Chapter

The Possible Role of Large-Scale Sewage Plants in Local Transport

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Abstract

Large-scale sewage plants in large cities are suitable for the production of large quantities of biogas, using economically viable biogas upgrading technologies and generally available public transport fleets of a sufficient number of local buses, as well as municipal vehicles. The conditions for the sale of locally produced CNGs do not depend on gas suppliers, they can be very well integrated with local waste management, and the local emission reductions occur in the inner city, where air pollution is the most serious problem. At the same time, the cogeneration solution currently of decisive importance for wastewater plants is more economically and environmentally advantageous in the production of biomethane. The consumption of heat and electricity by these plants is significant and must be supplied through the purchase of biomethane. However, for the local authority, when converting diesel buses, compressed biomethane (CBM) offers much greater savings, so at the municipal level, the process is economically profitable. The short-term spread of CBM (due to the small number of filling stations) is bound to local systems. If more and more cities operated a similar system (allowing refuelling within a few dozen kilometres), it would be expected that passenger cars would also be more widespread.

Keywords: sludge management, biomethane, local transport, sustainability, economics

1. Introduction

The EU-28 2016 energy use was 1147 million tonnes of oil equivalent (MTOE), 17% of which was from renewable energy sources; the proportion of renewable fuels was 7.1% [1]. The proportion of renewables was 9.5% in 2006, so renewable energies have cca. 8% growth per year in average during the last decade in the process of energy production [2].

However, the average levelized cost of electricity (LCOE) of fuel generation and biogas electrical power generation is still much higher than the reference [3], and therefore without financial support, it is not competitive with oil and other highly renewable electricity generation technologies (solar panels, geothermal energy, hydropower, solid-fired biomass power plants).

Biogas production is also a remarkable process in terms of the environment and energy production, but its efficiency, with new raw materials, technologies and markets, can be significantly increased. Due to the capital requirements and the uncertainty of innovative solutions, the establishment of biogas plants and their operation and the research conducted in this area are significantly supported by all EU member states. The dominant product of current biogas plants is green electricity, which is supported by competent power suppliers at a subsidised price and is acquired as a compulsory purchase by the relevant electricity suppliers, details of which are given for the EU-27, the EFTA countries and countries waiting to join in [4]. The feeding of biomethane purified with biogas to the natural gas pipeline is regulated by stringent standards in the EU member states, according to Szunyog [5]. However, gas with a lower methane content than natural gas may also be utilised as a propellant, although its compression and transport costs are larger, and the range is smaller than with compressed natural gas (CNG) [6].

Conversion of biogas will always increase investment and operational costs, and the energy efficiency of the process will be reduced, but it will produce more valuable, versatile and marketable main products (electricity, biomethane). According to Hakawatia et al. [7], on the basis of 49 different biogas transformation technology studies, the overall efficiency of the process ranges from 16 to 83% in the case of direct burning of biogas and 8 to 54% for cogeneration (for electricity and waste heat coupled production), while when producing biomethane for fuel, it varied from 4 to 18%. If the electricity generated by cogeneration is used in electric vehicles, the efficiency of propellant use can be increased to 33%.

Most of the wastewater plants produce electricity and waste heat from biogas. The reason for this is clear from direct heat utilisation: it is almost impossible to use biogas exclusively for heating purposes in larger-sized plants and during summer time. On a large scale, however, the summer utilisation of waste heat generated during the cogeneration process is also problematic. In order to avoid the problems of heat utilisation, in the case of large plants, biomethane can be considered as an alternative to biogas purification and the utilisation of by-product carbon dioxide in the algae sewage system. In our chapter, we would like to point out that the inclusion of biogas from wastewater treatment plants in large cities in vehicles involved in local transport (buses, taxis, public utility vehicles) can also be an environmentally and economically promising alternative, of which we can already find many well-functioning examples.

2. The transport sector, CNG and the significance of compressed biomethane (CBM)

Traffic is one of the most significant sectors in the EU-28, with around €651 billion in gross value added a year at basic prices (5% of total), with 11.2 million employees (5.2% of total), 6602 billion passenger km (on average around 12,962 km per person, of this 8.2% with buses and coaches) and about 1183 million tonnes of CO_2 equivalent (30.7% of total). Private households in the EU-28 spent EUR 230 billion on transport services (e.g. bus, train, plane tickets). It should be highlighted that changing consumer attitudes from fuel to more environment-friendly way of transport may help to promote the spreading of sludge-based transport fuels, too [8].

Globally, in 2014 transport was responsible for 23% of total CO_2 emissions from fuel combustion, and road transport was responsible for 20% [9].

At the same time, bus transport is one of the safest modes of transport: only 126 out of the 26,134 traffic deaths in 2015 occurred on buses.

Theoretically the existence of good public transport can deter car ownership. The paper by Cullinane and Cullinane [10] asserts, however, that once a car has been acquired, there is a tendency for it to be used irrespective of how good the public transport is.

Natural gas engine technology is already well established, and millions of vehicles using natural gas are in operation worldwide and suitable for using CBM.

While at the turn of the millennium, a million registered vehicles around the world were powered by CNG; by 2015 this figure had already increased to 22.3 million, an average annual increase of 22%, well above the growth in the total fleet of cars. Typically, most of the gas-fuelled vehicles (Iran, 4 million; Pakistan, 3.7 million; Argentina, 2.5 million; India, 1.8 million) [11] are found in low-income countries with a high population density. In the EU, 3345 refuelling stations provide for the operation of about 1.3 million gas-powered vehicles with an annual gas consumption of around 5 billion cubic metres. For the operation and further spread of this existing transport infrastructure, CBM could make a significant contribution [12].

The spread of biogas plants in the EU has been very rapid over the past decade: rising from 6227 to 17,662 between 2009 and 2013. Growth in farms was primarily significant (12,496 plants), the number of sewage plants was 2838 and the remainder were landfill waste plants. The number of plants has stagnated since 2015, but the installed electric capacity has increased further; currently it is 9985 MW [13]. Anaerobic digestion is a key technology for the treatment of large volumes of biowaste [14].

The energy significance of biogas is underlined by the fact that in the EU, the amount of biogas produced in 2015 reached 18.4 billion normal cubic metre (Nm^3), replacing 4% of natural gas consumption [15]. The amount of biomethane fed to the natural gas pipeline reached 1.5 Mrd m^3 (mainly the Netherlands), while the amount of biomethane used as propellant is considerably less, at 160 M m^3 (Sweden, 113 million m^3; Germany, 35 million m^3; Norway, 10 million m^3; Iceland, 2 million m^3; Finland, 0.2 million m^3) [16].

However, the use of purified biogas for transport in some countries is rapidly expanding: over 30 cities in Sweden power their municipal buses with biogas, which is also used by taxis and sanitation companies [17].

There are 247 biomethane plants around the world and around 80 in the EU. Their technology and the biomethane produced are characterised by the data in **Table 1**.

Regarding environmental performance, methane loss is of great importance, as methane is a greenhouse gas 21 times stronger than CO_2 [19]. As clarified by Beil and Beyrich [20], pressurised water scrubbing (PWS) is one of the best solutions in terms of efficiency and environmental performance.

Cleaning technology	Number of plants	Biomethane CH_4 content (%)	Specific operating costs (USD/Nm^3 biomethane)
Water wash	107	96.1	0.18
Pressure change adsorption	55	95.8	0.34
Chemical (amino) absorption	53	94.6	0.23/0.38*
Membrane	22	90.3	0.16/0.30*
Genosorb©	12	96	n.a.
Cryogen	1	88	0.59

**Hydrolysis purification.*
Source: Own construction based on Yang et al. [18].

Table 1.
Biogas cleaning technology and the cost of cleaning.

We need to grow food on even less land, with less water, using less energy, fertilizer and pesticide than we use today for feeding more and more people [21], so the energy use of wastes (e.g. sewage) instead of plants can be taken as one of the most important reserves of land management; with the use of them, the net use of land declines [22].

3. The environmental and technical characteristics of compressed natural gas (CNG)/compressed biogas (CBG) applications

Among the hydrocarbons known as energy carriers, methane is the simplest formulation molecule, with the highest hydrogen-to-carbon ratio. This feature allows it to achieve uniquely clean combustion among internal combustion engines (**Table 2**).

If the source material of the CNG is biogas, it can save a further 13 kg CO_2e/t when supplied with organic fertilisers, by replacing artificial fertilisers [23].

The CO_2 emissions of biogas plants throughout their life cycle also depend to a large extent on the composition of organic matter. Fuchsz and Kohlhéb [27] calculate that cogeneration-based animal fertiliser-based colonies in electricity production and in all environmental categories (GHG, eutrophication potential, acidification potential) are less effective than biogas plants which (also) use energy crops. This is equally true for both the period of setting up the plant and the operational period. The CO_2 emissions of all three examined types were below the average emissions of electricity currently produced in a natural gas-fuelled power plant. At the same time, Bordelanne et al. [26] explicitly analysed the life cycle of sewage waste, finding that with the fermentation of municipal wastes, energy plants also produce 7–10% less greenhouse gas emissions; thus, the biomethane production of fuel in our test is the most environmentally friendly compared to other biogas raw materials.

Examining the various pollutants, CNG CO and NOx emissions were 50–80% of those for EURO 4 petrol vehicles [26], while CH values were close to the same values.

The technology of diesel buses also significantly influences the environmental impact of CNG/CBM. According to Ryan and Caulfield's [28] estimates, the use of CNG in the case of all diesel particulates used in EURO 2–4 buses was reduced to a minimum of 70% for all pollutants and 100% for SO_2 and heavy metal emissions. The GHG emissions of the CNG tested were also 7% better than the CBM. Compared to EURO 5 buses, the emissions of CNG buses were at least 50% more

GHG savings over the entire life cycle (%)*				
Biomethane raw material	Maize silage	Fertiliser	Municipal solid waste	
Compared to diesel	66	96	95	
Compared to petrol	70	97	96	
GHG emissions produced during engine use (kg/GJ)				
CNG/CBG	Petrol	Diesel	Biodiesel	Bioethanol
56**/65***/74****	74**/93****	73**/93****	76***	71***
*Sources: Own construction based on * [23] ** [24], *** [25], **** [26] (figures refer to life cycles).*				

Table 2.
GHG savings with CNG.

favourable for most air pollutants, but the CO and non-methane volatile organic compound (NMVOC) values for diesel were slightly more favourable.

Regarding the emission factors of petrol- and diesel-fuelled cars and buses, it can be stated with great certainty that bus transport is the best option, in almost any of harmful gases with respect to g/pkm (passenger km), assuming that the car is not full of passengers. The emission factors strongly depend on size and utility of the given vehicles. CO and CH_4 emission is higher in petrol-fuelled cars, while NOx emission is stronger in diesel-fuelled vehicles including buses (**Figure 1**). It should be noted that CH_4 and CO emission can reach outstanding values regarding motorcycles.

Methane content also affects the emission of pollutants. Lim et al. [31] examined gases composed of 82–98% methane and found that total hydrocarbons (THC), CO, NOx and CO_2 emissions increased, while volatile organic compound (VOC) emissions decreased with an increased CH_4 content in the fuel.

Because the activation energies of high carbon-numbered hydrocarbons (HCs) (e.g. ethane or propane) are lower than those of low carbon-numbered HCs (methane), the combustion efficiencies of ethane and propane are greater than that of methane. Thus, a fuel with higher methane content has more incomplete combustion and/or poor oxidation of unburned hydrocarbons, resulting in higher emissions of HC [31]. The level of this, according to measurements taken by Subramanian et al. [32], was 12.5%.

Considering biogas and natural gas, NOx emissions were lower for biogas than for the natural gases.

Biomethane used as a biofuel produces emission savings which are 73–82% of the base values (GVA) used for the EU's sustainability legislation. Compared to biofuels

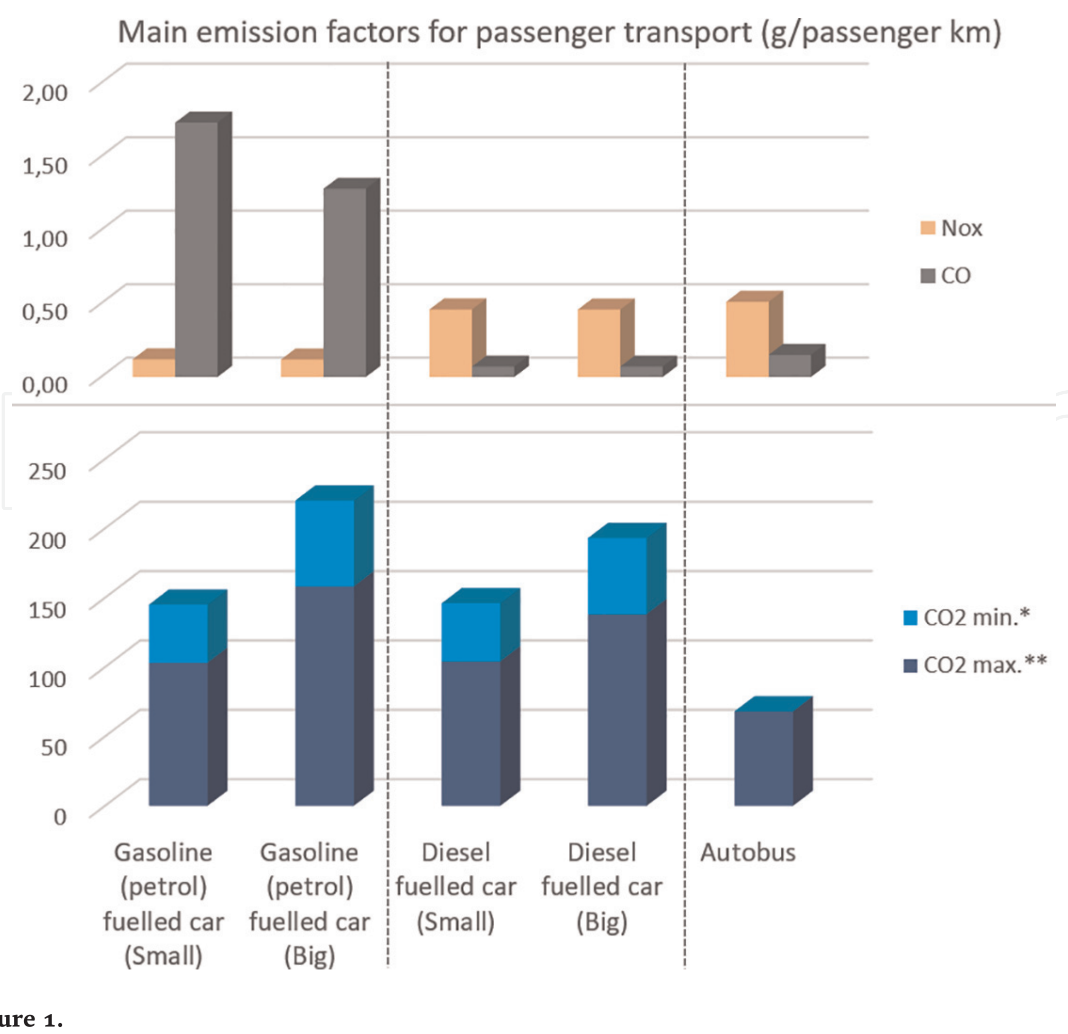

Figure 1.
Main emission factors for passenger transport (g/pkm). Source: Own construction based on [29, 30].

produced from other raw materials, this is very favourable because beet ethanol produces 52%, wheat ethanol 16–69%, maize ethanol 49% and rapeseed biodiesel 38% (Directive 2009/30 EC) [33].

According to data from Goulding and Power [34], the biomethane energy yield from grass silage is 2.5–3.3, which corresponds to 67–78 GJ of annual energy surplus per hectare. The figures for wastewater with the same biogas yield are between 3.5–4 and 85–90 GJ/year. These are also well above those of most biofuels.

The specific pollutant emissions per capita of public transport are much lower than those of car transport, and this is especially true if the fuel itself is environmentally friendly. Since many trips are local, the analysis by the Department for Transport (UK) shows that 44% of all CO_2 emissions from cars come from journeys of between 5 and 25 miles [35]. Although the pollutant emissions of buses per passenger kilometre are higher than those for trains and trams (**Figure 2**), their energy consumption is nearly identical and much better than for individual transport [29].

The use of raw biogas in CNG vehicles has been investigated. These tests have shown that raw biogas (not upgraded) can be used as a fuel, if blended with natural gas. In fact, the use of raw biogas can be envisaged in dedicated CNG engines, if new engine technologies (lean CNG combustion) are developed. In such a case, natural gas can be blended with up to 70% volume of non-upgraded biogas.

Tests by Bordelanne et al. have shown that raw (not upgraded) biogas can be used as a fuel, only if blended with natural gas, mainly in CNG engine types (lean CNG combustion). The biogas proportion of natural gas can be a maximum of 70% [26].

When comparing two identical brands and types of waste collection vehicles, Domanovszki [36] concluded that the average noise level measured by microphones located at a distance of 7 m from vehicles is 71 dB in the diesel engine and 66 dB in the gas engine version, which is about three times the noise load. Gas fuels do not contain anti-knock additives due to their high-octane number.

There are two technologies for compressing methane gas: CNG and LNG. In Hungarian and EU practice, among gas-fired propellants, propane-butane gas

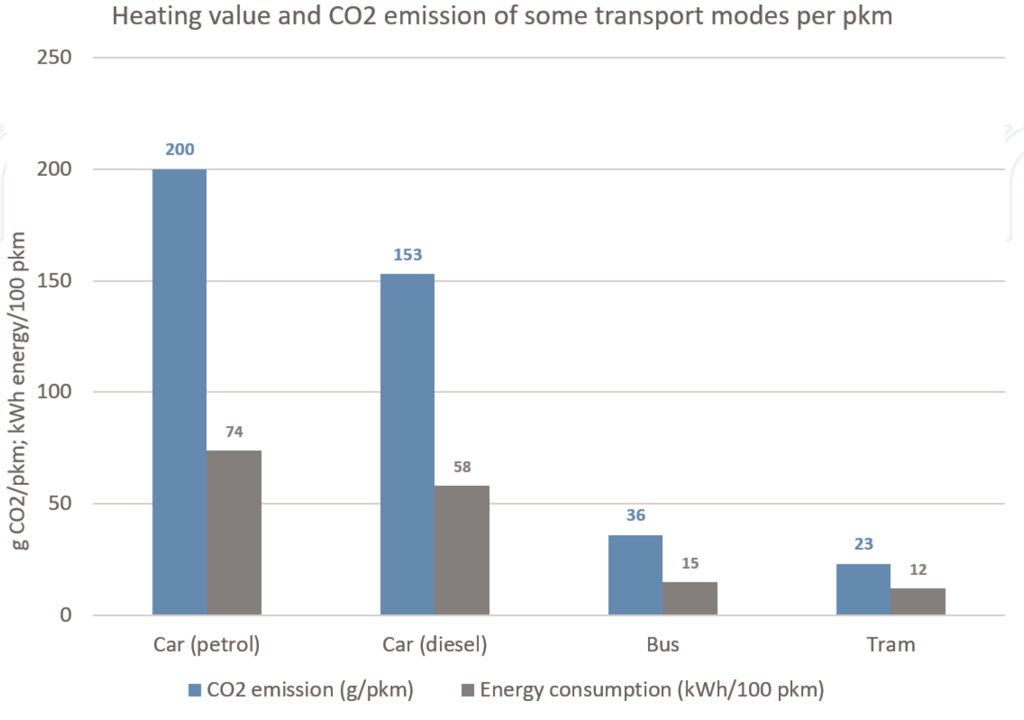

Figure 2.
Heating value and CO_2 emission of some transport modes per pkm. Source: Own construction based on [30].

(LPG) is the most widespread, while in the United States, it is compressed natural gas (CNG), and the infrastructure for the latter is perfectly suited to biomethane utilisation. CNG is, in theory, subjected to 200 bar pressure when put into steel or composite tanks. With LNG technology, a higher energy density (55 MJ/kg, 24–26 MJ/Nm^3) can be obtained by liquefaction at −161.6°C at atmospheric pressure. It can then be filled into well-insulated containers and stored under low pressure. Because of the higher calorific value, LNG is more suitable for long-distance traffic than CNG [36]. If biogas is the raw material, the CBM operation will have a combined efficiency of 15–18%, and LMS (liquified biomethane) an efficiency of 14–17%, but both significantly outperform the overall efficiency of the liquid fuel systems (4–13%) [7].

4. Economic characteristics of production and use

Large-scale sewage plants in large cities are suitable for the production of large quantities of biogas, using economically viable biogas upgrading technologies and generally available public transport fleets of a sufficient number of local buses, as well as municipal vehicles. The conditions for the sale of locally produced CNGs do not depend on gas suppliers, they can be very well integrated with local waste management and the local emission reductions occur in the inner city where air pollution is the most serious problem.

At the same time, it is not clear from the point of view of sewage plants whether it is the production of biomethane or the cogeneration solution—which is currently more important—which is more viable economically and in terms of harmful emissions. Here, it must be taken into account that the consumption of heat and electricity by these plants is significant, and this must be purchased when producing biomethane.

The economic and environmental approach should take into account not only the substituted energy source but also the cost and emissions of fossil fuels bought because there is no cogeneration (including the electricity and heat needed for self-consumption at sewage plants).

In this section we present the investment and operating costs of CBM production and the specific aspects of economic evaluation.

4.1 Investment and operating costs

The expected level of the biomethane plant's investment costs is greatly influenced by technology and size. Goulding and Power [34] provide the following equation for the average of the investment costs of biomethane plants operating with agricultural raw materials, with a 95.6% probability:

$$C = 1066.2x^{0.8455}$$

where C is the investment cost (€/t yearly raw material) and x is the processed raw material quantity (t/year).

The equation—with a 91% degree of confidence ($C = 21080x^{0.5367}$)—also shows that, in the case of larger dimensions, from an economies of scale perspective, it is advisable to use biomethane instead of cogeneration technologies. At the same time, at bigger dimensions cogeneration technology also has economies of scale. According to Patrizio et al. [37], the proportion of available heat and electricity between an operating capacity of 300 and 200 kWe increases from 58 to 70%, considering a value of 25 and 11% for plant self-consumption of electricity and for heat to maintain the mesophilic process.

Yang et al. [18] also explored the cost of investment in various cleaning technologies at various farm sizes, which support the economies of scale of large plants:

- 1000 Nm^3/h in crude (input) biogas capacity: 1.6–2 million USD
- 250 Nm^3/h in crude (input) biogas capacity: 0.7–1.1 million USD

The distribution of investment costs by the same source can be characterised by the following average numbers:

- Cleaning: 40–45%
- Compression: approx. 5%
- Distribution: 50–55%

Most of the investment costs are related to distribution, the proportion of which is largely dependent on the method used to transport methane [25]:

- CNG lorry transport: 12 €/GJ biomethane
- LNG lorry transport: 7 €/GJ biomethane
- CNG pipeline delivery: 5 €/GJ biomethane

The cost price of methane produced is also largely dependent on the size of the wastewater treatment plant, primarily because of the significant proportion of fixed costs (**Table 3**).

Regarding the economic indicators of the wastewater plants, it can be said that the existing rotting equipment and the larger size of the plant typically offer more favourable costs, thus allowing faster returns.

It should be noted that a reduction in the cost of biomethane can also be achieved by using carbon dioxide resulting from purification (in some cases in pure form), which has a significant increase in yields in greenhouses or algae plants. Algae can also be easily integrated into sewage treatment or can be used in bioenergy production and are capable of doubling their yield (up to 400 t/ha/year) with inorganic nutrients in wastewater and carbon dioxide [39, 40]. With the use of digested effluent *Paulownia tomentosa* [41] or *Sida hermaphrodita* [42], plantations may support the aim to meet the growing needs for site remediation and biomass production.

Source	Farm-sized plant (250 Nm^3/h)	Medium-sized plant (500 Nm^3/h)	Large operation (1000 Nm^3/h)
[25]	1.1	0.8	0.7
[38]	0.8–1*	0.7–0.9*	0.6–0.7*

**Assuming 0–100% of purchased raw material.*

Table 3.
Cost of biomethane based on farm size and raw material (EUR/kg).

Patrizio et al. [37] examining the influence of the low market value of CO_2 found that starting from a carbon price of 15 EUR/tCO_2, the cogeneration option is preferable if plants are located in the proximity of existing district heating infrastructure. CNG plants are only competitive starting at a carbon price of 70 EUR/tCO_2 in areas with high feedstock availability, when the first upgrading plant for CNG production is introduced into the optimum mix.

Finally, it should be noted that the consumption of diesel oils tested by Farkas et al. [43] in Hungary showed a 5% difference in the same vehicles. This is important because the substitution value of the biomethane and its environmental savings depend greatly on the quality of the substituted oil product.

4.2 The European market

Market prices are examined for the most important biomethane-producing countries and for Hungary. Including this latter country is justified by the fact that the case study we presented is also Hungarian. CNG is cheaper than its competitors —petrol and diesel—in all countries, not only in terms of unit price but also petrol and gas oil equivalents, with a typical price difference of between 33–57% and 25–48%. Interestingly, there is a large difference between the two most widely regarded model countries in the EU—Italy and Sweden; in the former it is consumed for reasons of economy, and in the latter because of the environmental consciousness there. CNG prices in the countries surveyed show that differences can be more than double, but petrol and gas oil prices are much more balanced (**Table 4**).

Rebuilding of passenger cars to use alternative fuels involves additional costs and changes in consumption, the values of which are:

- CNG conversion, approx. 1.600 EUR; extra consumption 0–10% [11]
- LPG conversion, approx. 1.000 EUR; extra consumption 5–20% [11]

Country	**Fuel consumer price**					**CNG price as percentage (%) of other propellants**	
	CNG EUR/kg	**EUR/l petrol equivalent**	**Petrol EUR/l**	**EUR/l diesel equivalents**	**Diesel EUR/l**	**Petrol**	**Diesel**
Bulgaria	0.71	0.52	1.2	0.59	1.23	43	48
Finland	1.34	0.98	1.54	1.11	1.47	64	75
Germany	1.07	0.79	1.53	0.88	1.4	51	63
Hungary	1.12	0.82	1.22	0.92	1.34	67	69
Italy	0.99	0.73	1.66	0.82	1.56	44	52
Sweden	1.87	1.37	1.48	1.54	1.58	93	98
Average	1.18	0.87	1.44	0.98	1.43	60	68
Relating to buses			1.08		1.07		

Units used: CNG, 43.6 MJ/kg; petrol, 32 MJ/l; diesel, 36 MJ/l [46].
Source: [44–46].

Table 4.
CNG, gasoline and diesel prices for key EU countries and two Central and Eastern European countries (October 2018).

- E85 conversion, EUR 300; extra consumption 20–25% [11]
- Vegetable oil conversion, from 1500 to 5000 EUR; excess consumption 10% [47]
- Biodiesel conversion, from 1000 to 4000 EUR; surplus consumption 10% [48]

For buses, conversion to CNG operation costs € 30,000–€ 50,000. CNG-powered cars are about € 3000 to 5000 more expensive than their petrol and gas oil counterparts of the same brand and with the same parameters.

It is clear that all alternatives to CNG involve increased consumption, ideally offset by the more favourable price of the alternative fuel.

4.3 Comparison of energy self-supply and biomethane production of sewage plants

In our case study, in order to quantify energy possibilities, we conducted our calculations for a nutrient-containing wastewater treatment plant using a anaerobic fermentation technology for a population equivalent of 100,000 inhabitants (equivalent to an adult inhabitant's wastewater), which was considered as average in Hungary. Based on our conception and data collection - which were partly promoted by the Higher Education Institutional Excellence Programme of the Ministry of Human Capacities in Hungary (No. 20428-3/2018/FEKUTSTRAT) - for the use of biogas produced during fermentation, we present two possibilities in this section:

- Cogeneration energy production and then own consumption (and, if possible, the sale of surplus heat energy)
- Biomethane production and sales: supply to the natural gas network or use as fuel

Basic data of the 100,000 household equivalent wastewater plants:

- Amount of treated wastewater: 13,000 m^3/day
- Biological oxygen demand (BOD) content: 6000 kg BOD/day (BOD, biological oxygen demand; oxygen demand for aerobic removal of organic matter from the aqueous phase through microorganisms)
- Specific biogas yield (per m^3 treated wastewater): 0.93 kWh/m^3
- CH_4 content of biogas: 65% (heating value: 6.5 kWh/m^3)
- Gas engine loss: 15%
- Heat energy/electricity ratio for power generation: 60%/40%
- Non-residential electricity average price in EU-28: 0.112 EUR/kWh
- Non-residential natural gas price in EU-28: 0.0078 EUR/MJ

Source: [49–51].

The amount of biogas generated by anaerobic technology, using the above (average) technological characteristics:

- 13,000 m^3 * 0.37 kWh/m^3 = 1860 Nm^3/day.

Allowing for a 15% loss of biogas above, a biogas calorific value of 6.5 kWh/m^3 and the energy consumed in energy production, and calculating using 60% heat and 40% electricity ratios, the quantity of the final product with the two technologies examined is shown below.

4.3.1 Expected revenue from cogeneration

Electricity generation

- Quantity of electrical energy that can be produced: 0.37 kWh/m^3 * 13,000 m^3 = 4837 kWh/day
- Consumption of electricity at the plant (Kárpáti [52] and authors' own calculations, allowing for 0.59 kWh/m^3 sewage sludge): 13,000 m^3 sewage * 0.59 kWh/m^3 = 7709 kWh/day
- Electricity balance: −2872 kWh/day (electricity self-sufficiency: 63%)
- Savings: 4837 kWh/day * 0.112 EUR/kWh = 542 EUR/day = 197,745 EUR/year

Thermal power generation

- Quantity and value of heat energy to be produced: 0,558 kWh/m^3 * 13,000 m^3 = 7254 kWh/day = 26,114 MJ/day
- The heat energy consumption of the plant (assuming a heat demand of 0.40 kWh/m^3): 5140 kWh/day = 18,500 MJ/day
- Heat energy surplus: 7614 MJ/day
- The amount of heat energy self-supply: in principle 91%

However, in practice, heat utilisation beyond the plant's own heat demand is problematic, especially in the summer, and in addition, the heat energy consumption is also lower. For district heating purposes, depending on the length and insulation of the piping system, 10–15% heat loss can be expected. If the remainder of the winter heat surplus is fully utilised by the district heating system and the summer hot water demand is considered, then about 55–70% of the heat generated can be utilised. In the following we calculate on an assumption of 60%:

Average value of savings: 34.411 MJ/day * 0.0078 EUR/MJ natural gas * 0.6 = 122 EUR/day = 45,000 EUR/year.

It should be noted that if total heat energy could be sold, the revenue and savings would reach EUR 203/day and EUR 74,000/year. This would be possible if sales were not for the heat-variable demands of the district heating system, but for the sufficiently high constant heat demand of an industrial consumer in a nearby industrial park (e.g. a bioethanol plant or a slaughterhouse) when the heat would be bought at the natural gas price. However, the latter is in practice much more insecure.

In the case of district heat sales, together with the electricity, revenue is 198,000 + 45,000 = 243,000 EUR/year.

The investment cost of CHP technology (with 266–280 kWe capacity) (with existing rotting equipment) following our own calculations is 231,000 EUR.

4.3.2 Biomethane production

For the calculation of biomethane production, the following basic data were used:

- The amount of biogas produced: 1860 Nm^3/day (from the previous calculation)
- The methane content of biogas: 65%
- Cleaning technology: 2% methane loss and 96% methane gas recovery
- The calorific value of the biomethane obtained: 34 MJ/Nm^3
- Natural gas purchase price: 0.0078 EUR/MJ (EU wholesale average price)
- CNG/CBM density: 0.78 kg/Nm^3
- CNG average price: 1.18 EUR/kg

The amount of biomethane produced is 1860 Nm^3/day * 65% biogas methane content * 98% efficiency/96% biomethane methane content = 1234 Nm^3/day biomethane.

In the case of supply to the natural gas network, the expected revenue is 1234 Nm^3/day biomethane * 34 MJ/Nm^3 * 0.0078 EUR/MJ = 327 EUR/day = 119,000 EUR.

When using the output as a fuel (CNG/CBM), since the prices are expressed in kg, it is therefore appropriate to convert the resulting quantity into this unit of measure: 1234 Nm^3/day biomethane = 963 kg/day biomethane.

Value of this: 963 kg/day biomethane * 1.18 EUR/kg = 1136 EUR/day = 415 EUR/year. This may further contribute to the potential recovery of CO_2 obtained during the cleaning process.

The value of the required cleaning equipment (120–130 Nm^3/h capacity), based on our own calculations: 860,000 EUR (this does not include investment costs related to sales).

However, it is important to take into account that if we convert biogas to biomethane, we need to purchase the sewage plant's self-consumption needs. Their values in the present case are:

- Electricity: 7709 kWh/day * 0.112 EUR/kWh = 863 EUR/day
- Heat: 18,500 MJ/day * 0.0078 EUR/MJ = 144 EUR/day
- Total: 1007 EUR/day = 368,000 EUR/year

The remaining sales revenue from biomethane sales:

- Natural gas sales: 119–368 = (−) 249,000 EUR/year
- Sales of propellants: 415–368 = 47,000 EUR/year

4.3.3 Effects on CO_2 emission

When calculating the effects of CBM on the CO_2 emission, we should start the calculation with the emission values of the given technological process (CHP, upgrading). Then we need to make a comparison between the CO_2 emissions of the used and of the substituted fuels (electricity, natural gas, diesel fuel). We used the following emission factors in our calculations (**Table 5**).

	Value	Measure	Source
Substitution of fuel			
• Diesel	69.95	kg CO_2eq/GJ	[52]
• CNG	49.75	kg CO_2eq/GJ	[52]
• Electricity	391	kg CO_2eq/kWh	[53]
Operation of sewage plants			
• CHP	11	kg CO_2eq/GJ	[37]
• Upgrading and feed-in station	41	kg CO_2eq/GJ	[37]
• Upgrading and fuelling	22	kg CO_2eq/GJ	[37]

Table 5.
Substitution and operation factors.

The use of the systemic approach in city operation and regional development requires that the interest and demand of the environment, the local communities and the economy would be satisfied on a mutually beneficial level [54]. We also used this approach.

If the sewage plant itself was evaluated environmentally, the decision would be very simple: because of lack of CBM-fuelled vehicle, the CHP technology would be considered as the most favourable option. At the level of municipality (considering the waste management, local transport and central heating system), we need to make a three-sided comparative analysis.

In the case of the conventional CHP technology, direct emission from the operation should be considered as basis, and it should be reduced with the self-consumed heat and electricity. In this case the saved emission of local transport and of central heating remains the same. Regarding the other two technologies, the emission savings will be derived from the saved natural gas or diesel fuel of buses, respectively (**Table 6**).

Technology	**CHP**		**Upgrading + gas pipeline**	**Upgrading + transport**
	Heat	**Electricity**	**Natural gas**	**Diesel**
	GJ/yr	**MWh/yr**	**GJ/yr**	**GJ/yr**
Savings in fuel (in given unit above)	4357	1815	15,316	15,316
Savings in CO_2eq (t/yr)	217	710	762	1072
Biogas input (GJ/yr)	15,004			
Emission from technology (t/yr)	165		615	330
CO_2eq emission (t/yr)	**−762**		**−147**	**−742**
Source: Own calculations.				

Table 6.
CO_2 emission balance of the evaluated technologies.

Table 6 shows that CBM production for feed-in has the highest energy demand and the lowest emission saving potential. The other two options could be regarded near equal, since though CBM for fuelling has slightly better emission saving potential, it needs more energy for the operation.

4.3.4 Comparison of the technologies examined

The three uses of the biogas produced from the wastewater analysed above can thus be characterised by the following end parameters for a 100,000 PE (population equivalent) sewage capacity (**Table 7**).

Sphere of use	Investment demand (thousand EUR)	Expected revenue (thousand EUR/year)	Emission saving (t CO_2eq/yr)
Cogeneration (electricity and heat)	231	average: 243, max. 272	762
Cleaning (supplying network)	860	−249	147
Cleaning (for fuel)	860	47	742

Source: Own calculations.

Table 7.
Parameters of the given plant.

The above values show that introducing biomethane into the natural gas network is the least competitive compared to the other two modes of recovery both in economical and in environmental aspects. In the case of existing digesters, the gas engine is very fast—and the most efficient return on investment, if it is connected to a sufficiently large district heating network, ideally an industrial park. Although sales of biomethane for propellants can theoretically achieve the highest turnover on their own, due to the self-consumption needs of the sewage plant, and the investment cost—which is more than three times higher—it is not the most favourable alternative from the sewage plant's perspective. Since the environmental effects are near the same, it can be stated that CHP could be evaluated as the best way for biogas utilisation for the sewage plant.

4.4 Economics of the use of CNG at the city level

In general, it can be stated that the long-term spread of a product market (in our case CNG/CBM) is only expected if the product is worthwhile to produce, market and use. In the event of any losses suffered by any actor in the market, in the absence of subsidies, the vertical relationship is interrupted, and so the interest of all actors must be ensured. A subsidy is justified by the macroeconomic benefits of the public finances (environmental protection, import substitution, employment). In addition, it must, of course, be cheaper and more accessible than competing fuels and must also ensure that the investment needed to operate is recovered within a reasonable period of time. Does biomethane meet all of these criteria under current economic conditions?

It can be clearly seen from the economic data listed in **Table 3** that biomethane can be produced essentially at the consumer price (0.8–1.1 EUR/kg) at relatively small (250 Nm^3/h) biogas plants, while the price-equivalent own costs for its substitutes, i.e. petrol and diesel (0.87–0.98 EUR/l on average), are significantly below their average consumer price (1.43–1.44 EUR/l). In the case of non-final sales (i.e. not to private individuals) but for business use (buses, machines), equivalent values for petrol and gas oil prices reduced by VAT and other price discounts must be taken into account (cca 1.08 EUR/l in both cases, with an average 25% reduction), with which the smallest agricultural biomethane plants (with a capacity of 250 Nm^3/h) are just competitive (0.8–1.1 EUR/kg), while larger farm sizes are able to produce cheaper biomethane. For farm-sized plants, it is economical to produce and use local CBM only when using their own by-products and primarily for the fuel supply of their own vehicles.

Therefore, in the vertical market structure (with the appropriate size and type of user), profits are generated in the current economic conditions, as well. At the same time, in the case of internal use (e.g. operation of a common sewage plant gas and local public transport system), the state loses significant tax revenue, which is, however, easily offset by the externalities present in the public finances.

Consequently, the cost of compressed biomethane (CBM) as a propellant is typically just below or at the CNG price level (average 1.18 EUR/kg) but much cheaper than the diesel typically used in local transport vehicles.

Finally, the conversion of vehicles to CNG operation and the return on the CNG premium can be estimated as follows.

In the case of a city bus, taking into account a life expectancy of 1000,000 km, single buses use cca. 370,000 l, and articulated buses cca. 470,000 l of diesel fuel in their lifetime. The fuel cost savings during the CNG operation can be estimated at 37,000 EUR and 47,000 EUR per bus, taking into account the average reclaimed VAT and the wholesale discount. Thus, a local public transport service of county town size (e.g. Debrecen, Hungary, with 210,000 local inhabitants; a fleet 100 of single and 40 articulated buses) can save up to € 5–6 million over the entire lifetime but also hundreds of thousands of EUR on a yearly basis. The expected return on the conversion of a single bus is as follows.

Basic calculation data:

- 60,000 km/year performance (16–17 years calculated lifetime)
- 37 l/100 km gas oil consumption
- An average saving of 0.1 EUR/l of gas oil equivalent with CNG (gas oil wholesale price)
- 40,000 EUR conversion cost/acquisition surplus cost
- Considering 3%/year increase in gas oil price and the same as opportunity cost (assuming use of own money in financing)

Based on CNG purchased on the basis of this data, the investment will be repaid after approximately 18 years without subsidy, so slightly beyond the useful life of the vehicle; however, with a subsidy the payback period is much shorter, and the benefits of environmental protection have not yet been taken into consideration. Increasing performance (better use of buses) and rising gas oil prices can significantly reduce the payback period. Since gas fuelling has a positive effect on engine wear, it does not endanger the potential performance; it is rather determined by the transport features. One-hundred thousand kilometre use of bus per year results in 11-year-long repayment period.

In the case of CBM produced in its own wastewater plant, savings are much greater than with diesel; therefore, with the same technical parameters, the payback period will be reduced, even without subsidy.

Environmental advantages of a CNG-/CBG-fuelled bus fleet are also significant. Considering the average value of 18 kg/GJ GHG saving of CNG/CBG compared to gas oil and the bus fleet of Debrecen with the above-mentioned characteristics, the GHG saving can reach 14.4 tonnes/bus in a year, or 15,000–20,000 tonnes/bus fleet, moreover in the city centre, mostly suffering air pollution.

Average data used for calculation of passenger cars:

- 15,000 km/year performance (15-year lifetime)
- 8 l/100 km of petrol consumption
- An average saving of 0.57 EUR/l of petrol equivalent with CNG (at consumer prices)
- Conversion cost of EUR 1600 and extra purchase cost of EUR 4000
- Considering 3%/year increase in petrol price and the same as opportunity cost (assuming use of own money in financing)

In the case of the above parameters, the conversion is expected to take place within 2–3 years, while the purchase price of the new car would be repayable in 5–6 years, mainly depending on the mileage and current petrol prices, if there was no problem with refuelling. In the case of a local public CNG filling station, gas-fuelled cars can be recommended primarily to those private individuals who are involved in local transport and travel long distances in a year (e.g. local taxi drivers) or those that are more environmentally sensitive and thus appreciate the benefits of using gas-fuelled cars.

4.5 Reference plants

Biomethane production based on various types of waste and its use as a propellant can be found in several places. At this point, we will introduce some international examples, focusing in more detail on wastewater-based biomethane production.

As the study by Barisa et al. [55] shows, there are many potential waste-based raw materials available to a settlement that are suitable for biogas and biomethane production:

- The organic proportion of unsorted municipal solid waste (MSW)
- Separately collected biowaste from restaurants and grocery stores
- Separately collected green waste from garden and park management
- Wastewater sludge (including the amount generated by the dairy plant)
- Organic waste from the industry (e.g. brewer's grain)

With regard to their available volume, it can be said in general that in a given settlement the municipal solid waste, separated green waste and sewage sludge produced in the sewage plant make up the largest amount. However, considering the costs of collecting and separating these three types of raw materials, there may be significant differences. The utilisation of sewage sludge in the sewage plant—continuously and, in a relatively homogeneous amount, free of charge—can be considered cost-effective in this respect. In addition, other waste materials can be used safely for biogas production and its subsequent purification in sewage plants.

In practice, wastewater treatment plants in many cases include organic food waste/by-products that contribute to improving the carbon-nitrogen ratio of sewage and sewage sludge, thereby achieving higher biogas and biomethane yields.

In what follows we present a few examples of biogas or biomethane production plants based on organic waste or sewage.

4.5.1 Sweden

In Linköping, Sweden, biomethane is used in urban transport, not only for buses and heavy and light motor vehicles but also for trains [56]. The total cost of EUR 14,000,000 invested in 1996 can be mentioned as one of the successful examples of the integration of fuel supply for agriculture, the community and individual transportation. In the Linköping waste-to-energy plant, biogas production was initially based on the by-products and wastes of the crop and livestock (slaughterhouse) sector, while in the framework of a development programme, from 2001, they have also produced renewable propellants from organic waste from public institutions and restaurants [57]. Since 2002, there are only biogas buses in the urban transport fleet, and the CO_2 emissions have been reduced by more than 9000 tonnes per year [58].

Another Swedish example is the Nordvästra Skånes Renhållning AB (NSR) biomethane plant in Helsingborg, which generates 80 GWh of biomethane per year from 160,000 tonnes of separated food waste. The methane produced is supplied to the grid and is used for the operation of trucks, taxis and private cars. From 160,000 tonnes of digested food waste in the biogas plant, approximately 490 tonnes of N, 90 tonnes of P and 170 tonnes of K are available for recirculation as fertilizer each year [59].

Another interesting example is the Swedish city of Uppsala. As early as 1996, animal manure and slaughterhouse waste were used for biogas production, and then for biomethane production after purification, which was used for the operation of buses. Thereafter, developments in two stages up to 2010 resulted in the production of biomethane from significant quantities of organic waste from their own city and other settlements; annual production has reached 3000,000 Nm^3 [60]. Overall 71 of the city buses were fuelled by biomethane, which amounts for 35% of fuel used in public transport in Uppsala in 2014 [61].

Considering the Swedish examples, it is not surprising that in Swedish households 60% of organic waste is collected separately and utilised.

Sewage water-based biomethane production was implemented in Hammarby Sjöstad (Stockholm), Sweden. Within the framework of the project, an integrated closed wastewater-energy system has been implemented based on local authority/municipal sewage. After the sewage is purified in the system, propellant biogas and biomethane are also produced, as well as heat and electricity. Hammarby Sjöstad is located in one of the most progressive cities in the world with regard to sustainability. The city has reduced carbon emissions by 25% per resident since 1990 and has established a target of reducing emissions to 3 tonnes of CO_2 per capita in 2015. This value is extremely low for developed countries, considering the entire country of Sweden has an average emission rate of 4.5 tonnes of CO_2 per capita, while the average for Europe is approx. 6.5 tonnes per capita, and the average for the United States is 16.5 tonnes per capita [62, 63].

4.5.2 Hungary

Sewage-based, biomethane propellant production was also implemented in Zalaegerszeg (Hungary) (**Figure 3**). The investment began in 2011 and cost 140 million HUF (about 444,000 EUR), of which HUF 120 million was for the biogas

Figure 3.
Zalaegerszeg wastewater treatment plant with biomethane filling station. Source: Own photo.

cleaning system, while the cost of the filling station was HUF 20 million. Daily biomethane production is 3600 m^3, while the biomethane's unit cost is 0.52 EUR/m^3 [64]. Although this value is slightly higher than the consumer price of natural gas, it is just about half as much as the price of diesel oil. Since the substituted buses typically run on diesel oil, the use of CBG should result positive economic effect. The composition of the biogas is 65% methane, 30% carbon dioxide and 5% other gases, including hydrogen sulphide. Raw biogas significantly reduces the lifetime of machines because of its hydrogen sulphide content. For a safe and efficient use, a multistage cleaning process is initiated: gas is pressurised through an activated carbon filter, which reduces sulphur content, other gas content and humidity. Subsequently, 75% methane and 25% carbon dioxide gas is subjected to an aqueous wash, whereby the carbon dioxide is converted to carbonic acid and transferred from the biogas to the aqueous solution. During the production of biomethane, the purified biogas is pressed at a pressure of about 6 bars into the washer, in which the chemical transmission process occurs. After aqueous washing, a 99.7% methane gas is produced, which is excellent for use in CNG vehicles. The biofuel produced fuels for municipal vehicles (12 vans and 3 buses). The CO_2 saving can be estimated 22 tonnes/year [65, 66].

4.5.3 United Kingdom

At the beginning of the 2000s, the largest wastewater-based power plant in the United Kingdom was operating at Minworth. During the operation of the plant, several technological developments were introduced, resulting in an increasing amount of biogas production.

The total investment cost of the plant was €8,150,000, which allowed the production of 3400 Nm^3/h of biogas (nearly half of which is upgraded to biomethane) with 16 digesters, totalling 80,000 m^3/day. The type of raw material is sewage sludge (4000 m^3/h). The development of biomethanic purification is due to two important factors: (1) simultaneously with the increase in the quantity of biogas produced—due to the variable amount of energy—the amount of electricity that can be supplied to the electricity grid was limited; (2) a significant amount (40%) of heat loss was also a serious problem. All of this led to the construction of biomethane purification capacity, which keeps the energy produced from sewage well stored and also avoids heat loss. The unit uses absorption, which provides a high-pressure water scrubbing process to clean biogas and to increase the methane concentration [67]. With an annual biomethane production of 63,000,000 kWh, Minworth is the first connection of unconventional gas into the local transmission system, with a significant impact on reducing CO_2 emissions [68].

4.5.4 Other examples of good practice

In the following we present other international examples, and cases of good practice of use as a fuel and for supply to the natural gas grid, using as a source the Bin2GRID (2016) project [69]:

Good practice for usage of biomethane and CNG vehicles:

- Margarethen am Moos (Austria)
- Rechnitz (Austria)
- Norrköping (Sweden)
- St. Gallen (Switzerland)
- Lille (France)
- Madrid (Spain)
- Sevilla (Spain)

Good practice of biomethane injection into the natural gas grid:

- Margarethen am Moos (Austria)
- Vienna (Austria)
- Utzenstorf (Switzerland)
- Norrköping (Sweden)
- Madrid (Spain)

5. Conclusions

Public transport, sewage treatment and district heating are mostly operated by local authorities and can therefore be influenced by local decisions, so biomethane can be well integrated into local transport systems, and the terms of sale are not dependent on gas suppliers, either. The latter may be significant in the event of potential future gas price rises, which does not affect the cost of locally produced biomethane. At the same time, it should be noted that the economic interests of biomethane-producing wastewater plants are rather geared towards traditional cogeneration technologies rather than biomethane production because of the significant electricity and heat demand of sewage treatment technologies.

From an environmental point of view, it is also noteworthy that the reduction of the emissions of cadmium due to the use of local public transport with CNG occurs right in the city centre, where air pollution is the most serious problem. From the operation point of view, it is essential that in the case of local transport, there is no danger of emptying fuel tanks, since the filling station is available locally, unlike with long-distance transport. The public education objective of technology is not negligible as many people (those travelling by public transport) are affected by the use of environmentally friendly fuel.

Midterm proliferation is expected to take place, given that in October 2014 the European Parliament and the Commission adopted the “Clean Fuel for Transport” package, which obliges member states to take the first steps by 2020 in cities and suburbs and by 2025 on motorways, to make CNG fuelling stations for cars and then allow transport by LNG trucks on Europe’s main transport lanes.

Due to the above, the production of biomethane at metropolitan wastewater plants for transport purposes can serve the interests of residents in an efficient way, both economically and environmentally, also enabling them to enjoy a kind of energy self-sufficiency.

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Conflict of interest

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