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Biomethane as an Environment-Friendly Fuel for Municipal Transport

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Abstract

An idea to replace the conventional engine fuel with biomethane has been described. The effects of such a swap have been analysed for municipal transport buses in Warsaw. The replacement has been shown to result in a significant reduction of toxic exhaust emissions and in economic savings. The analysis results have been presented in the form of tables and graphs.

1. Introduction

Declining resources and rising prices of crude oil result in increasing importance of natural gas as an engine fuel. The natural gas makes it possible to cut vehicle operation costs and to reduce toxic exhaust emissions. In 2020, methane will make 10% of the whole market of automotive fuels, according to forecasts of the EU Energy and Transport Directorate-General.

Increasing use of compressed natural gas (CNG) as an engine fuel for municipal transport may be observed in many countries. The introduction of city buses fuelled with natural gas makes it also possible to use biomethane for this purpose.

Biomethane is obtained during methane fermentation of organic waste. For the production of this gas, agricultural, municipal, and industrial waste may be used. This means that the municipal waste generated by urban agglomerations may be utilised for the production of the fuel used by city buses and other municipal vehicles. The fuels of this kind are generally considered as being environment-friendly.

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Since 2006, the Department of Vehicles of the University of Zielona Góra has been participating in the European project entitled "Biogasmax – Biogas as vehicle fuel" [1]. The Biogasmax program is conducted by 28 participants from 8 European countries, i.e. Switzerland, France, Sweden, the UK, the Netherlands, Germany, Italy, and Poland. The geographic range of the project is shown in Fig. 1.

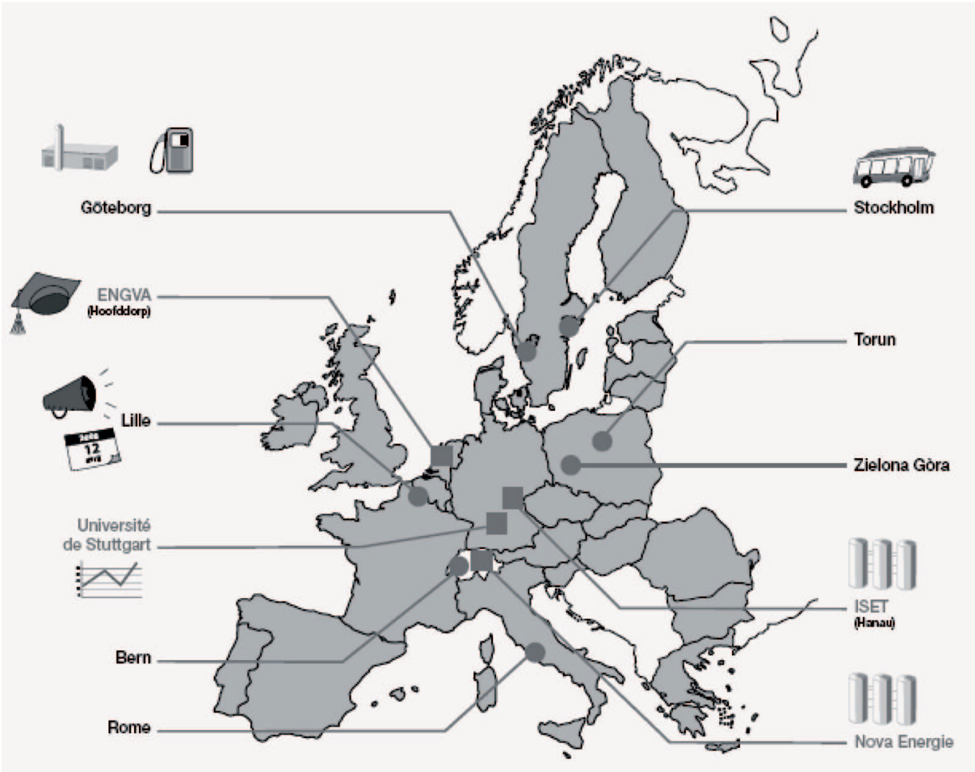

Fig. 1. Participants in the Biogasmax project

The main objective of this project is examining of the technical reliability, cost-effectiveness, and environmental and social benefits of the use of biomethane fuels. A method making it possible to evaluate the economic and environmental benefits of the use of biomethane for the fuelling of municipal transport buses, specially developed for the purposes of this project, has been presented in a subsequent part of this paper. Moreover, such an analysis has been carried out with the use of this method for the city of Warsaw.

The vehicle exhaust gases contain a variety of compounds harmful for human health and the environment. The most poisonous components of the exhaust gases are hydrocarbons (HC), nitrogen oxides (NO_x), carbon oxides (CO), solid particles, and small quantities of butadiene, benzene, formaldehyde, and acetaldehyde.

The vehicle exhaust gases are particularly dangerous in large urban agglomerations. City buses run close to buildings and places with human traffic, with emitting pollutants dangerous to human health. In European cities, efforts are made to reduce the emission of harmful components of bus exhaust gases. The gas fuelling of bus engines is increasingly used. Biogas becomes an alternative for diesel oil. In terms of the energy obtained, the total emission of pollutants generated during the whole cycle of the obtaining and use of various vehicle fuels is the lowest in the case of CNG (Fig. 2). However, biomethane is even better in this respect.

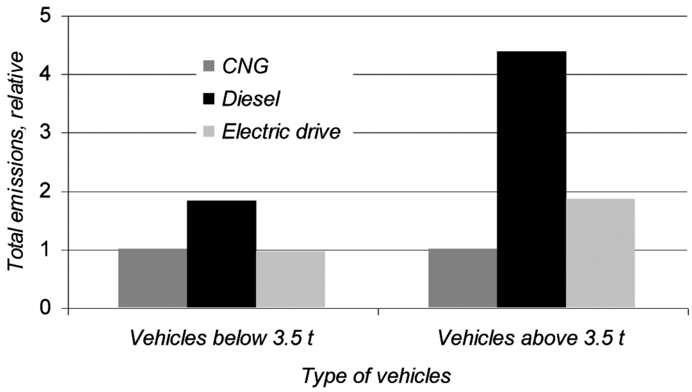

Fig. 2. Total exhaust emissions for different fuels in comparison with CNG [2]

For CNG, the emissions of specific exhaust pollutants are lower than those recorded for diesel oil (Fig. 3). The exhaust gases do not contain SO_2 or smoke and the smog effect is not generated, thanks to which methane is more environment-friendly than conventional vehicle fuels.

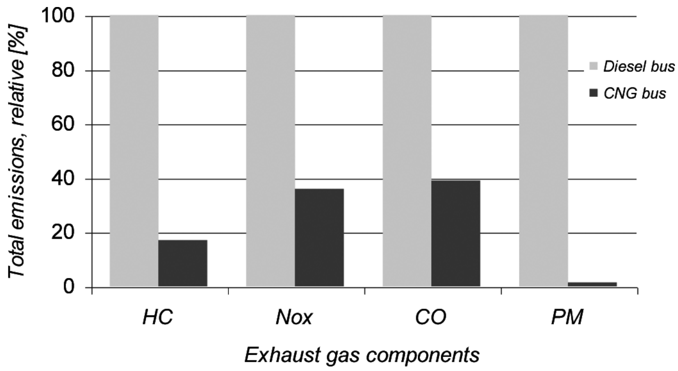

Fig. 3. Exhaust emissions of buses fuelled by diesel oil and CNG [2]

2. Biomethane as an Engine Fuel

Biogas is generated in result of the process of anaerobic fermentation of organic waste taking place with participation of methanogenic bacteria [2]. The methane content in biogas reaches a level of 65%; the remaining gas components include carbon dioxide, hydrogen sulphide, hydrogen, carbon monoxide, nitrogen, and oxygen. The average chemical composition of biogas is presented in Table 1.

The biogas output and quality depends on the type of input materials, fermentation degree, and process time and temperature. The input materials used for biogas production chiefly consist of organic waste, including municipal waste.

Table 1

Chemical composition of biogas

Component	Percentage content [%]
Methane (CH_4)	52÷85
Carbon dioxide (CO_2)	14÷18
Hydrogen sulphide (H_2S)	0.08÷5.5
Hydrogen (H_2)	0÷5
Carbon monoxide (CO)	0÷2.1
Nitrogen (N_2)	0.6÷7.5
Oxygen (O_2)	0÷1

For biogas to be suitable for vehicle fuelling, it must be finally purified so that its methane content is raised to approximately 92÷96%. During the final purification of biogas, such components as carbon dioxide, hydrogen sulphide, and siloxanes are removed from it [2]. The biogas upgrading process may be divided into the following stages: compression, cooling, absorption of carbon dioxide and hydrogen sulphide, drying, and removing of siloxanes. Carbon dioxide and hydrogen sulphide are absorbed with the use of special absorbent. The gas leaving the absorption column consists in 95÷98% of methane. At the next process stage, the gas is subjected to absorption drying to a level at which the separation of condensate is no longer possible. The filtering out of siloxanes in a filter with active carbon is the finishing stage of the biogas upgrading process. Siloxanes are chemical compounds of silicon, oxygen, and hydrogen, which are accountable for the precipitation of deposits. The methane content in the biogas obtained in result of such a process ranges from 98 to 99%. The biogas thus upgraded is suitable for the fuelling of vehicle engines.

3. Effects of Swap Diesel Oil for Biomethane

3.1. Economic effects

The analysis was based on an assumption made that the quantity of mechanical energy E_M generated by the bus engine should be identical regardless of the fuel type used. In the analysis, the calorific value and mass of both fuel types as well as the effective efficiency of both types of the IC engines were taken into account.

So, the quantity of mechanical energy E_M generated in result of the combustion of 1 dm^3 of diesel oil by a bus engine will be:

$$E_M = \rho_{DO} \cdot w_{DO} \cdot \eta_{DO} \cdot D_{DO} \tag{1}$$

where:

ρ_{DO} = mass density of the diesel oil used in the municipal transport system;
w_{DO} = calorific value of the diesel oil;
η_{DO} = efficiency of the diesel engine;
D_{DO} = volume of the diesel oil consumed;
E_M = the quantity of mechanical energy to be determined.

Using equation (1), we may also determine the quantity of natural gas needed to obtain the same quantity of mechanical energy E_M as that generated by the combustion of 1 dm^3 of diesel oil. Thus:

$$D_{CNG} = \frac{E_M}{\rho_{CNG} \cdot w_{CNG} \cdot \eta_{CNG}} \tag{2}$$

where:

E_M = mechanical energy;
ρ_{CNG} = mass density of natural gas;
w_{CNG} = calorific value of natural gas;
η_{CNG} = efficiency of the gas-fuelled engine;
D_{CNG} = quantity of CNG in m^3, equivalent in energy terms to 1 dm^3 of diesel oil consumed.

Knowing the mass of 1dm^3 of diesel oil and the mass of the energy-equivalent quantity of CNG, we may now calculate the gas-to-oil mass fuel consumption growth ratio:

$$\Delta_{FC} = \frac{G_{CNG} - G_{DO}}{G_{DO}} \tag{3}$$

where: $G_{DO} = D_{DO} \cdot \rho_{DO}$; $G_{CNG} = D_{CNG} \cdot \rho_{CNG}$

Hence, the CNG mass equivalent in energy terms to 1 dm^3 of diesel oil is:

$$G_{CNG} = \frac{\rho_{DO} \cdot w_{DO} \cdot \eta_{DO} \cdot D_{DO}}{w_{CNG} \cdot \eta_{CNG}} \tag{4}$$

The increment in CNG consumption as against that of diesel oil will be:

$$\Delta_{FC} = \frac{w_{DO} \cdot \eta_{DO}}{w_{CNG} \cdot \eta_{CNG}} - 1 \tag{5}$$

Based on the annual number of kilometres travelled and the consumption of diesel oil, the annual mass CNG consumption of all the buses of a specific type has been determined as:

$$G_{CNG/a} = G_{DO/a} \cdot \frac{w_{DO} \cdot \eta_{DO}}{w_{CNG} \cdot \eta_{CNG}} \tag{6}$$

By summing-up the annual CNG consumption for all the bus types used by a specific company, the fuel purchase costs may be calculated. Based on the method and assumptions as above, a computer tool has been developed to estimate the financial benefit obtainable from the diesel oil-for-CNG swap within a specific company.

3.2. Ecological analysis

The toxicity of exhaust gases was analysed by calculating the annual average work done by every bus, with taking into account the emissions of specific exhaust gas components per unit work done. Individual vehicles were categorised in terms of the exhaust emission standards met. The total annual emissions of individual exhaust gas components were calculated for the fuelling with diesel oil and then the same was done with an assumption made that the same buses would be fuelled with biomethane or natural gas.

The work done by a bus was calculated from a formula:

$$W_d = P_{av} \cdot k_N \cdot \frac{S}{V_{av}} \tag{7}$$

where:

W_d = work done by a bus [kWh];

P_{av} = maximum engine power [kW];

k_N = power utilisation factor [%];

S = annual number of kilometres travelled by the vehicle [km];

V = average cruising speed [km/h].

The quantity of toxic components of exhaust gases annually emitted by a bus is:

$$T_x = L_x \cdot W_d \tag{8}$$

where:

T_x = quantity of toxic exhaust compounds of the "x" type, emitted in result of the combustion of a specific energy carrier [g];

L_x = quantity of the "x" type pollutants emitted when the work done by the bus is 1 kWh [g/kWh].

Based on the method and assumptions as above, a computer tool has been developed, thanks to which the environmental impact of fuel replacement may be evaluated quickly and easily.

4. Analysis for the City of Warsaw

The analysis was based on data obtained from Municipal Bus Service Company in Warsaw. The calculations were done for all the Company's buses with the use of the computer tool developed. The results obtained have been presented in Table 2.

Table 2

Economic effects of fuel replacement in municipal buses in Warsaw

Bus model	Quantity of buses	Annual expenditure for diesel oil [PLN]	Annual expenditure for CNG [PLN]	Gain from the fuel replacement [PLN]
IKARUS 260	119	10 524 106	4 902 920	5 621 186
MAN NM 223	15	1 144 091	533 003	611 087
JELCZ M121M	109	11 245 173	5 238 847	6 006 326
JELCZ 120MM	39	3 355 711	1 563 342	1 792 368
SOLARIS URBINO 12	120	8 629 935	4 020 472	4 609 462
JELCZ M121 (M 121l4)	50	6 528 412	3 041 425	3 486 987
Other, non-articulated	3	18 236	8 496	9 740
IKARUS 280	340	33 969 688	15 825 635	18 144 052
NEOPLAN	103	13 864 023	6 458 904	7 405 118
JELCZ M181M MB	46	5 982 827	2 787 250	3 195 576
SOLARIS URBINO 15	167	21 253 959	9 901 692	11 352 267
MAN NG 313	103	19 574 925	9 119 472	10 455 453
SOLARIS URBINO 18	250	34 622 452	16 129 742	18 492 710
Large capacity buses	5	156 644	72 976	83 667
TOTAL	1469	170 870 190	79 604 184	91 266 006

Similarly, the impact of the fuel replacement on toxic exhaust emissions was analysed with the use of the computer tool developed. The calculation results were summarised in Tables 3 and 4.

The pollutant emissions of all the municipal transport buses in Warsaw fuelled by diesel oil and CNG have been summarised in Table 5. As it can be seen, the toxic exhaust emissions significantly dropped, even by about 80÷90%, depending on specific pollutants.

5. Recapitulation and Conclusions

The data obtained from the Municipal Bus Service Company in Warsaw made it possible to estimate the annual costs of purchasing diesel oil and the energy-equivalent quantity of gas. To carry out the analyses, data concerning compressed natural gas (CNG) were used, with an assumption made that the quantities of energy

Table 3

Exhaust gas emissions of municipal buses in Warsaw fuelled by diesel oil

Bus model (quantity of buses)	Diesel oil fuelling			
	NO_x [t]	CO [t]	PM [t]	HC [t]
IKARUS 260 (119)	298.22	167.75	13.42	41.00
MAN NM 223(15)	25.88	3.42	0.52	3.42
JELCZ M121M(109)	289.01	165.15	6.19	45.42
JELCZ 120MM (39)	105.82	59.52	4.76	14.55
SOLARIS URBINO 12 (120)	129.76	17.05	0.74	17.05
JELCZ M121 (M 121 l4) (50)	108.66	14.28	0.62	14.28
IKARUS 280 (340)	747.76	420.61	33.65	102.82
NEOPLAN (103)	351.26	200.72	7.53	55.20
JELCZ M181M MB (46)	128.06	73.18	2.74	20.12
SOLARIS URBINO 15 (167)	531.42	303.67	11.39	83.51
MAN NG 313 (103)	356.51	47.06	7.13	47.06
SOLARIS URBINO 18 (250)	570.27	75.13	7.70	75.13
TOTAL	3642.63	1376.37	96.39	519.56

Table 4

Annual exhaust gas emissions of Warsaw municipal buses fuelled with CNG or biomethane

Bus model	CNG fuelling			
	NO_x [t]	CO [t]	PM [t]	HC [t]
IKARUS 260 (119)	35,04	11,18	0,60	5,96
MAN NM 223 (15)	4,87	1,55	0,08	0,83
JELCZ M121M (109)	38,81	12,39	0,62	6,61
JELCZ 120MM (39)	12,43	3,97	0,20	2,12
SOLARIS URBINO 12 (120)	34,85	11,12	0,56	5,93
JELCZ M121 (M 121 l4) (50)	29,18	9,31	0,47	4,97
IKARUS 280 (340)	87,86	28,04	1,40	14,96
NEOPLAN (103)	47,17	15,05	0,75	8,03
JELCZ M181M MB (46)	17,20	5,48	0,27	2,93
SOLARIS URBINO 15 (167)	71,36	22,77	1,14	12,15
MAN NG 313 (103)	67,02	21,39	1,07	11,41
SOLARIS URBINO 18 (250)	128,08	40,88	2,04	21,81
TOTAL	573,89	183,15	9,16	97,68

Table 5

Annual exhaust gas emissions of Warsaw municipal buses

	Toxic emissions, diesel oil [t]	Toxic emissions, CNG [t]	Emission reduction [%]
NO_x	3 642,63	573,89	84
CO	1 376,37	183,15	88
PM	96,39	9,16	90
HC	519,56	97,68	81

generated and toxic exhaust components emitted in result of methane combustion do not depend on the source of the methane used as the fuel. The analysis carried out has shown that the natural gas purchase costs will be lower by more than 50% in comparison with the costs of the purchase of diesel oil. It is difficult to estimate the biogas production costs with adequate reliability. These costs will depend on a great variety of factors, including the type of the organic input material used and the gas production technology employed. Therefore, the analyses of this kind should be carried out individually for every specific production case.

The ecological analysis has revealed in turn that the replacement of diesel oil with natural gas or biomethane may result in a reduction of toxic exhaust emissions of the buses operated by the Municipal Bus Service Company in Warsaw to even less than one tenth. It should be stressed, however, that the buses meet various exhaust emission standards (from EURO I to EURO IV). The greatest and lowest reductions took place in the case of particulate matter and hydrocarbons (by about 90% and about 80%, respectively). For details, see Tables 3, 4, and 5.

Therefore, the possibility of replacing conventional fuel with methane in the municipal bus service system is worth considering. If adequate infrastructure is built to generate methane from municipal organic waste then the obtaining of sufficient fuel supply from this source will be realistic. Thus, a number of problems encountered at present by many urban agglomerations would be simultaneously solved. The problem of municipal wastes would no longer exist and the emissions of toxic exhaust components and noise would be considerably reduced, thanks to which our cities would become friendlier towards their inhabitants.

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