TRANSACTIONS OF THE INSTITUTE OF FLUID-FLOW MACHINERY

No. 137, 2017, 41–58

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Optimization of biogas utilization — realization smart community idea

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Abstract

The paper presents an analysis of the possibilities of using biogas in energy management of the cities and communities, including the purification of biogas excess to balance the unevenness in demand and supply side of biogas market (operating agricultural biogas plant). The case study describes the four technical acceptable scenarios of using agricultural biogas: variant I – combined heat and power production, variant II – supply of the local heat source, variant III – supply of the local heat source and the use of treated biogas (biomethane) in the local urban transport and variant IV – combined heat and power production and injection of conditioned biogas (biomethane) into the gas distribution grid. The identified variants were evaluated using the analytic hierarchy process multicriteria decision aid method in which the main evaluation criteria were technical, economic, social and environmental, as well as risk criterion. The results of the analysis indicate the possibility of rational use of excess biogas production by: treatment and use of liquefied biomethane for energy production or transport, or combined heat and power production, or use of biomethane injected into the distribution gas network, which can be the basis for the implementation of smart city and community strategy.

Keywords: Biogas utilization; Smart communities; Energy planning

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1 Introduction

Current European Union energy and climate policy, having reflected in the policies of the member states, moves towards the implementation of the idea of 'smart' to the concept of smart cities and communities (SCC) and other industry concepts. Synergy of actions in the sectors, i.e., information and communication technologies (ICT), energy and transport is intended to develop innovative solutions for cities and communities in the field of transport improvements, to achieve greater mobility and air pollution, which has a direct impact on the environment and energy efficiency.

Urban and semiurban areas (approx. 37% of Polish communities) generally are characterized by having a district heating (e.g., heat-only boiler station or CHP), developed municipal transport fleet and agricultural land located outside the city. Operation of the district heating and transport system is a source of anthropogenic environmental pollution, especially atmospheric pollution. Aspiration to the energy efficiency improvement of existing municipal management systems and increasing the use of renewable energy sources in these systems makes it possible to significantly reduce the use of fossil fuels, thus reducing the carbon footprint.

Energy use of agricultural biogas in the community can provide added value through activation of farms, increased energy security and improving the environment. However, the functioning of agricultural biogas plants has its limitations and barriers that limit their development. One of the main limitations is unevenness of the supply side and demand, resulting in the overproduction of biogas. Management of this overproduction of biogas through its treatment to biomethane and its subsequent condensation or injecting to the gas distribution network/grid can increase the profitability of agricultural biogas plants, and significantly improve their energy efficiency.

The paper presents an analysis of the potential for improving the energy efficiency of the use of biogas produced in selected agricultural biogas plant. The choice of implementing the community-based energy economy of agricultural biogas is treated as a decision problem and its proposed solution using one of the methods of multi-criteria decision support – analytic hierarchical process (AHP).

2 Case study

2.1 Agricultural biogas plant

As a case study of energy economy community analysis was adopted agricultural biogas plant with operating parameters listed in Tab. 1.

Table 1: Operating parameters selected for agricultural biogas plant.

Operating parameter	Unit	Value
Substrates Input: corn silage	tonnes/annum	31 149
Substrates Input: slurry	tonnes/annum	84 622
The content by weight dry matter: corn silage	%	32.6
The content by weight dry matter: slurry/liquid manure	%	8.0
Content by weight of dry organic matter in dry matter: maize silage	%	94.7
Content by weight of dry organic matter in dry matter: slurry	%	81.3
The potential for biogas production: corn silage	Nm^3/Mg d.o.m.[1]	317
The potential production of biogas: slurry	Nm^3/Mg d.o.m.	225
Total production of biogas[2]	mln Nm^3/annum	4.3
The volume of methane in the biogas	%	65
The lower heating value of biogas	kWh/Nm^3	9.17
Time working biogas plants per year	h/annum	8 040

[1] d.o.m – dry organic matter
[2] without the needs of their own biogas plants

Total heat demand in the community is approx. 107.6 GWh/annum. Local heat source with a heat distribution network meets the energy needs of the following buildings:

- public utility – 875 MWh/annum,
- residential buildings (multifamily blocks) – 2 500 MWh/annum,
- service – 750 MWh/annum,
- local industry – 2 500 MWh/annum,
- for all analyzed variants the assumed development opportunities, which would result in increased sales of heat to the level of, are respectively: for the variant I – 11 832 MWh/annum and variant II – 24 922 MWh/annum, either possibility of development and resale in the commune and beyond liquified biomethane in the amount of 1.4 million Nm^3/annum (variant IIIA and IIIB) or sale of treated biomethane injected into the gas distribution network (variant IV) in an amount of 0.9 million Nm^3/annum,

- in the commune operates local public transport, which total mileage is approx. 630 000 km/annum (10 buses) and unit consumption per liquid natural gas/compressed natural gas (LNG/CNG) single bus is 37.80 kg/100 km.

2.2 Variants of the energy economy

The case study covers four technically acceptable scenarios for the use of agricultural biogas:

- variant I – combined heat and power production,
- variant II – supply the local heat source (heat-only boiler station),
- variant IIIA – supply the local heat source (heat-only boiler station) and the use of treated biogas (biomethane) in the local urban transport (cryogenic treatment),
- variant IIIB – supply the local heat source (heat-only boiler station) and the use of treated biogas (biomethane) in the local urban transport (membrane treatment),
- variant IV – combined heat and power production and injection conditioned biogas (biomethane) into the natural gas distribution network.

Implementation of energy management community in variant I assumes, that agricultural biogas is used for combined heat and power production in the cogeneration unit (gas engine) with an efficiency of heat production at 43% and the efficiency of electricity production at 38%. The produced electricity is resold to the grid and heat is supplied to the district heating network, which distributes heat to customers connected to the network – Fig. 1.

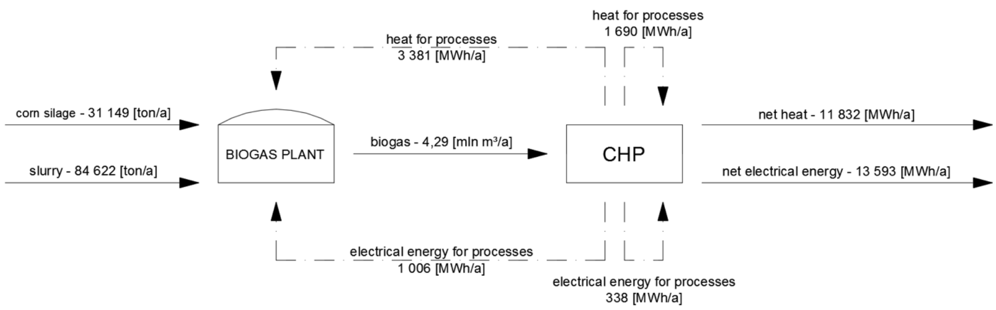

Figure 1: Diagram of the use of agricultural biogas according to the variant I.

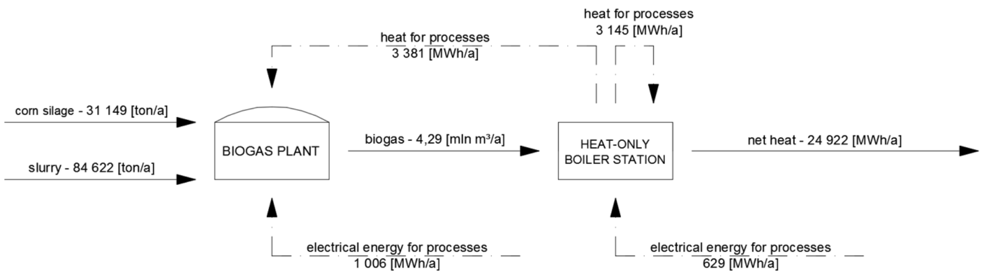

Figure 2: Diagram of the use of agricultural biogas according to the variant II.

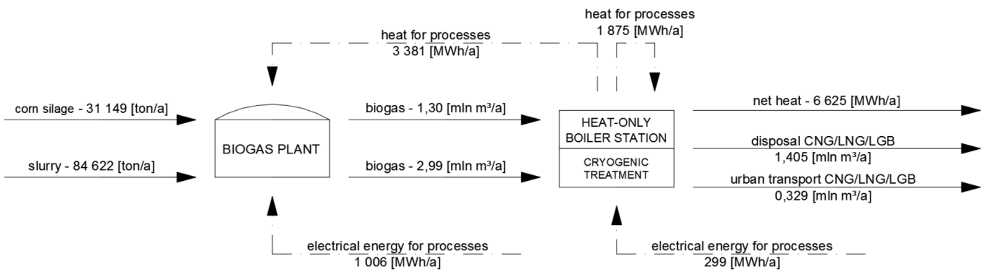

Figure 3: Diagram of the use of agricultural biogas according to the variant IIIA.

In variant II produced agricultural biogas is used to supply the local heat source (boiler with a thermal efficiency of 80%), powering the district heating system which supply heat consumers located in the community – Fig. 2.

In variant IIIA obtained agricultural biogas is used to supply the local heat source (boiler with a thermal efficiency of 80%), powering the district heating system which supply heat consumers located in the community. The overproduced biogas is treated using cryogenic technology. As a result, the treated liquified or compressed biogas (biomethane) LCNG/LCBG (liquid compressede natural gas/liquidfied compressed biogas) is used in the local urban transport, as fuel supplying the city buses fleet or in the liquified phase LNG/LBG (liquidfied natural gas/liquidfied biogas) for further energy use in another place or time – Fig. 3.

In the variant IIIB obtained agricultural biogas is used to supply the local heat source (boiler with a thermal efficiency of 80%), powering the district heating system which supply heat consumers located in the community. The overproduced biogas is treated using membrane technology and then condensed into biomethane.

Liquified or compressed biomethane LCNG/LCBG is used in the local urban transport, as a fuel to supply city buses fleet or in the liquified phase LNG/LBG for further energy use in another place or time – Fig. 4.

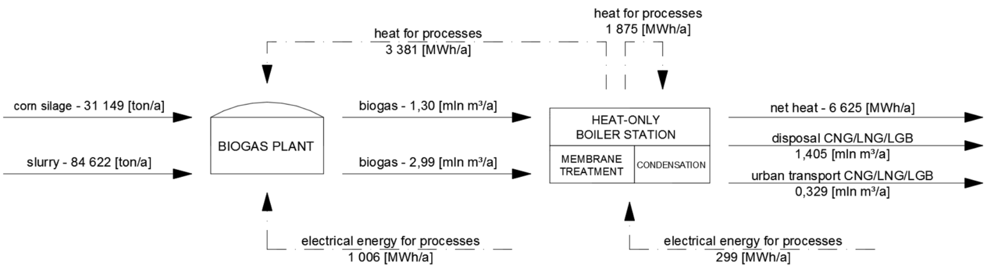

Figure 4: Diagram of the use of agricultural biogas according to the variant IIIB.

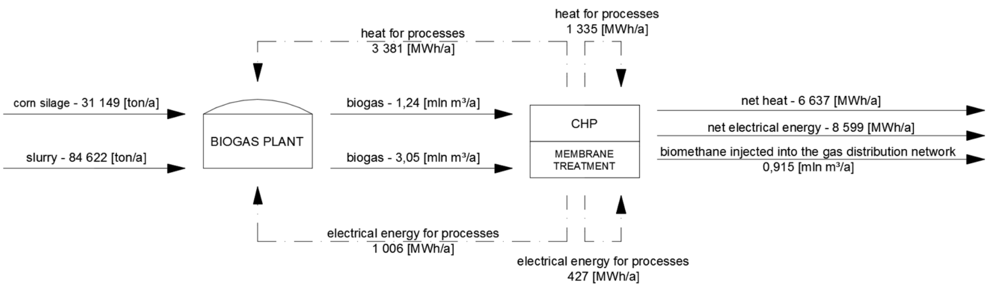

Figure 5: Diagram of the use of agricultural biogas according to the variant IV.

In the variant IV produced agricultural biogas is used for combined heat and power production in the cogeneration unit (gas engine) with an efficiency of heat production at 43% and the efficiency of electricity production at 38%. Energy production is adapted to the level of the demand for heat in the community. At the same time, produced electricity is resold to the grid. The overproduced agricultural biogas is treated using membrane method and the resulting biomethane is injected into the gas distribution network (Fig. 5), which increases the energy security of the community or the city [11].

Table 2 shows the estimated capital expenditures (CAPEX) and average unit costs of combined heat and power, costs of heat production in the local heat source (heat-only boiler station), biogas treatment, liquefaction, filling and injection to the distribution network of gas biomethane [1–7].

The main factor in achieving profitability projects mentioned above is the appropriate level of revenue generating financial surpluses in cash flows, which allow you to cover operating costs and capital expenditures. In the analyzed scenarios includes revenues like: (i) the sale of electricity to the power grid, (ii) red certificates, (iii) purple certificates, (iv) the sale of heat to the district heating system, (v) the sale of LNG/LCNG for urban transport, (vi) the sale of LNG for resale and energy use, and (vii) the sale of biomethane into the gas distribution network. Information about the average price of electricity on the competitive market or on a separate charge replacements for cogeneration in 2015 published the President of the Energy Regulatory Authority [8,9]. Financial support from the sale of certificates, value pricing and cost plays a crucial role in the functioning and development of renewable energy projects and cogeneration as well. Red certificates (marked 'Ozk') apply to cogeneration installations with a capacity more than 1 MWe producing electricity and heat in combination. Purple certificates (marked 'Ozm') apply to cogeneration units, which are fired with methane obtained in the mines or biogas. Implementation of brown certificates can be an asset for projects of biomethane injection into the gas distribution network, making projects become profitable and open up this market segment. Obtaining co-financing of energy investments projects, thereby reducing the expenditure on implementation, can also raise their profitability. More details about how to obtain co-financing investment projects supporting environmental protection, among others, renewable energy sources (RES) projects and improve energy efficiency are described in [10]. Taking into account the expected amount of substrates, biogas plant will produce agricultural biogas in the amount of 4.29 million Nm^3/annum. The quantity of that biogas can be used to locally meet energy needs – current and future demand for fuels and energy in the community. Table 3 summarizes the quantities of agricultural biogas and liquified biomethane for the analyzed variants.

Agricultural biogas in the variants IIIA, IIIB, and IV requires treatment in order to adjust the quality parameters corresponding to the parameters of high-methane gas [11]. The paper [13] described cryogenic or membrane technologies of gas purification in which liquefied biogas is widely used in the transport or to meet energy needs of the community. However, the paper [17] presents an analysis of the possibilities of mixing biogas (without treatment) with natural gas, taking

Table 2: Investment and average unit costs for the analyzed variants.

Specification	Unit	Variant				
		I	II	IIIA	IIIB	IV
total CAPEX*	thous. PLN	11 500	2 000	23 900	14 900	25 500
CAPEX CHP** 1.86 MWe and 2.1 MWt	thous. PLN	11 500				11 500
CAPEX local heat source (heat-only boiler station) 2.1 MWt	thous. PLN		2 000			
CAPEX modernization local heat source (heat-only boiler station) 2.1 MWt	thous. PLN			500	500	
CAPEX cryogenic biogas treatment installation	thous. PLN			19 500		
CAPEX filling station LNG/LCNG	thous. PLN			3 900	3 900	
CAPEX membrane biogas treatment installation	thous. PLN				6 500	6 500
CAPEX biomethane liquefaction station	thous. PLN				4 000	
CAPEX biomethane injection station into natural gas network	thous. PLN					7 500
average unit costs of producing electricity and heat in CHP	PLN/kWh	0.05				0.07
average unit cost of heat production	PLN/kWh		0.07			
average unit costs of biogas treatment (cryogenic)	PLN/m^3			0.69		
average unit costs of biomethane filling	PLN/m^3			0.20		
average unit costs of biogas treatment (membrane)	PLN/m^3				0.24	0.44
average unit costs of biomethane liquefaction	PLN/m^3				0.32	
average unit costs of biomethane filling	PLN/m^3				0.20	
average unit costs of biomethane injection into natural gas network	PLN/m^3					0.80

* CAPEX – capital expenditures, ** – combined heat and power

Table 3: The annual quantities of agricultural biogas for energy use within the analyzed variants in thousands m^3 per year.

Specification	Variant				
	I	II	IIIA	IIIB	IV
total volume of biogas to use	4 286.77	4 286.77	4 286.77	4 286.77	4 286.77
volume of biogas to CHP unit	4 286.77				2 879.17
volume of biogas to local heat source (heat-only boiler station)		4 286.77	1 619.50	1 619.50	
volume of biogas to treatment installation			2 667.27	2 667.27	1 407.60
volume of treated biogas (biomethane)			1 733,73	1 733.73	914.94
volume of LNG/LCNG to supply local urban transport			328.63	328.63	
volume of LNG/LCNG for further energy use in another place or time			1 405.09	1 405.09	
volume of treated biogas (biomethane) to injection into natural gas network					914.94

into account the limit of the required quality of gas in distribution network. This case can be an alternative to the analyzed variant IV, due to avoiding the costs of treatment. To keep the quality parameters, the uniformity of solutions (standardization), interchangeability of gas criteria, and the legislation are the main determinants of the possible development of agricultural biogas (treated or not) injected into the gas network (transmission and distribution) [12,16,18-20]. Identified variants of the energy economy community, based on the agricultural biogas produced there, were evaluated using a multicriteria tool – analytical hierarchy process. The analysis is based on four main criteria (features): (i) technical, (ii) economic, (iii) social and environmental, and (iv) risk factors.

3 Multicriteria analysis

3.1 The methodology of calculation

A detailed description of the method of AHP can be found in the papers [14,15]. The variants are evaluated by multicriteria assessment where: (i) hierarchical structure of the decision problem is built, (ii) preferences of the decision maker are defined, (iii) a pairwise comparisons matrix is constructed, (iv) the eigenvectors matrix and standardized matrix are set, (v) a matrix consistency is test, and (vi) final ranking is created based on hierarchy user ratings. The calculation algorithm is an iterative process – in case of any doubts related to the results obtained, it allows to return to the input data to redesign assessments. The measure of evaluation pairs consistency is the consistency ratio, CR, determined as

$$\mathrm{CR} = \frac{\mathrm{CI}}{\mathrm{RI}} \,, \tag{1}$$

where CI is the consistency index, and RI is the random consistency index, given by Saaty for the decision problems, when the number of alternatives, n, does not exceed 15 (Tab. 4).

Table 4: Values of random consistency index RI.

n	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

3.2 Calculations

The calculations of individual criteria and subcriteria are the basis for the multi-criteria analysis AHP, which is made later on. The results of the criteria and subcriteria calculations for the all analyzed variants are shown in Tab. 5.

Table 5: The set of decision criteria for the analyzed variants of the possibilities of using agricultural biogas.

No.	Assessment criterion:	Symbol	Unit	Variant				
				I	II	IIIA	IIIB	IV
1	2	3	4	5	6	7	8	9
I	Technical criterion	$\mathbf{K}_{tech}$						
I.1.1	City heat supply dependence	k_{sd}^{T}	HHI	0.80	0.63	0.88	0.88	0.88
I.1.2	City electricity supply dependence	k_{sd}^{T}	HHI	0.57	1.00	1.00	1.00	0.51

1	2	3	4	5	6	7	8	9
I.1.3	Urban transport fuel supply dependence	$k^{T}{}_{sd}$	HHI	1.00	1.00	1.00	1.00	1.00
I.2.1	Biogas and bioethane production	$k^{T}{}_{pBG}$	mln m^3/year	4.29	4.29	4.29	4.29	4.29
I.2.2	Biogas and bioethane production	$k^{T}{}_{pBG}$	mln m^3/year	0.00	0.00	1.73	1.73	0.91
I.3.1	Share of renewable energy to the total energy demand for heating	$k^{T}{}_{sRES}$	%	11	25	6	6	6
I.3.2	Share of renewable energy to the total energy demand for electricity	$k^{T}{}_{sRES}$	%	69	0	0	0	44
I.3.3	Share of renewable energy to the total energy demand for local urban transport	$k^{T}{}_{sRES}$	%	0	0	100	100	0
II	Economic criterion	$\mathbf{K}_{econ}$						
II.1	CAPEX	$k^{E}{}_{CAPEX}$	thous. PLN	16 800	12 500	23 900	15 400	28 000
II.2.1	Economic evaluation – NPV	$k^{E}{}_{NPV}$	thous. PLN	11 533	-15 881	-5 943	9 290	-8 940
II.2.2	Economic evaluation – IRR	$k^{E}{}_{IRR}$	%	15.32	–	2.01	14.28	0.63
II.2.3	Economic evaluation – DPP	$k^{E}{}_{DPP}$	years	7.30	–	25.30	7.70	33.30
II.3	Co-financing	$k^{E}{}_{cfEU}$	0,1	1	0	1	1	1
III	Social and environmental criterion	$\mathbf{K}_{social-envir}$						
III.1	Reduction of CO_2 emissions into the environment	$k^{S}{}_{CO2}$	kg CO_2/year	286 907	303 021	89 487	89 487	142 539
III.2.1	Activation of farms – the area of crops	$k^{S}{}_{af}$	ha	1 888	1 888	1 888	1 888	1 888
III.2.2	Activation of farms – surface sheds	$k^{S}{}_{af}$	m^2	45 063	45 063	45 063	45 063	45 063
III.3	Income increase of the Commune – real estate tax (investment)	k^{S}_{incom}	thous.PLN/year	230	40	478	298	510
IV	Risk criterion	$\mathbf{K}_{risk}$						
IV.1	Investment risk	$k^{R}{}_{i}$	points	11	9	12	11	15
IV.2	Risk of lack of substrates supply for biogas plant	$k^{R}{}_{lss}$	points	4	4	4	4	4
IV.3	Operating risk	k^{R}_{o}	points	11	9	14	14	16

The hierarchical decision-making process model (AHP) is constructed from the mentioned above the main goal, the secondary purpose (criteria and subcriteria) and variants. The model of analyzed decision-making problem is shown in Fig. 6.

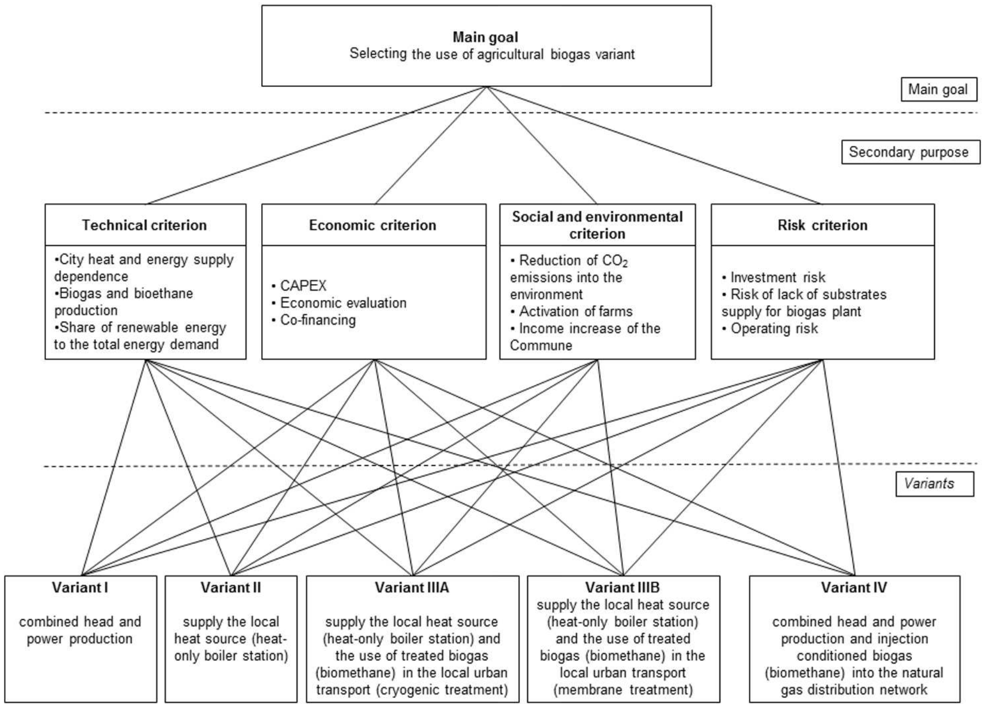

Figure 6: The hierarchical structure diagram of defined decision problem.

One decision maker's model of preferences (investor of agriculture biogas plant) took into account in the analysis of AHP to evaluate the pairs of individual criteria and variants at all of the levels of the hierarchical structure.

3.3 Calculation results

The result of multicriteria analysis is variants final ranking, for which calculated aggregate value of utility function. Tables 6 and 7 show the results for given comparison of the adopted models preferences.

Line-up of the variants were achieved as a result of the AHP analysis for the predetermined decision maker preference (Fig. 8). The highest score was achieved

Table 6: The comparison criteria matrix for the analyzed variants.

1.	Technical criterion			Ktech	
Investor of agricultur biogas plant					
Criterion	Variant I	Variant II	Variant IIIA	Variant IIIB	Variant IV
k^{T}_{sd}	0.0218	0.0131	0.0069	0.0069	0.0218
k^{T}_{pBG}	0.0045	0.0045	0.0246	0.0246	0.0126
k^{T}_{sRES}	0.0402	0.0084	0.0696	0.0696	0.0240

2.	Economic criterion			Kecon	
Investor of agricultur biogas plant					
Criterion	Variant I	Variant II	Variant IIIA	Variant IIIB	Variant IV
k^{E}_{CAPEX}	0.010	0.018	0.004	0.010	0.0019
k^{E}_{NPV}	0.082	0.013	0.036	0.082	0.0000
k^{E}_{dUE}	0.028	0.006	0.028	0.028	0.0284

3.	Social and environmental criterion			Ksocial-envir	
Investor of agricultur biogas plant					
Criterion	Variant I	Variant II	Variant IIIA	Variant IIIB	Variant IV
k^{S}_{CO2}	0.037	0.037	0.007	0.007	0.0187
k^{S}_{af}	0.004	0.004	0.004	0.004	0.0036
k^{S}_{incom}	0.005	0.002	0.018	0.008	0.0177

4.	Risk criterion			Krisk	
Investor of agricultur biogas plant					
Criterion	Variant I	Variant II	Variant IIIA	Variant IIIB	Variant IV
k^{R}_{i}	0.006	0.012	0.003	0.006	0.0012
k^{R}_{Iss}	0.002	0.002	0.002	0.002	0.0018
k^{R}_{o}	0.007	0.012	0.003	0.003	0.0012

for variant IIIB, where the agricultural biogas is used to supply the local heat source and in the treated form (LNG/LCNG) in the local urban transport, and for resale and energy use.

4 Sensitivity analysis

As a supplement to the results obtained a sensitivity analysis were made – the impact of capital expenditures changes and revenues and costs to check the change of net present value of variant IIIB. The sensitivity analysis uses the relationship

$$\frac{\mathrm{NPV_j}}{\mathrm{NPV_{j,nom}}} = f\left(\frac{x_i}{x_{i,nom}}\right) , \tag{2}$$

and the results are presented in Fig. 9, where $\mathrm{NPV_j}$ is the net present value j case of the variant, $\mathrm{NPV}_{j,nom}$ is the the base net present value of j case of the variant, x_i is the i component (capital expenditures, income, costs) determining the net present value of the variant, $x_{i,nom}$ is the base component of i case of the variant, and symbol f represents function of the relationship.

The profitability of the project (NPV $>$ 0) remains even with a 20% drop in revenue (line c_R), 35% capital expenditure increase (line c_CAPEX), or 45% operational costs increase (line c_C). In contrast, the highest sensitivity of NPV changes concerns the change of projects revenue. The 40% revenues decline reduces the NPV of 193%. The project is characterized by a lower sensitivity to change of capital expenditures or operating costs of the project, e.g., 40% of

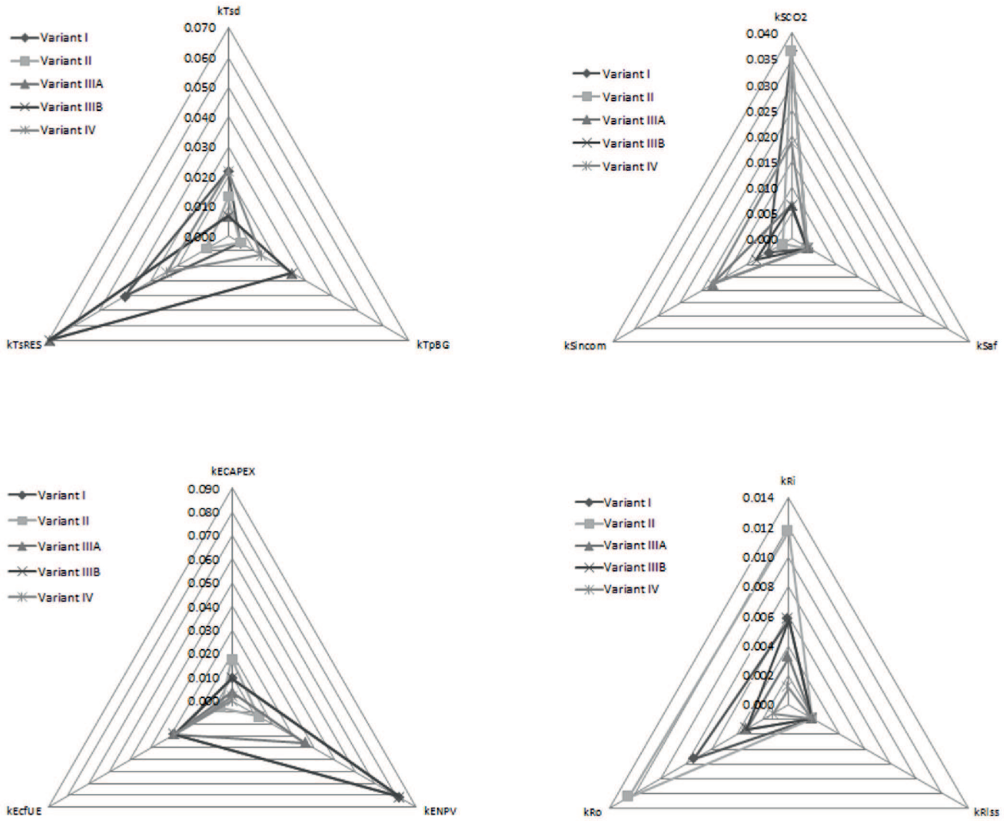

Figure 7: The results of pairwise comparisons decision criteria.

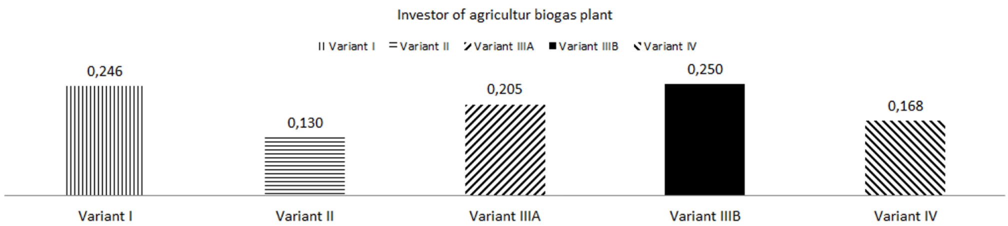

Figure 8: The final evaluation weight of the analyzed variants.

expenditures or costs change, causes NPV changes, respectively by 115% and 80%.

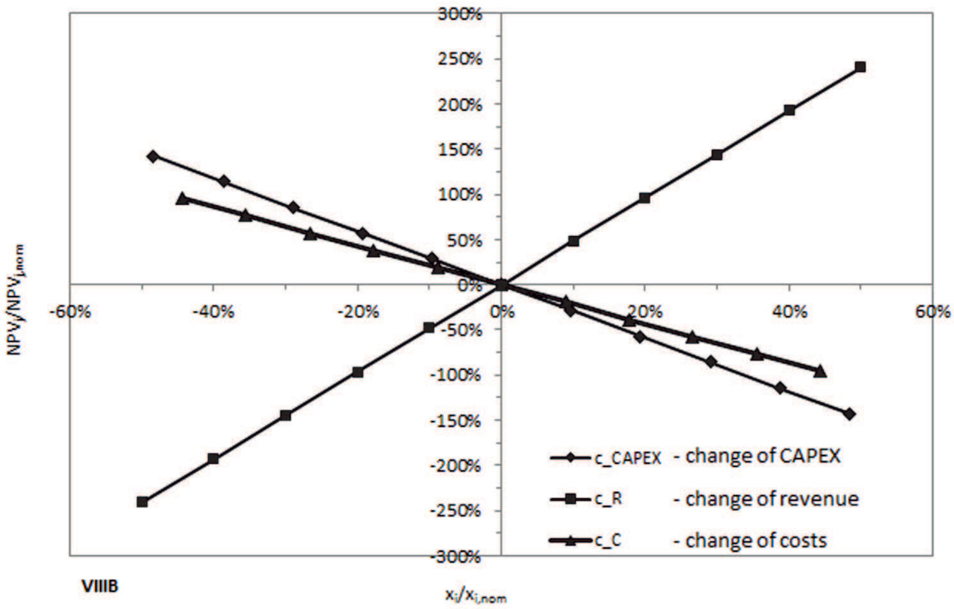

Figure 9: Sensitivity analysis of variant IIIB.

4.1 Discussion of calculations results

Multicriteria and sensitivity analysis results allow to draw to the following conclusions:

- there is the possibility of using biogas surplus production from agricultural biogas plants, which allows to reduce the carbon footprint (reduction of carbon dioxide emissions from 90 to 300 thousand kg CO_2/year);
- variant I and IIIB demonstrates the economic efficiency, which is a crucial thing from the investor point of view;
- variant IIIB shows high degree of flexibility in terms of behavior of economic efficiency;
- obtaining external financing can further increase the projects profitability;
- relevance of the final products prices from agricultural biogas plant and support system (certificates) as well;
- biogas treatment to biomethane form (1.7×10^6 Nm^3/year) enables its energy use in the city and community;

- approximatelly 19% from the volume mentioned above can meet the urban bus fleet needs with total mileage 630 000 km (10 buses);
- the remainder part of the liquified biomethane (1.4×10^6 Nm^3/year) can be transported with cryogenic tanks to other location and be distributed by LNG gas regasification station and gas network to supply the end users installations;
- there is a possibility to use the full amount of biogas in the combined heat and power (variant I), but the seasonality of heat demand on the market is the weakness of this variant;
- there is a possibility of utilizing the entire volume of produced biogas through its treatment and injecting (0.9 million Nm^3/year) to the gas distribution network (variant IV), balancing supply and demand side of the local market;
- lack of support of external financing (brown certificates) and current regulations limit the possibility of biogas plants development in the context of production and injection agricultural biogas to the gas network;
- the membrane biogas treatment technology is cheaper (capital and operating expenditures) than cryogenic technology.

5 Conclusions

The paper presents an analysis of the possibilities of using biogas in the energy economy of cities and communities, particularly to balance an uneveness of the energy demand on the market to agricultural biogas production. Potential opportunities to energy economy improvement by biogas is combined heat and power production, and biogas treatment to the liquified biomethane form or injection into the gas distribution network. The conducted considerations show, that the most attractive variant from the investor's point of view (including local government), is variant IIIB in which surplus agricultural biogas production is used to supply the local heat source and to use in local urban transport through the membrane technology treatment and then liquefaction. Liquified or compressed biomethane LCNG/LCBG can be used in the local urban transport, as a fuel to supply city buses fleet or in a liquified form LNG/LBG for further energy use in another place or time (to meet the current and future energy needs). The combined heat and power (variant I) recived similar results. Revenue largely determines the profitability of analyzed projects – the main part of the revenue comes from the certificates than fuel or energy sales. The current regulations and lack of practical certificate financial backing does not create conditions for the development of this market segment. However, agricultural biogas use in the regional economy can activate local farms, increase energy security and improve the air quality. The AHP analysis used in the research has proven to be an effective tool for energy planning and helpful to the selection of the recommended variant of biogas use, which allows the implementation of smart cities and communities strategy (SCC).

Acknowledgements The authors wish to thank the Polish Gas Company Ltd. and Poznan University of Technology for the financial and substantive support related to the preparation of this publication.

Received in November 2016

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