R 49, for testing car engines.
- ESC (European Stationary Cycle), in accordance with regulation No. ECE R 49, for testing car engines.
- NRSC (Non-Road Stationary Cycle), identical to the C1 test according to ISO 8178-4, for testing self-ignition engines in machinery.

Schematic representations of the engines' test bench are shown in Figure 3.

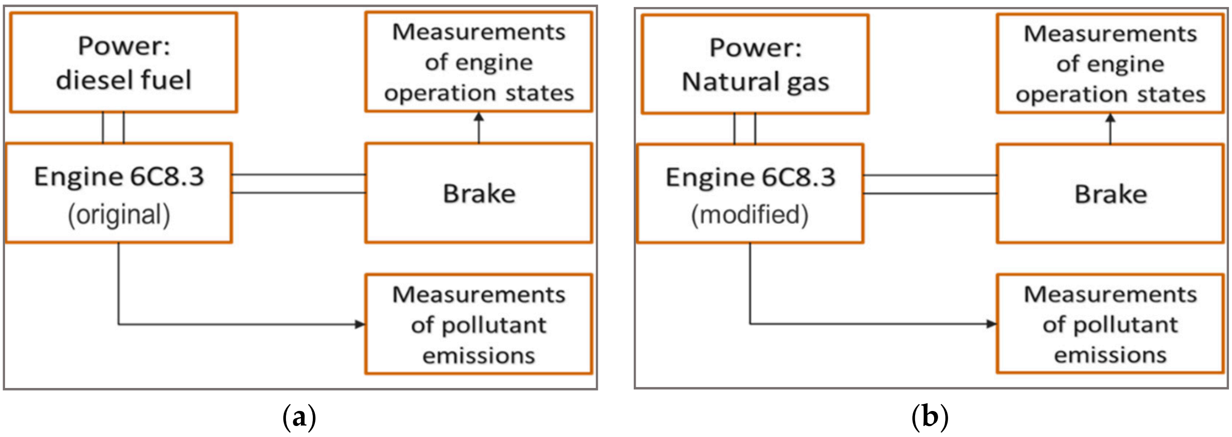

Figure 3. Scheme of the test bench with the tested engines: (**a**) original Cummins 6C8.3 engine, and (**b**) modified Cummins 6C8.3 engine.

3.3. Stage Two

In the second stage, the Cummins 6C8.3 engine (which is a universal engine that can be used as a drive for vehicles and machinery and power generators) was compared with two cogeneration engines used in biogas plants. The Cummins 6C8.3 engine was powered by diesel fuel (self-ignition version) and natural gas (version after modification for spark-ignition). The main reason for the conversion of a self-ignition engine to a spark-ignition engine to methane fuel was the need to reduce the emission of pollutants, especially particulate matter and nitrogen oxides.

Two variants of this engine were compared with Liebherr G9512 and MAN E3262 LE212 engines. The tested Liebherr and MAN are turbocharged, spark-ignition engines, highly specialized with a large displacement volume, adapted to work on a very lean mixture. They are used to drive power generators in agricultural biogas plants. In the CHP case, alternative diesel engines are not used. Moreover, CHP engines are not supplied with a natural gas, so during the tests, they were fueled with biogas (containing approximately 60% of methane). Table 2 shows the technical data of tested turbocharged Liebherr G9512 and MAN E3262 LE212 stationary CHP engines.

Table 2. Technical data of tested Liebherr G9512 and MAN E3262 LE212 stationary CHP engines used in agricultural biogas plants.

Title 1	Unit	Liebherr G9512	MAN E3262 LE212
Cylinder arrangement	–	12 V	12 V
Displacement volume	dm^3	25.0	25.8
Compression ratio	–	13.3	13.6
Rated engine speed	min^{-1}	1500	1500
Rated effective power	kW	515	550
Brake mean effective pressure in nominal rating	MPa	1.65	1.71
Excess air coefficient	–	1.6	1.6

In order to compare engines used for operation in different conditions and fueled by different fuels, the D2 test in line with ISO 8178-4 was chosen. This test is a basic test for studying the overall efficiency of the emission of pollutants from internal combustion engines used to drive power generators with variable load. The instrumentation used in the tests complied with the requirements of approval tests. The tests were conducted in the laboratories of engine manufacturers. Schematic representations of the engine test bench are shown in Figure 4.

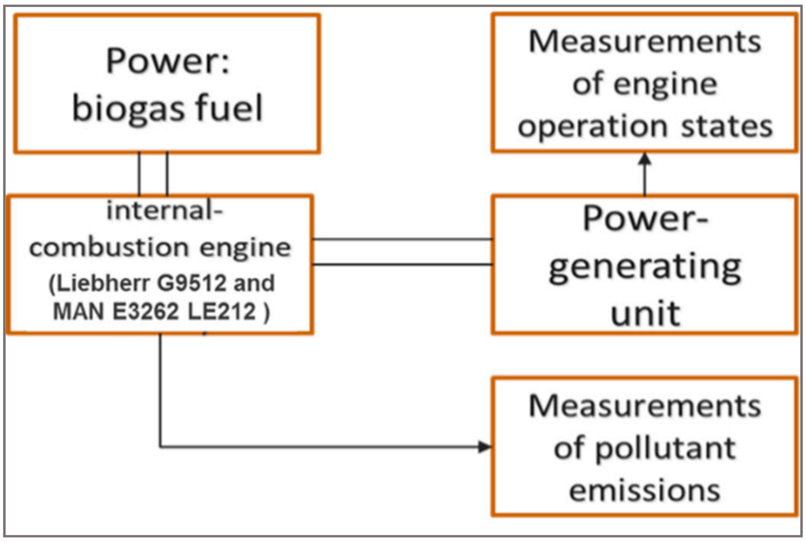

Figure 4. Scheme of the test bench with the two tested CHP internal combustion engines.

4. Results

4.1. Stage One

Figure 5 shows the external speed characteristics of the torque and effective power for a self-ignition Cummins 6C 8.3 engine running on diesel fuel—designated DF—and a Cummins 6C 8.3 engine, modified as a spark-ignition methane-fueled engine—natural gas—designated MF.

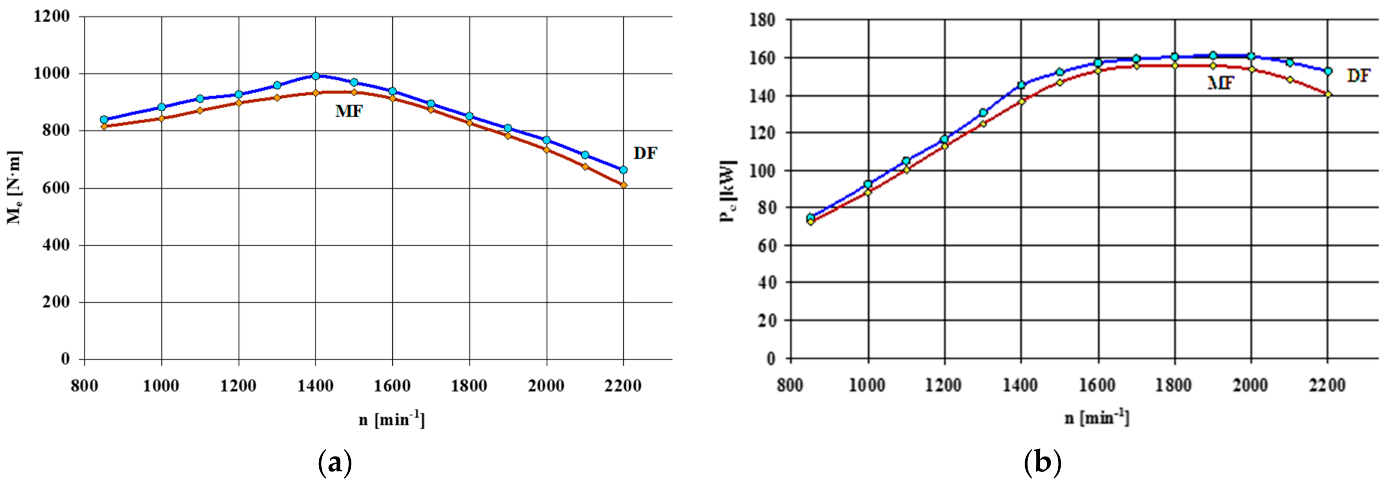

Figure 5. External speed characteristics of Cummins 6C 8.3 engine: (**a**) torque and (**b**) effective power, for a self-ignition, diesel-fueled engine (DF), and a spark-ignition, methane fuel—natural gas—supplied engine (MF).

The average engine torque and effective power difference in the studied engines were approximately 0.04, and higher torque and effective power values were recorded for the self-ignition, diesel-fueled engine. This results primarily from the better filling of the cylinders, since the upgrading of the engine to a spark-ignition engine did not involve the modification of the engine charging control algorithm.

Figure 6 shows the overall efficiency of the tested engines.

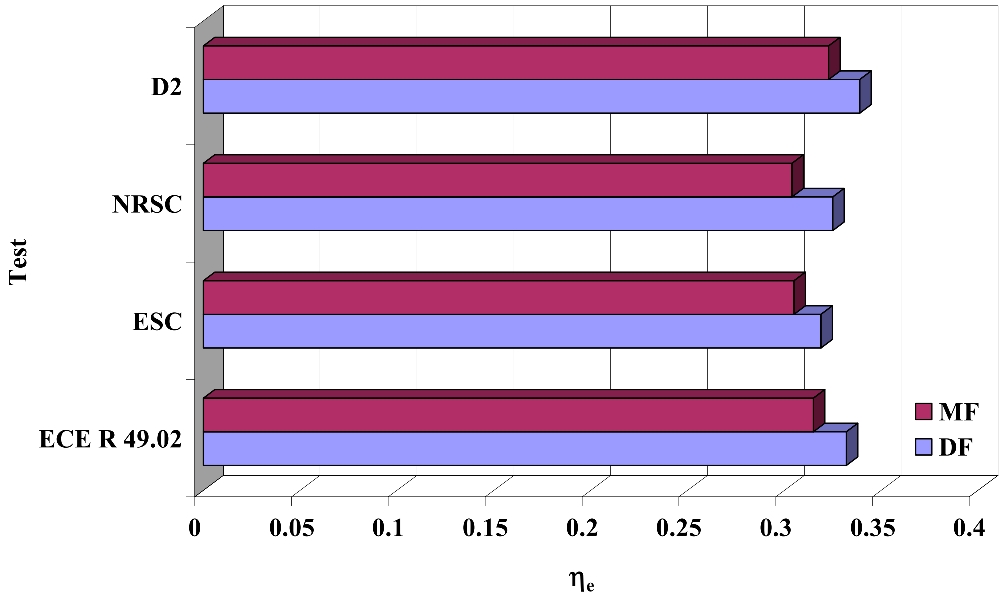

Figure 6. General efficiency in a self-ignition Cummins 6C 8.3 engine running on diesel fuel (DF), and a spark-ignition Cummins 6C 8.3 engine running on methane fuel—natural gas (MF).

In all tests, the overall efficiency was higher for a self-ignition engine fueled with diesel. This is also due to the better filling of the cylinders in a self-ignition engine. The fact of the relatively low sensitiveness of the engine in overall efficiency of their operating states varying within various tests is also significant. The measure of the sensitivity of a quantity to engine operating states is the coefficient of variation (ratio of the mean standard deviation to the value) of that quantity for various engine states. The variation coefficient for the overall efficiency in all tests was 0.026 for the self-ignition engine and 0.029 for the spark-ignition engine.

Figure 7 shows the specific brake emission of pollutants for a self-ignition Cummins 6C 8.3 engine running on diesel fuel, and a spark-ignition Cummins 6C 8.3 engine running on methane fuel—natural gas. The particulate matter emission from the engine supplied with natural gas was on the boundary of measurement accuracy, therefore, these tests were discarded, assuming for comparative purposes that the specific brake emission of particulate matter from the engine supplied with natural gas was 0. Although there is no practical possibility of comparing the particulate matter emissions from the tested engines, it was decided to present the results for a self-ignition engine to show the absolute benefit of using a modified positive-ignition natural gas engine instead of the original self-ignition engine.

Decreased specific brake emission of pollutants was owing to replacing a self-ignition engine with a spark-ignition engine supplied with natural gas.

The emissions of carbon monoxide, hydrocarbons, nitrogen oxides and particulate matter for driving and stationary tests of the engine have been compared. The test was conducted for a self-ignition Cummins 6C 8.3 engine fueled with natural gas and for an original self-ignition Cummins 6C 8.3 engine supplied with diesel fuel. Figure 8 shows a relative decrease in the specific brake emission of pollutants owing to the application.

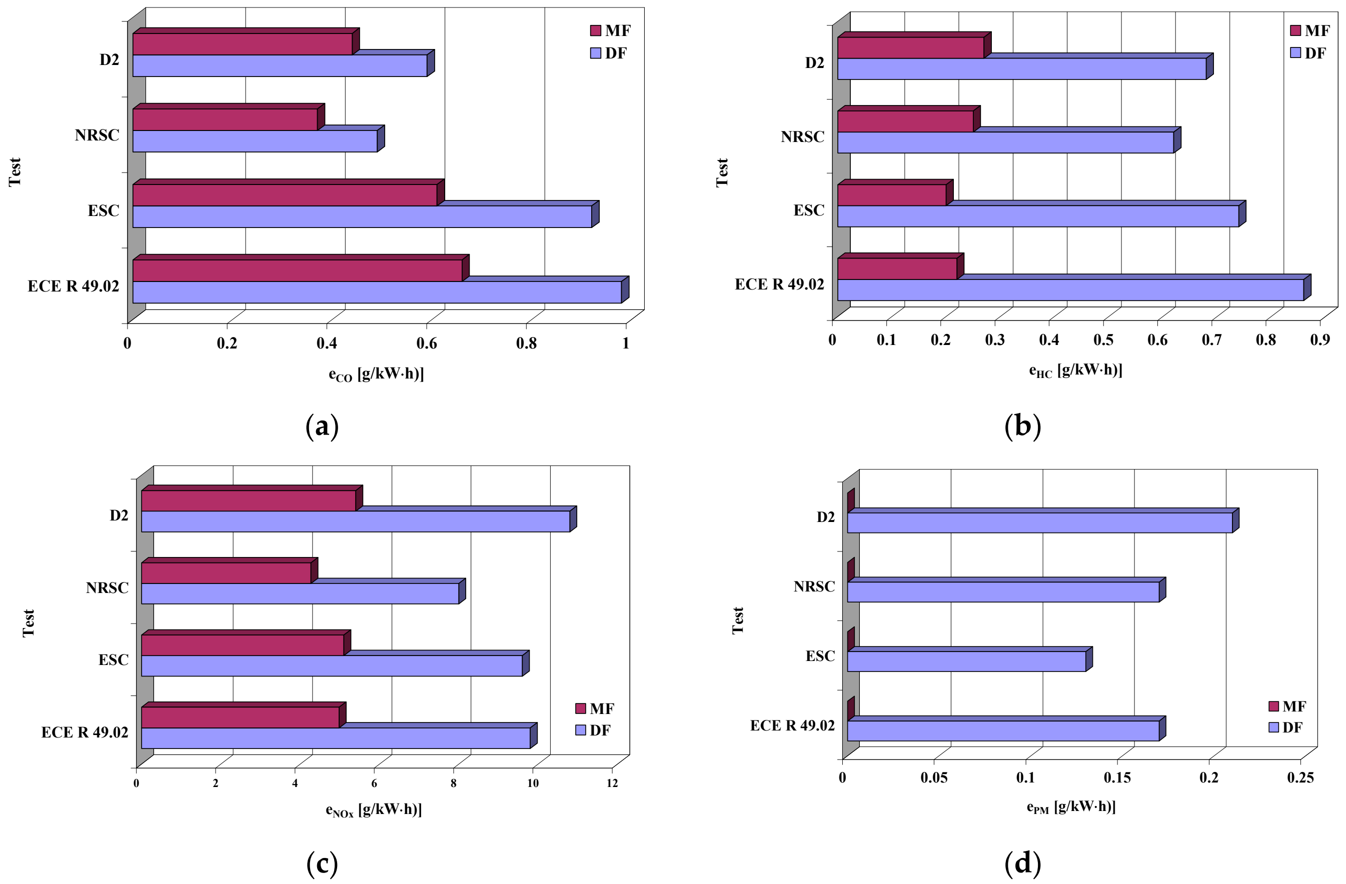

Figure 7. Specific brake emission: (**a**) carbon oxide, (**b**) hydrocarbons, (**c**) nitrogen oxides and (**d**) particulates, in tests for a self-ignition Cummins 6C 8.3 engine running on diesel fuel (DF), and a spark-ignition Cummins 6C 8.3 engine running on methane fuel—natural gas (MF).

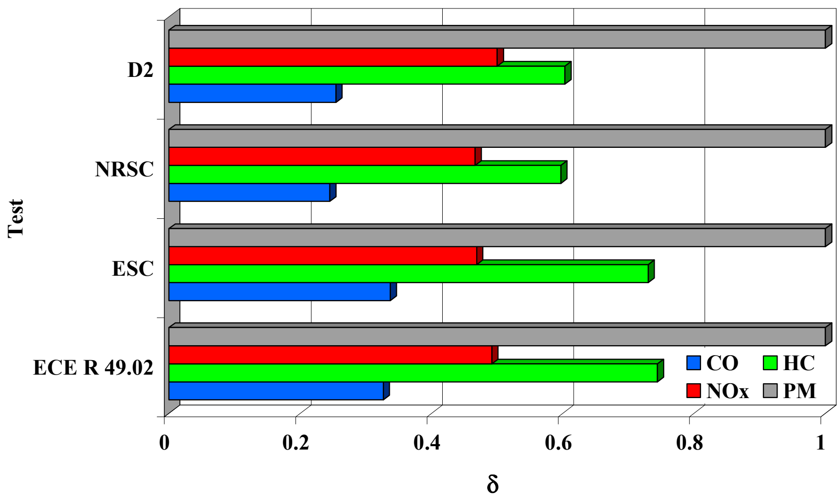

Figure 8. The relative decrease in the specific brake emission of pollutants due to replacing diesel fuel with natural gas as the Cummins 6C 8.3 engine fuel.

The average relative decrease of the specific brake pollutant emission owing to supplying the engine with natural gas instead of diesel fuel is, therefore:

- Carbon oxide: 0.29,
- Hydrocarbons: 0.69,
- Nitrogen oxides: 0.48,

- Emission of particulate matter: 1.

The higher sensitivity of specific brake pollutant emission to the operating states in individual tests is visible. Figure 9 shows the variation coefficient for the specific brake pollutant emission in all tests for both a self-ignition and spark-ignition Cummins 6C 8.3 engine.

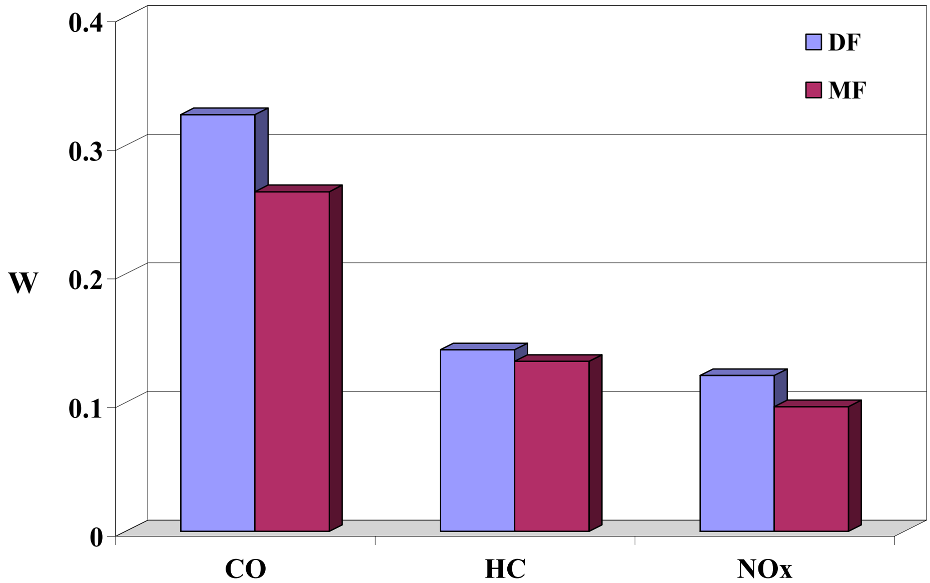

Figure 9. The variation coefficient for the specific brake pollutant emission in all tests for a self-ignition engine running on diesel fuel (DF), and a spark-ignition Cummins 6C8.3 engine running on methane fuel—natural gas (MF).

Specific brake emission of carbon oxide is the most sensitive to the operating states of the engine: 0.324 for a self-ignition engine and 0.264 for a spark-ignition engine, with the least sensitive being specific brake emission of nitrogen oxide: 0.121 for a self-ignition engine and 0.097 for a spark-ignition engine.

4.2. Stage Two

Figures 10 and 11 show the specific brake emission of carbon monoxide, hydrocarbons and nitrogen oxides within the D2 tests of the studied engines in the conditions of the homologation test of engines used for driving power generators: MAN E362 LE212, Liebherr G9512, fueled with biogas, and the Cummins 6C8.3 engine: in the original version of the self-ignition engine, fueled with diesel, and in the modified version as an ignition engine spark plug fueled with methane fuel (natural gas).

The specific brake emissions of carbon oxide and hydrocarbons are similar and relatively high for the Liebherr G9512 and MAN E3262 LE212 stationary engines supplied with the biogas. Specific brake emission of carbon monoxide is over 0.9 g/(kW·h) and specific brake emission of hydrocarbons is over 0.5 g/(kW·h) for both engines. However, the emission of these substances does not pose a significant threat in the operating conditions of power generator engines. On the other hand, a clear benefit in terms of nitrogen oxide emission has been achieved (about 1 g/(kW·h) for MAN E3262 LE212 and about 3 g/(kW·h) for Liebherr G9512), let alone particulate matter emission.

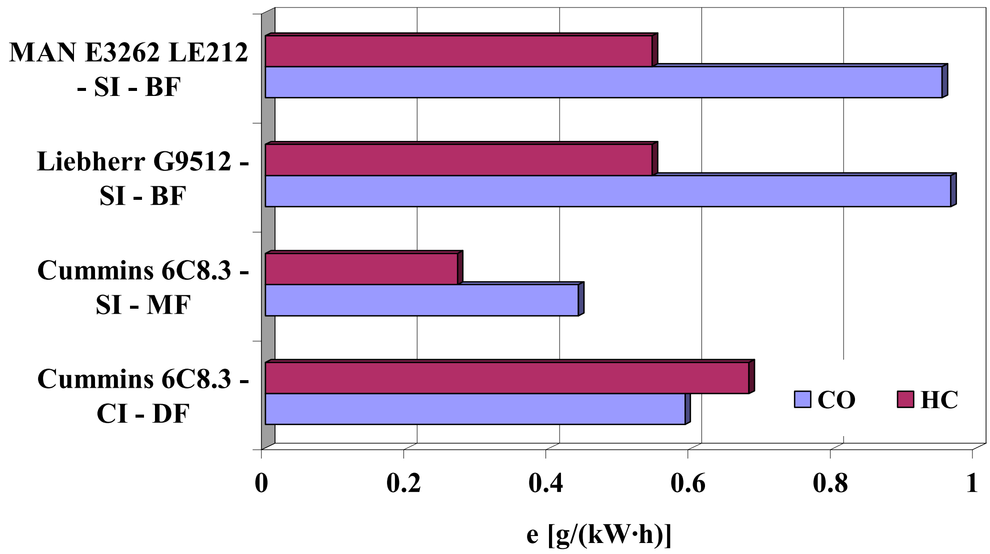

Figure 10. Specific brake emission of carbon oxide and hydrocarbons in the D2 test for the studied engines running on diesel fuel (DF), methane fuel—natural gas (MF) and biogas (BF).

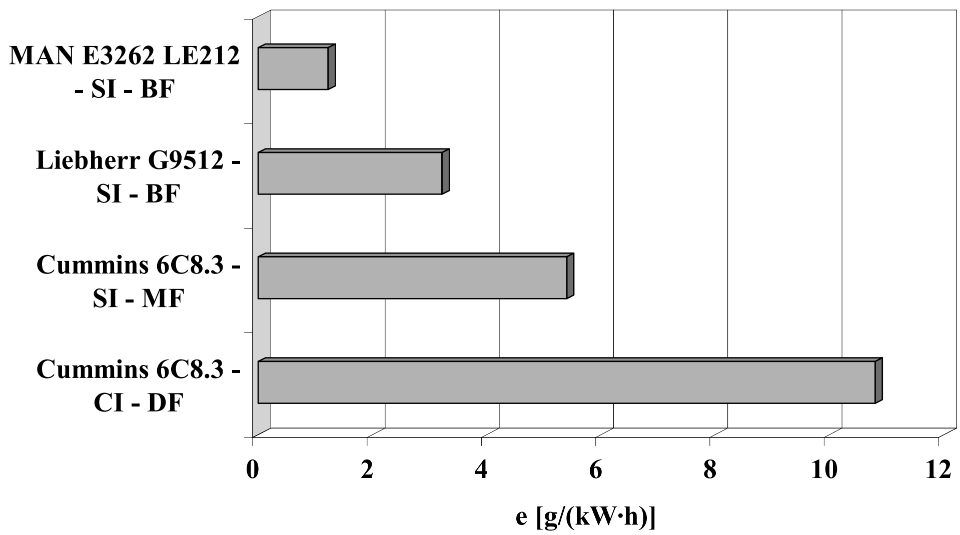

Figure 11. Specific brake emission of nitrogen oxides in the D2 test for the studied engines running on diesel fuel (DF), methane fuel—natural gas (MF) and biogas (BF).

Significantly, the specific emission of carbon monoxide and hydrocarbons for the Cummins 6C8.3 engine in both versions (fueled with the diesel and natural gas as a substitute for biomethane) is relatively low (above 0.4 g/(kW·h) of carbon monoxide and above 0.2 g/(kW·h) of hydrocarbons for SI engine and respectively above 0.5 g/(kW·h) of carbon monoxide and above 0.6 g/(kW·h) of hydrocarbons for CI engine), while the specific emission of nitrogen oxides is significantly higher than for typical engines for CHP aggregates supplied with the biogas. This is due to the fact that the Cummins 6C8.3 engine was originally intended for the drive of motor vehicles, and in the modified configuration, for the drive of working machines. These are the engine operating conditions, characterized by a relatively low relative load (in relation to the maximum engine load), which is particularly visible for the average relative power use in the research tests for ECE R 49.02 and ESC, as well as NRSC in relation to the D2 test. In addition, the algorithms for controlling the work processes of Liebherr G9512 and MAN E3262 LE212 engines are adapted only to work in the driving conditions of power generators with the priority of reducing the specific emission of nitrogen oxides, because it is one of the most important problems of this type of engines, while the original algorithms controlling the work processes in the engine Cummins 6C8.3 are adapted to the operating conditions for typical conditions of use, i.e., for a lower relative load for the use in cars and working machines in relation to the relative load in the application for driving power generators.

The presented research has shown that the use of methane fuels (biogas, natural gas and biomethane, which can be used as a substitute for natural gas) causes beneficial environmental effects in comparison to conventional fuel. The use of methane fuels enables the reduction of emissions of pollutants: carbon monoxide, organic compounds, especially cyclic hydrocarbons, and their derivatives, especially polycyclic aromatic hydrocarbons, nitrogen oxides and solid particles. This is largely due to the combustion of highly homogeneous air–fuel mixtures in the engine cylinders and, therefore, the possibility of burning very lean mixtures. It should be mentioned that biogas and biomethane can be produced from various biodegradable raw materials, including bio-waste. The use of bio-waste provides additional environmental benefits, because for the calculation of GHG emissions throughout the life cycle of these fuels, the stage of obtaining the raw material is zero-emission. It results directly from the provisions of Directive 2009/28/EC. It is important from the perspective of decreasing the impact of our civilization on the intensification of the greenhouse effect, thus counteracting climate changes. Using fuels produced from wastes is also an element of rationalizing the application of natural energy resources, which is particularly advantageous when using local biogas sources, among others, originating from municipal resources of urban agglomerations.

5. Conclusions

The paper presented the results of research on the supply of methane fuels to internal combustion engines, especially in terms of their environmental impact. The authors converted the universal Cummins 6C8.3 diesel engine into a spark-ignition one (supplied with natural gas) and carried out various approval tests of both engines' versions. Additionally, both Cummins 6C8.3 engine versions were compared with two cogeneration engines used in biogas plants (Liebherr G9512 and MAN E3262 LE212 supplied with biogas). The tests were carried out for various operating states of the engine, resulting from various operating conditions, e.g., in motor vehicles, working machines and power generators.

As a result of the conversion of the Cummins motor from diesel fuel to methane fuel, the reduction of specific brake emission of carbon monoxide was seen in the range of 26–34%, hydrocarbons in the range of 60–75%, depending on the type of approval test, the reduction of specific brake emission of nitrogen oxides by approximately 50% and complete elimination of particulate matter was seen in all tests. Moreover, the engine conversion caused lower sensitivity of pollutant emissions to various operating states of internal combustion engines for the use of natural gas, which is a methane fuel, compared to the use of diesel fuel in a self-ignition engine. Specific brake emission of carbon oxide is the most sensitive to the operating states of the engine: 0.324 for a self-ignition engine and 0.264 for a spark-ignition engine, with the least sensitive being specific brake emission of nitrogen oxide: 0.121 for a self-ignition engine and 0.097 for a spark-ignition engine. Conversion of the engine from self-ignition into spark-ignition (and therefore changing diesel fuel into methane fuel) was characterized by the environmental advantages.

In the second stage of the work, it was found that the specific brake emissions of carbon monoxide and hydrocarbons were similar and relatively high for the stationary CHP engines. Specific brake emission was over 0.9 g/(kW·h) and over 0.5 g/(kW·h) for carbon monoxide and hydrocarbons respectively, for both engines. Significantly, the specific emission of carbon monoxide and hydrocarbons for the Cummins engine in both versions (fueled with the diesel fuel and natural gas as a substitute for biomethane) was relatively low (above 0.4 g/(kW·h) of carbon monoxide and above 0.2 g/(kW·h) of hydrocarbons for the SI engine and respectively above 0.5 g/(kW·h) of carbon monoxide and above 0.6 g/(kW·h) of hydrocarbons for the CI engine). The specific brake emission of nitrogen oxides was achieved at about 1 g/(kW·h) and 3 g/(kW·h) for MAN E3262 LE212 and Liebherr G9512 respectively, while for Cummins engines, it was significantly higher.

The application of biogas for supplying CHP spark-ignition engines provided tangible ecological advantages only in terms of nitrogen oxides emission in comparison with using diesel-fueled self-ignition engines. Suppling the Cummins engine with natural gas caused a significant reduction of hydrocarbons and carbon monoxide levels of emission. Generally, it can be stated that the change of conventional fuel into methane fuels causes a significant decrease in the emission of pollutants particularly harmful to the health of living organisms, and others that are hard to eliminate, primarily particulates and nitrogen oxides, as well as carbon oxide, under conditions simulating the operation of an internal combustion engine for driving a power generating set.

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Nomenclature

ANG	Adsorbed Natural Gas
BANG	Adsorbed Biomethane
BCNG	Compressed Biomethane
BF	Biogas Fuel
BLNG	Liquefied Biomethane
CHP	Combined Heat and Power
CI	Compression Ignition
CNG	Compressed Natural Gas
CO	carbon oxide
CO_2	carbon dioxide
CO_2-eq	carbon dioxide equivalent
DF	Diesel Fuel
e	specific brake emission
ECE	Economic Commission for Europe
ESC	European Stationary Cycle
GHC	Greenhouse Gas
HC	hydrocarbons
ISO	International Organization for Standardization
LNG	Liquefied Natural Gas
LPG	Liquefied petroleum gas
M_e	torque
MF	Methane Fuel
NGVs	Natural Gas Vehicles

NO_x	nitrogen oxides
NRSC	Non-Road Stationary Cycle
P_e	effective power
PM	particulate matter
RED	Renewable Energy Directive
SI	Spark Ignition
W	variation coefficient
δ	relative decrease
η_e	general efficiency

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