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THE POTENTIAL OF GASEOUS ALTERNATIVE FUELS AND LEGAL CONDITIONS OF THEIR USE IN CAR ENGINES AND MACHINES IN THE CONTEXT OF IMPACTS ON THE ENVIRONMENT.

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Abstract

This publication presents the possibility of using gaseous alternative fuels, in particular based on methane, such as Compressed Natural Gas (CNG), Liquefied Natural Gas (LNG) or agricultural biogas and hydrogen, which gain in popularity as fuels for engines used in the automotive industry, in the segment of both passenger cars and trucks. Increasing efforts to reduce emissions of carbon dioxide (CO_2), carbon monoxide (CO), oxides of nitrogen (NOx) and particulate matter into the atmosphere have been supported by legal environment shaped both at European Union level and in international regulations and translate into the growing importance of alternative gaseous fuels. This publication will present, among other things, the essential elements of "Clean energy for Transport", and "type approval of motor vehicles with respect to emissions" directives and of the Kyoto 1997 Climate Change Conference. It also demonstrates potential economic benefits of replacing traditional fuels with alternatives gas fuels. Cities of Tychy and Gdynia, which implement environmentally friendly solutions for public transport services, will serve as an example. The publication also recognizes direct environmental benefits arising from the replacement of currently used fuels – gasoline and diesel – with natural gas and fuels derived from renewable energy sources. In particular, the following publication deals with the use of gases, which are a by-product of human activity – gases from animal breeding and coal, mine methane drainage.

Keywords: *CNG, LNG, methane, gaseous-fuelled engines, methane in the automotive industry, alternative fuels, exhaust gas emissions*

1. Introduction

Over the past 25 years, the quality of atmospheric air in EU member states has doubtlessly improved. During that time various legal instruments have been designed and implemented to aid atmospheric air quality improvement (also by sector: in road transportation, industry, agriculture) by asserting control over the emissions of substances harmful to both human health and natural environment [1]. Much attention in European and global legal regulations has been also paid to reductions of greenhouse gases, especially CO_2 and methane. Key legal acts and agreements that bind the signatory states to reduce negative impact on natural environment include among others:

- The Kyoto 1997 Climate Change Conference protocols, according to which by 2012 own emissions had to be reduced by the negotiated amounts (at least 5% of the emissions level in 1990 of carbon dioxide, methane and nitrogen oxide as well as HFC, PFC and SF6 – i.e. gases that contribute to the greenhouse effect). Although the treaty expired in 2012, EU and some other countries agreed to extend their declarations resulting from the treaty until 2020,
- Directive 2001/77/EC of 2001 titled "On the promotion of electricity produced from renewable energy sources in the internal electricity market", which legally binds EU member states to take adequate steps aimed at increasing the consumption of electricity from renewable energy sources and at using renewable energy sources,

- A series of EU directives introduces European emission standards that regulate the emission of nitrogen oxides (NOx), hydrocarbons (HC), carbon oxides (CO) and particulate matter (PM) from cars, trucks, buses, trains, tractors and other agricultural machinery, as well as barges, yet excluding seagoing ships and airplanes. Drive unit manufacturers are therefore forced to search for new design solutions or to introduce new, alternative and more environmentally friendly fuels. Emission limit values for particular standards are shown in Tab. 1,
- EU directive "Clean Power for Transport" of 2014, which is aimed at reducing both the dependence of EU's transport on oil and the emissions of exhaust gases caused by transport, requires member states to deploy alternative fuels refuelling infrastructure. The main obligations resulting from the document are inter alia the development and implementation of construction plans for:
  a) compressed natural gas (CNG) fuelling stations and electric vehicle charging stations in big urban areas by 2020,
  b) CNG fuelling stations (every 100 kilometres) and LNG stations (every 400 kilometres) for transit transport along TEN-T transport routes by 2025.

Additionally, some member states incurred voluntary obligation to build hydrogen-fuelling stations in urban areas by 2025. Poland did not sign this obligation.

Tab. 1. Values of emission limits for exhaust gases in EURO standards

Emissions [g/km]	Engine	EURO 1	EURO 2	EURO 3	EURO 4	EURO 5	EURO 6
CO	Gasoline	2.72	2.20	2.30	1.00	1.00	1.00
	Diesel	3.16	1.00	0.64	0.50	0.50	0.50
HC	Gasoline	-	-	0.20	0.10	0.10	0.10
	Diesel	-	0.15	0.06	0.05	0.05	0.05
NO_x	Gasoline	-	-	0.15	0.08	0.06	0.06
	Diesel	-	0.55	0.50	0.25	0.18	0.08
HC+ NO_x	Gasoline	0.97	0.50	-	-	-	-
	Diesel	1.13	0.70	0.56	0.30	0.23	0.17
PM	Gasoline	-	-	-	-	0.005	0.005
	Diesel	0.14	0.08	0.05	0.009	0.005	0.005

2. Green transport

The above regulations and actions that follow play a doubtlessly very important role in stimulating the positive trend to reduce emissions of most of harmful substances to the atmospheric air. By way of example, between 1990 and 2010 total emission to the atmosphere of ozone precursors, i.e. carbon oxide and nitrogen oxides has fallen by 62% and 47%, respectively. Since 1990, emission of nitrogen oxides from road transport has been reduced by approximately 40%, mainly due to the introduction of three-way catalytic converters in cars, as well as of more rigorous regulations regarding emissions of harmful substances from heavy transportation vehicles in Europe. Considering the influence of road transportation on nitrogen oxides and carbon oxide emissions, this may be judged an unquestionably significant achievement. In 2012 vehicle car, transportation alone generated harmful substances that amounted to 42% of total NO_x compounds emissions, 29% of total CO emissions and over 30% of total CO_2 emissions [3]. The percentage changes of some harmful substance emissions from EU's economic sectors as compared to a given substance's total emission level in 2012 are shown in Fig. 1 (data for 27 member states).

Despite the above listed successful results, inappropriate quality of atmospheric air in Europe, including Poland, continues to produce particular effects:

- negative impact on human health of particulate matter and ozone (and to smaller extent also of nitrogen dioxide, sulphur dioxide, carbon oxide, lead or benzene), as well as negative impact of

heavy metals and organic pollutants on human health and the surrounding ecosystems,
- damage of various types of materials due to exposure to acid contamination and ozone,
- climate warming due to high CO_2 and methane emissions to the atmosphere.

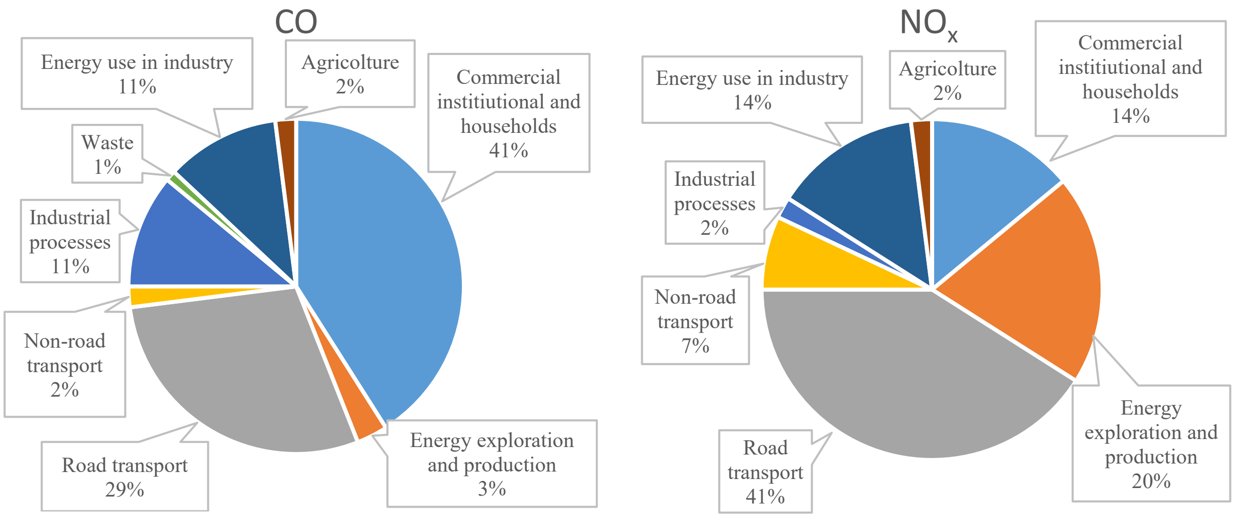

Fig. 1. Harmful emissions from particular economic sectors as compared to a given substance's total emission level in EU in 2012 – percentage share [3]

This creates the need to continue support for actions aimed at decreasing the amounts of harmful compounds and greenhouse gases emitted to the atmosphere. The importance of transport sector for the above-mentioned processes justifies focusing the efforts on this particular branch of economy. The influence of cars on natural environment can be precisely estimated only after analysing all components, inter alia primary energy sources (fossil or renewable), type of energy used to power the vehicle and type of propulsion system used (internal combustion engine, electric motor powered from batteries or fuel cells). The above-mentioned components serve as the basis for CWEG (Cost, Water, Energy, Greenhouse Gases (GHG)) score [5]. The score was used to create a rank, in which the highest number of points indicates the most environmentally friendly vehicle over its complete life cycle. Cars powered with compressed natural gas scored 70.61 points. Subsequent positions were taken by vehicles powered with:
- diesel (CWEG=40.89),
- ethanol (CWEG=37.43),
- hydrogen from coal gasification (CWEG=36.84),
- gasoline (CWEG=35.81),
- Hydrogen from electrolysis using power from the electric grid (CWEG=12.84).

The above comparison shows that vehicles powered with compressed natural gas are most environmentally friendly, unlike hydrogen-powered vehicles using electricity from the grid. The latter vehicles occupy the lowest position despite the fact that when running, they do not emit any harmful compounds. Traditional gasoline and diesel engines have a remarkably lower CWEG score than CNG-powered engines. Big city centres are densely populated places where harmful substances may affect many people for long periods. Therefore, harmful emissions in those areas should be handled with much care, especially as the emissions in those areas are particularly intensive due to business and public activity as well as to gigantic traffic congestion. The most common source of harmful emissions from transport in the cities are public transport buses [2], The majority of which is equipped with diesel engines known for heavy emissions of nitrogen oxides and particulate matter, further increased due to the fact that the buses' operating conditions vary in time, e.g. during acceleration [7]. Another serious issue is the noise emitted by public transport buses. Hence, solutions are searched that decrease the impact of public transport buses on human health and the environment. Therefore, support to initiatives aimed at increasing the usage of natural gas to power internal combustion engines, especially on public transport buses, seems justified.

Pro-environmental properties of natural gas result mainly from the fact that its main flammable constituent is methane CH_4, whose content varies, depending on gas source, from 90% to 99%. Methane is the simplest hydrocarbon with one carbon atom and is commonly known to be non-toxic. As methane particle comprises one carbon atom and four hydrogen atoms, burning it produces approximately 24.5% less carbon dioxide than burning traditional liquid fuels. Methane used to power vehicle engines may be also produced from biogas, the product of anaerobic fermentation of biomass, i.e. of sewage sludge, animal waste (liquid and solid manure), agro-food waste, energy crops (corn, grass, sugar beet etc.) or landfill biomass. By way of example, 1 m^3 of liquid manure may give 20 m^3 of biogas and 1 m^3 of solid manure may give 30 m^3 of biogas of calorific value approximately equal to 23 MJ/m^3. The biogas thus produced, intended for use in vehicle engines, must be subjected to conditioning processes, which consist in removing CO_2, water, H_2S and other impurities present in raw biogas. To be considered vehicle fuel, biogas must meet the following purity standards: minimum 96% of methane content and vapour content lower than 15 mg/Nm^3, H_2S content not exceeding 100 mg/Nm^3, and particulate matter size not greater than 40 micrometres. Another significant source of methane for engines may be bituminous coal mines, which are second largest, after landfills, percentage source of methane emissions in the country. Methane drainage of bituminous coal beds and prospective methane filtering from mine ventilation air may positively affect coal-mining safety, as methane – despite intensive preventive actions – remains one of the greatest dangers in Polish mining industry. Other sources of methane emissions are shown in Fig. 2.

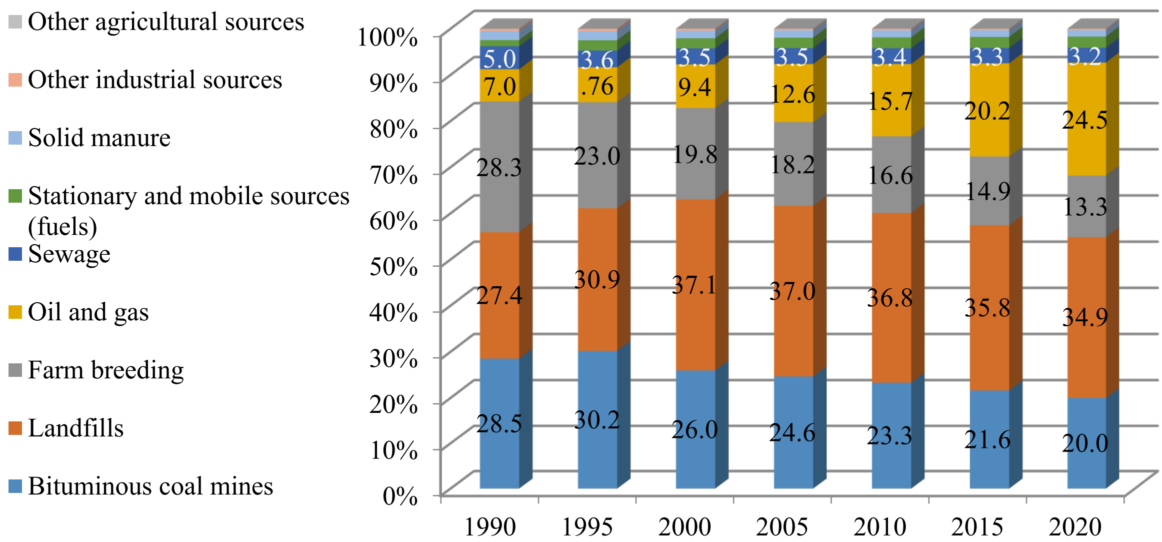

Fig. 1. Structure of methane emissions in Poland with forecast up to 2020 [8]

Another important fact is that only water vapour and carbon dioxide are greenhouse gases that have more devastating influence on the environment than methane has. Regardless of its source, methane escaping to the atmosphere contributes to climate change. Estimations show that its influence as greenhouse gas may be even 21 times greater than carbon dioxide, and hence it is considered a greater threat to the environment. Reducing methane emissions by 1 metric ton gives results similar to avoiding emission of 21 metric tons of CO_2, which is why devising means to reduce methane emissions to the atmosphere has become a necessity. One of the possible solutions might be to use methane as energy source, including as fuel in transport. This mode of utilization is where Global Methane Initiative sees great perspective for environment protection, generating an impulse for economic growth and increasing energy security. The partnership was established in 2004 and consists of over 40 countries worldwide (including Poland, which joined it in 2007), as well as more than 1000 public and private organizations. Its main goal is to limit methane emissions and use it as energy source in the country's economy. Implementation of GMI initiatives includes harvesting methane from:

- coal mines,
- landfills (landfill gas) and sewage systems,
- gas and petroleum installations,
- agriculture.

3. Domestic sources of methane

The potential for using methane in Polish economy, as an alternative fuel in car transport, agricultural machinery and in energy industry becomes especially important in the view of current geopolitical situation and growing need for the diversification of supplies of energy sources. Effective utilization of the vast potential offered by Polish methane emission sources may become for Poland a solution and at the same time a great chance to significantly limit the dependency on external energy resources. Analysis of those sources shows that methane content in Polish mines was estimated to reach 828.24 million m^3 in the previous year alone. This value means that each minute 1574.72 m^3 of CH_4 were emitted. Significantly, in previous years absolute methane content in bituminous coal mines has systematically risen, despite decreasing number of mines and mining production levels. The reason for such situation is that mining operations are performed on increasingly lower levels. For comparison, in 1999 absolute methane content in mining plants reached 744.5 million m^3, of which 216.15 million m^3 were caught with demethanization systems and 528.4 million m^3 were released, together with ventilation air, to the atmosphere. Last year the values were respectively 828.24 million m^3, 266.75 million m^3 and 561.49 million m^3 [13]. As can be observed, although demethanization efficiency increased from 29% to over 32%, additional 33 million m^3 of the greenhouse gas were released to the environment. The observed increase in demethanization efficiency of approx. 3-4% over the last 10 years cannot be viewed with optimism, if noted that at the same time the level of methane hazard measured by the amount of methane released per unit of production (m^3/t) grew by approx. 55%. In Poland, most methane in coal deposits may be found in the area of Upper Silesian Coal Basin. Researched and documented economic resources of recoverable methane are 99.04-bn m^3, of which currently mined deposits contain approx. 33.7 bn m^3, while yet unmined reserve deposits and deep deposits (below 1 km) contain approx. 66 bn m^3. Potential resources of methane form coal deposits in Upper Silesian Coal Basin are up to 350 bn m^3 [6]. Prospective and estimated resources in Upper Silesian Coal Basin are believed to be approx. 254-bn m^3, of which economically recoverable resources are 150-bn m^3. The numbers for Lublin Coal Basin and Lower Silesian Coal Basin are less promising, with prospective resources of approx. 15 bn m^3 and 1.75 bn m^3 respectively [9].

Documented natural gas deposits in Poland, which are at the disposal of Polish main gas (and petroleum) producer – PGNiG S.A. – comprise 98-bn m^3 [10]. Polish natural gas resources are located mainly in the Polish Lowland region (66% of documented resources), the Carpathian Foreland region (29.5%), Polish Exclusive Economic Zone of the Baltic Sea (3.2%), and the Carpathian Mountains (only approx. 0.9%). The above estimations concern conventional natural gas, while unconventional resources are estimated by independent consulting companies to comprise 1.4 trillion m^3 (Wood Mackenzie), or 3 trillion m^3 (Advanced Resources International). Poland may also have approx. 150-bn m^3 of shale gas [12].

Referring now to landfills, which are the second methane emission source, in optimal conditions one metric ton of waste may serve to produce 400-500 m^3 of landfill gas. However, not all-organic waste is fully degradable and fermentation processes depend on several factors.

Therefore, assumed amount of landfill gas obtainable from one metric ton of waste is estimated at approx. 200 m^3. At present, Poland has approx. 700 active landfills registered. Their annual methane production has been estimated at over 600 million m^3. Practically recoverable landfill gas resources do not exceed 30-45% of the total landfill potential. Therefore, methane resources practically recoverable from landfills are estimated to be 135-145 million m^3 annually. As is the case with methane in bituminous coal deposits, this potential is also currently exploited to a limited degree. Biogas from sewage treatment plants also has high technical potential. Poland has presently 4300 sewage treatment plants and this number is growing. Normally 1 m^3 of sludge (4-5% of dry matter) is enough to obtain 10-20 m^3 of biogas comprising 60% methane. Biological sewage treatment systems, which are used in all public treatment plants and in part of industrial treatment plants, are best suited to direct production of biogas. As treatment plants have relatively high auxiliary electrical and heat energy demand, using biogas from sludge fermentation as source of power may significantly increase their economic viability. Economic constraints, however, limit the use of biogas as power source only to larger treatment plants, with capacity exceeding 8000-10,000 m^3 of sludge per day.

The potential for tapping methane from animal waste produced by Polish animal farms is estimated at 3.31 bn m^3 annually, but practical biogas installations are possible only in large-scale animal farms.

4. Methane as a fuel

Gas obtained from the above-mentioned resources may become in Poland, just as it is already the case in many other countries worldwide, a common alternative to gasoline and diesel.

This would be impossible without the dynamic development of gaseous fuelling systems, which led to the possibility of using methane as fuel. Such systems currently have several versions. Spark-ignition single-fuel engines use modern solutions based on multi-point injection systems. Such solutions are very popular in buses and are developed by several major manufacturers, including MAN, Volvo, Fiat, Peugeot, or Mercedes. Adapting diesel engines to gaseous fuel is also possible, although it involves design modifications. Despite this complication, most buses in Poland that run on gas have modified diesel engines. Solutions based on single-fuel engines are judged to offer best economic effects. Another solution includes biofuel or biopower engines adapted to run on both gas and gasoline. Such vehicles are manufactured by many producers but are also the result of modifications introduced to originally gasoline-powered vehicles. The usual procedure is to equip the vehicle with a small gasoline tank (approx. 15 litters) and bigger CNG tanks (approx. 120-150 litters). Apart from the tanks, the vehicle is also equipped with appropriate systems for feeding gaseous fuel and controlling its delivery to the engine. Another solution, called dual-fuel, is based on delivering a mixture of diesel and gas to the CI engine. For each stroke cycle, the engine uses little portion of diesel for pilot ignition, and the resultant temperature enables burning of methane-air mixture. Such solution is possible due to large-scale implementation of common rail systems, which enable precise control of pilot dose and thus assure expected results.

Another classification of natural gas fuel systems may be done in relation to fuel storage methods in the vehicle and fuel source. Storage methods are an important issue, as natural gas under normal ambient conditions has very low density (over 1000 times lower in comparison to traditional liquid hydrocarbon fuels) and therefore to power vehicle engines it requires implementation of adequate storage methods – compression or liquefaction. As far as gas sources are considered and natural gas is distinguished from purified biogas, further classification might include compressed natural gas (CNG) and compressed biogas (CBG). The two types are the result of compression up to 20-25 MPa, which leads to an increase in density of up to ρ_g =160 kg/m3, rising stored energy density approx. 220 times. Compressed gases are stored in pressure tanks made of steel or composite materials. The tanks are filled using gas compressor or through levelling the pressure between distributor tank and vehicle tank.

Another method comprises using liquefied natural gas (LNG) or liquefied biogas (LBG). Liquefaction process requires lowering of gas temperature and maintaining it below boiling temperature, i.e. approx. -162 °C at normal pressure. Liquefied gas density is almost 580 times higher than in normal conditions and equals ρ_g=425 kg/m3. This kind of fuel is stored in a special cryogenic tank, usually with vacuum insulation, which reduces heat transfer into the tank. Present generation of IC piston engines powered with liquefied gas has no technology that would allow for delivering gas in liquid form directly to the engine. In all presently used fuel feeding and delivery systems, liquid gas is not allowed to enter the engine – it must be first evaporated in an exchanger, which uses heat from the vehicle's cooling system. Therefore, versions of engine feeding and delivery systems are the same for both compressed and liquefied gas. Only fuel storage methods are different.

5. Economic benefits

In the view of the above issues, consideration should also be given to the economic viability of using natural gas or biogas to power vehicle engines, especially public transport bus engines. The considerations will be based on the example of Przedsiębiorstwo Komunikacji Miejskiej sp. z o.o. in Gdynia (Public Transport Services in Gdynia Inc.), which put into service buses powered with compressed natural gas as a result of the project titled "CNG – Green Public Transport for Gdynia". 16 buses were purchased (5 vehicles in 2007, 5 vehicles in 2009, 4 vehicles in 2010 and 2 vehicles in 2012), which covered a total distance of 4.93 million kilometres between September 2007 and September 2012 and allowed the company to save 3.916 million pln as compared to other diesel-powered buses operated by the company. Additional savings were brought by lower environmental taxes due to emission reductions of car exhaust by 809 metric tons, as well as emission reductions of toxic compounds such as: NOx by 50-80%, CO_2 by 20%, CO by 60-80%, PM10 by 99%, aldehydes by 70%, aromatic hydrocarbons by 90% [4]. Similar conclusions can be drawn in case of Przedsiębiorstwo Komunikacji Miejskiej sp. z o.o. in Tychy (Public Transport Services in Tychy Inc.), which currently uses as many as 40 CNG buses that annually cover total distances of approx. 2.9 million km. Using CNG as fuel for buses between January 2012 and March 2014 allowed the company to save 2.26 million pln, as compared to diesel buses. As was the case with Public Transport Services in Gdynia, environmental taxes were also lowered from almost 50,000 pln in 2008 to 13,500 pln in 2013 [11].

6. Conclusions

According to the expectations of European Natural Gas Vehicles Association, by 2020 the share of alternative fuels in automotive sector will grow to 20-23%, with natural gas and biomethane being the second most popular fuel for vehicles in EU, after liquid fuels. This means that European roads will be used by approx. 23 million vehicles running on methane, i.e. 20 times more than at present. The reason is that methane as an alternative fuel has the greatest potential for being used to power piston IC engines [14] due to its features that include accessibility, ecological combustion process in IC engine, ability to be stored in the vehicle, attractive pricing as compared to traditional fuels. Endeavours to use biomethane, which is a fully renewable alternative fuel, should be considered of particular strategic importance in Poland, as it is also part of the efforts to make the country's economy independent from imported oil and natural gas.

Public transport buses with engines powered by biomethane have been already made widely popular in many European countries (e.g. Sweden and Norway). Vehicles that run on this fuel are also operated by other public services, as well as postal companies and waste disposal companies. The potential offered by the country's resources of natural gas, biomethane and methane that accompanies bituminous coal deposits was also noticed in Poland, allowing starting the same processes. The next necessary step at this stage is to create favourable legal regulations that would stimulate the development of infrastructure and help create conditions for popularizing methane as alternative source of energy.

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