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Feasibility study of biogas project development: technology maturity, feedstock, and utilization pathway

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Abstract: Biogas production has a big potential to provide clean energy. To evaluate the future production and maturity of biogas technology the generalized Weng model was proved to be effective, due to it has the minimum error. The simple algorithms to determine its parameters have been proposed. The simulation results for China, USA, and EU have been presented. The quantity and quality analysis for biogas feedstock has been carried out. Energy Return on Energy Invested (EROEI) indicator for different biofuels was considered. According to analysis done biogas from maize residue and chicken manure has high EROEI. Shannon Index was suggested to evaluate the diversity of feedstock supply. Biomass energy cost indicator was grounded to be used for feedstock energy and cost assessment. Biogas utilization pathways have been shown. Biogas boilers and CHP have the highest thermal efficiency, but biogas (biomethane) has the highest potential to earn as a petrol substitute. Utilization of biogas upgrading by-product (carbon dioxide) enhances profitability of biogas projects. Methods to assess the optimal pathways have been described.

Introduction

Energy has played a substantial role throughout economic development of human civilization. The prosperity and economic development of society depend on the consumption of energy resources, especially fossil fuels (Hall and Klitgaard 2012, Tverberg 2012). Economic growth is a function on both the total quantity of energy and its costs.

Energy resources are the driving force for the economical development. Their extraction, reprocessing, and utilization cause environmental degradation and pollution. In addition, exhaustibility of the fossil fuel resources and ecological issues dictate development the biofuels market in the world (Havrysh and Nitsenko 2016).

Total primary energy consumption and renewable energy consumption have been increasing in the last years. But increment for renewable energy is higher compared with the primary energy: 15% instead of 1.5% (figures 1 and 2).

Total primary energy supply of biomass reached 59.2 EJ. This makes up 10.3% of all energy globally. The share of biogas in biomass energy was 2.15% or 1.27 EJ. China is a leader in the world biogas production. This country produces 0.32 EJ of renewable gaseous fuel. The second position belongs to the USA – 0.18 EJ (IEA 2017).

Biogas industry is growing rapidly. By 2014 its production reached 58.7 billion nm^3 (figure 3). Top leaders are (billion nm^3): EU-28 – 28.9; China – 15.0; Germany – 14.1; USA – 8.5; and Poland – 0.45 (BP 2017, WBA 2017, USA's GAIN 2017).

Although biogas production in the world has grown in the last decades, its history is more than 3000 years old (Chasnyk et al. 2015). Now the European Union is the leading market for the production of biogas and generating electricity from it. The region has more than 17,000 biogas plants with power generation capacity exceeding 8 GW. In the same time, in the USA, the capacity for electricity generation is around 2 GW.

Share of biogas production in the European Union countries makes up 136.6 million tons of oil equivalent or 32.55%. Among countries, China is the leader. It consumes 86.1 million tons of oil equivalent or 20.52%. The current share of renewable fuel in transportation is about 2.8% due to use of biofuels (biodiesel, hydrotreated vegetable oil (HVO), bioethanol, biogas, etc.).

This market contributes to the solution of population's employment. Employment in the world renewable energy sector increased from 8.1 (in 2015) to 8.305 million jobs (in 2017) (IRENA 2016; REN 21 2017). The contribution of biogas plants is 333 thousand jobs or 4.0% (REN 21 2017). China has the biggest amount of biogas installations – 42,600,000 (REN 21 2017).

Renewable energy sources, including biogas, are one of the ways to create sustainable energy systems (Cerović et al. 2014, Cucchiella and D'Adamo 2015). The biogas production and its utilization have a number of advantages. Its production can impact on both power engineering and transport. Biogas can substitute fossil fuels. As a result it reduces greenhouse gases emission (Carchesio et al. 2014), decreases dependence on import (Poggi-Varaldo et al. 2014, Igliński et al. 2015), favors development of the economy and creates new jobs (Pantaleo et al. 2014, Igliński et al. 2015).

Biogas is an important and versatile energy resource. Some European countries, especially Germany, represent the advanced level of biogas production, technology and policy (Poeschl et al. 2010). The biogas utilization has reached a high level of commercialization (Fallde and Eklund 2015, Bojesen et al. 2014).

To verify the viability of any biogas project the preliminary feasibility study is needed. Scientists studied logistic planning for feedstock supply (During et al. 2017), a cost-benefit analysis (Mohammed et al. 2017), the potential energy production from animal waste and agricultural residues (Dell'Antonia et al.

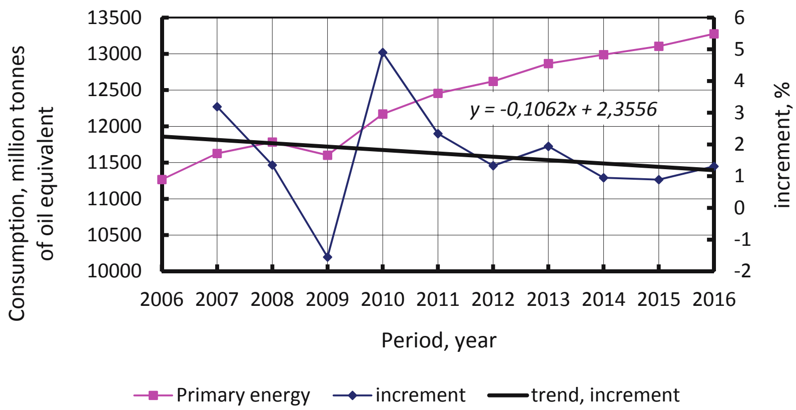

Fig. 1. Primary energy consumption
Source: adapted from (BP 2017)

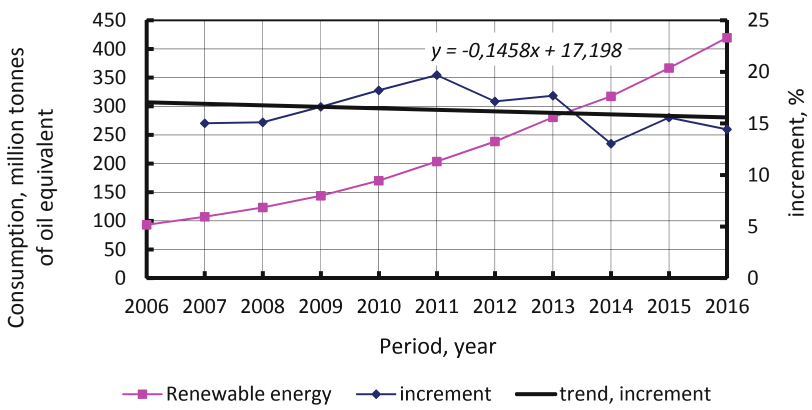

Fig. 2. Renewable energy consumption
Source: adapted from (BP 2017)

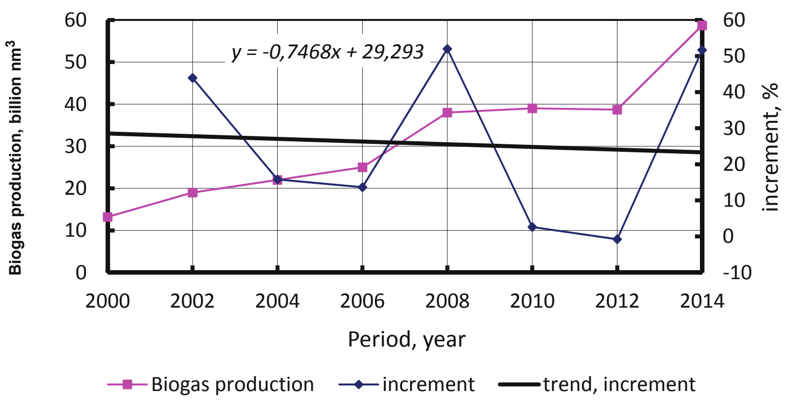

Fig. 3. Biogas production globally
Source: adapted from (WBA 2017)

2014, Włodarczyk et al. 2017), biogas upgrading systems (Mel et al. 2016), different biogas projects (JICA 2015, Dekelver et al. 2005, Dereli et al. 2012), the feasibility of a centralized biogas plant for an animal farm (Trivett and Hall 2009, Dereli et al. 2012), etc.

Despites numerous publications, some problems are not revealed enough, including the following chain: maturity of technology → quantity and quality assessment of feedstock → utilization pathways. Countries and regions have different feedstock availability, amount of existing biogas plants, and energy requirements. It impacts on the prospect of biogas technology development. So, before any project realization, the maturity of technology, quantity and quality assessment of feedstock, and utilization pathways should be examined according to the above chain. Therefore, the aim of this paper is to ascertain feasibility of biogas projects on the initial stage.

Methodology

Reports, statistical data, and researches of scientists have been the methodical bases of our study. Our study is divided into three parts: technology diffusion; feedstock supply; optimal biogas utilization pathways.

A time-depend approach was employed in the investigation and predicting the trend of biogas production. The approach has been used to study biogas technology diffusion or maturity of technology. To determine the parameters of a mathematical model (describing the forecast for biogas production), data collection was carried out for development of simplified and suitable methods.

Energy evaluations, diversity of feedstock supply, economic assessment, and potential of biogas production have been carried out. This study used energy and economic metrics for the assessment of bioenergy potential. We did this by comparing different sources (microalgae, crop residues, and manure) for biogas production. Energy return on energy invested indicator may be used as a means to measure the quality of various feedstocks for biogas production. Existing studies of the above indicator were analyzed. The standard approach was applied in the current study. There are different technologies available for conversion of biogas into energy (boilers, internal combustion engines, fuel cells, etc.). Biogas utilization pathway studies have undergone extensive research. In this study we investigated possible utilization ways, their energy and economic efficiency, optimal distribution of biogas utilization pathways.

Data collection was carried out for the development of mathematical models. Various necessary parameters were taken from existing studies and developed by the authors. Cost indicators were calculated on the basis of data obtained from statistical data and personal investigation.

Maturity of technology or technology diffusion

A scientific prediction of biogas production is of great significance for decision making for investors. Firstly, the maturity of biogas technology should be investigated. It requires the state and trend of biogas production to be investigated. A time approach method is usually employed. However, it is proved to be successful only for a short time forecast.

The time-dependent approach to technology diffusion was first applied for industry by Mansfield (1961). As a rule, it has a form of a bell-shaped curve. In some cases, the curve has multiple cycles.

To cope with different situations, scientists developed some derivative logistic models, including symmetric bell-shaped, asymmetric bell-shaped and multiple cycled. They have been adopted in many fields including energy sources (Brandt 2010, Hook et al. 2011, Sorrell 2010).

Biogas production can be studied as a process of technology diffusion. A general process of technology diffusion has a bell-shaped curve form (Figure 4). It includes three phases: ascent, maturity, and descent. But it is possible to be presented as a multiple bell-shaped curve.

Statistical data demonstrates that the biogas production may be represented as a bell-shaped curve or part of a bell-shaped curve. Therefore, the biogas production may be considered as a technology diffusion process. That is why this theory was applied to biogas production forecast (Gu 2016, Zuberi and Fahrioğlu 2015, Lund 2010).

The state of biogas production in some countries or regions (China, USA, and the European Union) demonstrates the acceptability of the above theory. Let us consider world leaders

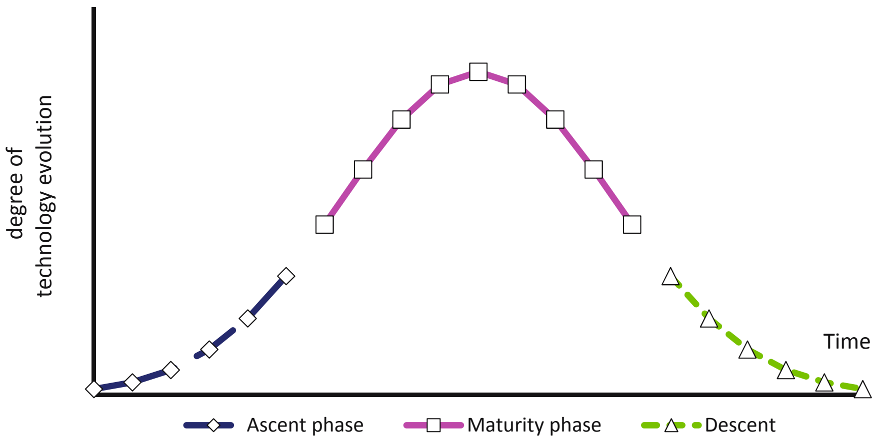

Fig. 4. Stages of technology diffusion
Source: Gu et al. 2016

of biogas production. In China, the total biogas production achieved the first peak in 2013 and then decreased (Figure 5) (CSYD 2015).

The situation in the USA is the same (figure 6) (USEPA 2016). In the EU the biogas production did not reach the peak (figure 7) (USDA'S GAIN 2017).

To make the forecast some models can be used (Gu et all. 2016):

- The Hubbert model;
- The generalized Weng model;
- The H-C-Z model;
- The Weibull model.

They describe different types of bell-shaped transformation. For biogas market the generalized Weng model has the least error in comparison with other models (Gu et al. 2016). It determines the annual production $q(t)$ at t year

$$q(t) = a \cdot t^{b} \cdot e^{-t \cdot c}, \tag{1}$$

where a, b, c are the parameters.

There are different mathematical methods to explore stochastic system parameters (Atamanyuk 2002, 2005). Different methods are used to determine parameters a, b, and c

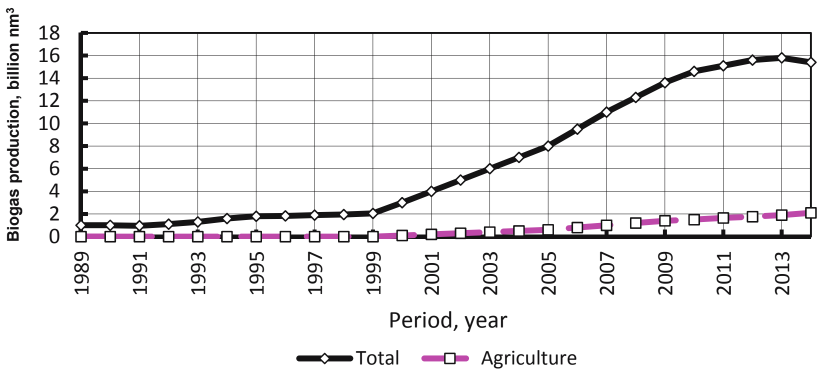

Fig. 5. Biogas production in China
Source: adopted from (CSYD 2015)

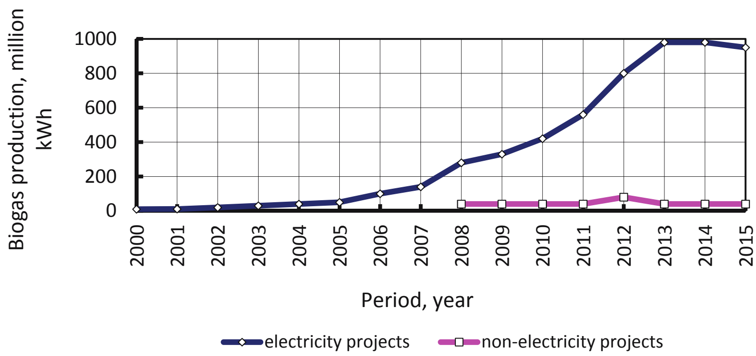

Fig. 6. Biogas production in the USA
Source: adapted from (USEPA 2016)

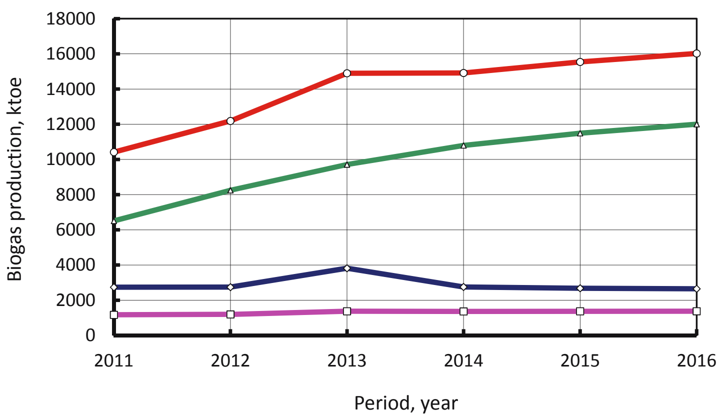

Fig. 7. Biogas production in the Europe Union
Source: adapted from (USDA'S GAIN 2017)

of the generalized Weng model (Wang 2015, Cao 2014). In our opinion, they are rather difficult for practical application. That is why we suggest a simpler one.
By taking logarithms of both sides of equation (1), we get

$$\ln\{q(t)\} = \ln(a) + b \cdot \ln(t) - c \cdot t. \quad (2)$$

If $Q = \ln(q(t))$, $T = \ln(t)$, and $A = \ln(a)$, then equation (2) can be written as

$$Q = A + b \cdot T - c \cdot t. \quad (3)$$

Assuming there are experimental data (t_i, q_i) $(i = 1, 2, 3, ..., n)$ we search for function $f(t)$ which makes the squares sum of the deviation of function value in the point t_i $(i = 1, 2, 3, ..., n)$ and the observed data minimize

$$\sum_{i=1}^{n}\left(f(t_i) - q_i\right) \to \min. \quad (4)$$

Then we apply the method of least squares and get a system of equations

$$\begin{cases} A \cdot n + b \cdot \sum_{i=1}^{n} T_i + c \cdot \sum_{i=1}^{n} t_i = \sum_{i=1}^{n} Q_i \\ A \cdot \sum_{i=1}^{n} T_i + b \cdot \sum_{i=1}^{n} T_i^2 + c \cdot \sum_{i=1}^{n} (t_i \cdot T_t) = \sum_{i=1}^{n} (Q_i \cdot T_i) \\ A \cdot \sum_{i=1}^{n} t_i + b \cdot \sum_{i=1}^{n} (t_i \cdot T_t) + c \cdot \sum_{i=1}^{n} t_i^2 = \sum_{i=1}^{n} (Q_i \cdot t_i) \end{cases} \quad (5)$$

The system can be solved by Cramer's rule.

To find the parameters a, b and c the Solver function of MS Excel can be applied. An objective function is a minimum of mean absolute error (MAE)

$$\sum_{i=1}^{n} \frac{(q_i - f(t_i))}{q_i} \to \min. \quad (6)$$

There are constraints $a > 0$; $b > 0$; $c < 0$.

If there is an obvious peak, one more constraint must be added

$$-\frac{b}{c} = t_p, \quad (7)$$

where t_p is the peak time.

The results obtained for China, USA and Germany are shown in figures 8, 9, and 10. To evaluate the performance of model for the above countries, the criteria of MAE are listed in Table 1.

The concept of market maturity technology was applied to analyze biogas deployment throughout the European Union. Biogas plant quantity was applied as a criterion for the analysis. The EU Member States were divided into three groups dependent on their market maturity: mature, moderate and immature markets. The analysis results in the following: mature market – Germany, Italy, United Kingdom, France, Sweden, Czech Republic; moderate market – the Netherlands, Belgium. Denmark, Finland, Hungary, Portugal, Poland and Slovakia; immature market – others countries of the EU (EC 2017).

Main barriers for biogas utilization sectors depend on different types of market (i.e. mature, moderate, and immature market). Moreover, the information about the maturity of

Table 1. Mean absolute error

Country/Region	Field	Using information about peak time		Forecast for Peak time, year
		–	+	
European Union	agriculture	0.79	–	2020
European Union	Total	1.66	–	2027
China	Total	33.34	36.22	–
USA	Total	24.43	46.18	–

Source: developed by authors

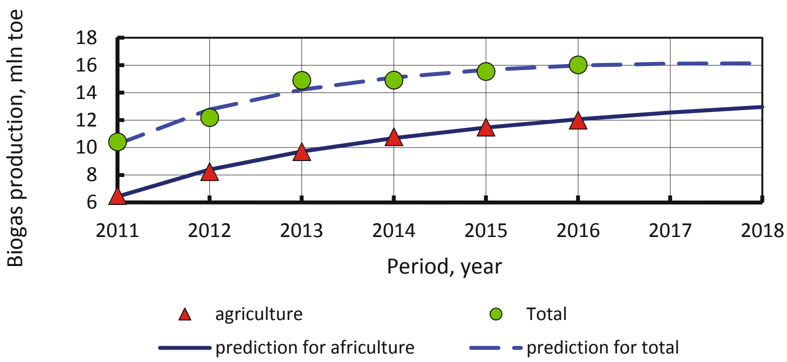

Fig. 8. Biogas production in the EU
Source: developed by authors

biogas technology represents the specific technology costs (Kampman et al. 2016).

Quantity and quality assessment of feedstock

Feedstock quantity

Profitability of a certain biogas plant depends on the cost of biomass supply chain. To overcome the above barrier, the biomass supply chain optimization is necessary. The optimization includes: a choice of substrate with high biomethane yield and the coordination of transportation and storage (Baños et al. 2011, Bravo et al. 2012).

For biogas production, diverse organic feedstock is used (Chodkowska-Miszczuk et al. 2017). It includes energy crops (maize silage, grass, etc.), animal (*e.g.* manure) and agricultural by-products (*e.g.* straw), industrial and municipal waste. High developed agriculture (plant growing and animal husbandry) and agri-food industry are the main source of biomass (Piwowar et al. 2016). Production costs for biogas depend on feedstock and biogas plant capacity (scale factor) (fig. 11) (IRENA 2017).

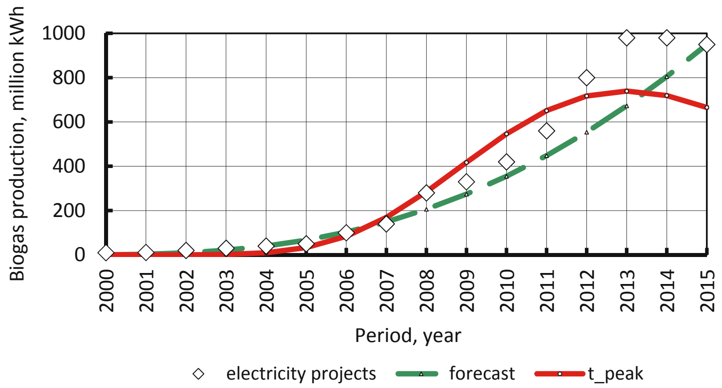

Fig. 9. Biogas production in the USA
Source: developed by authors

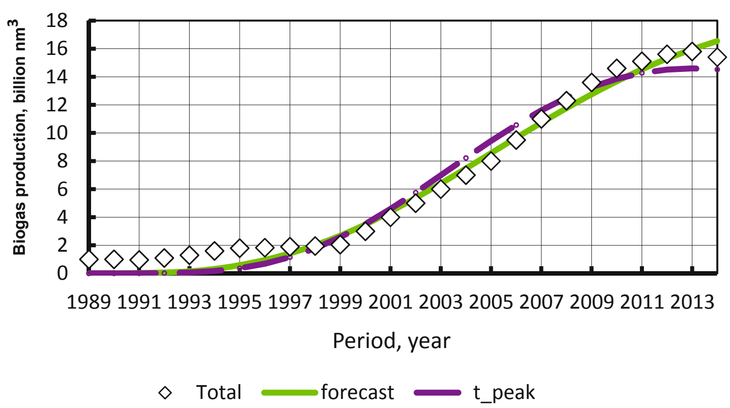

Fig. 10. Biogas production in China
Source: adapted from (Gu et all. 2016)

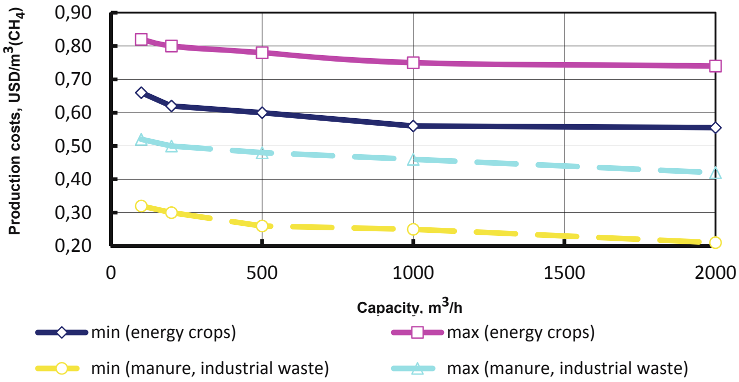

Fig. 11. Production costs for biogas (Energy crops)
Source: adapted from (IRENA 2017)

Biogas plant capacity is a function of amount and quality of substrate

$$BPC = \sum_{i=1}^{n} \left(Ms_i \cdot Ys_i \right), \text{ m}^3 \text{ per year,} \tag{8}$$

where Ms_i is the annual i^{th} biomass resources, t; Ys_i is the biogas yield of i^{th} substrate, m³/t.

The diversity of feedstock supply

The cost of feedstock depends on the transportation distance from the feedstock source to a biogas plant. For this reason, to increase the biogas production profitability it is rational to reduce the transportation distance (Delzeit and Kellner 2013, Rajendran et al. 2014). According to research a maximum distance for feedstock transportation is up to 10...25 km (Gebrezgabher et al. 2010, Pukšec and Duić 2012). Therefore, it is important to ensure stable biomass supply to avoid instability in biogas production process (Bojnec and Papler 2013). That is why it is recommendable to use some different feedstock sources to ensure security in the feedstock supply (Palm 2010).

A biogas plant must not rely on only one feedstock supply source. The diversity can endow the security of supply. To measure diversity the Shannon Index may be applied. The Shannon index is a simple indicator often used to assess the diversity in energy security analysis and bioethanol production (Jansen et al. 2004, Li et al. 2008, Kruyt et al. 2009, Silalertruksa and Gheewala 2010). In our opinion, the Shannon Index may be applied to assess the security of supply in terms of diversity of feedstock sources. The Shannon Index is as follows

$$SI = -\sum_{i=1}^{n} \left(p_i \cdot \ln p_i \right), \tag{9}$$

where p_i is the share of i^{th} feedstock resource; n is the amount of feedstock resource.

The higher the Shannon Index the more security of feedstock supply. As a rule, it is not higher than 2 (Silalertruksa and Gheewala 2010). It means that feedstock sources is equal to 7…8 (figure 12).

Energy assessment of biogas production

The use of monetary evaluation, biomass yield, energy output, etc. alone may be misleading. Some farming activity may be subsidized or use much conventional fuels. It skews the real picture of energy efficiency. Certain agricultural practice may be economically profitable under existing market condition, but economically ineffective.

One should be sure that the biogas production is energy efficient. The energy analysis uses some indicators: energy surplus, energy balance, the Net Energy Gain (NEG) and the Energy Return on Energy Invested (EROEI) indices. They are used for assessing the sustainability of energy production process. We agree with Hall et al. (2014) that EROEI is a preferable indicator. The use of such indicator as EROEI gives advantage in supply chain evaluation. The importance of the EROEI as an indicator was discussed in separate publication (Arodudu et al. 2012). The EROEI is dimensionless. It is recommended that EROEI must be above 3 to ensure effective energy production (FAO 2008, Hall et al. 2009).

The EROEI values for oil, natural gas, liquefied petroleum gas and coal tend to be relatively high. Although in recent years the global oil and natural gas EROEI values are declining. The above value has decreased from around 33 to 18. For coal production the EROEI value ranges from 27 to 80 (Hall et al. 2014). Besides the heating value of coal mined has decreased also (Hall and Klitgaard 2012).

According to research conducted, the production of fossil fuel energy resources has reached a production plateau (Hughes 2013). And despite the global EROEI is rather high the EROEI will continue to decline over coming years (Gagnon et al. 2009).

Renewable energy resources, including biogas are environmental friendly, but lack the desirable traits of fossil fuels. As such they have less heating value and relatively low EROEI.

The EROEI of a certain biogas production system depends on feedstock properties. To determine the EROEI, two energy flows (the energy invested into obtaining energy from various feedstocks and the energy output from them) must be studied. Information on the biomass sources can be obtained from statistical data. They include arable area, crop yield, crop residue yield, and the availability of manure.

According to the existing research, the EROEI for biogas is higher as compared to biofuels, such as bioethanol and biodiesel. According to K. Wajszczuk et el., the EROEI for bioethanol ranges from 1.16 (for rye technology) to 2.41 (the sugar beet technology) (Wajszczuk et al. 2016). Similar results have been obtained by Arodudu et al. For maize ethanol production, the EROEI constitutes from 1.2 to 5.9. Its value depends on agricultural production system (Arodudu et al. 2017).

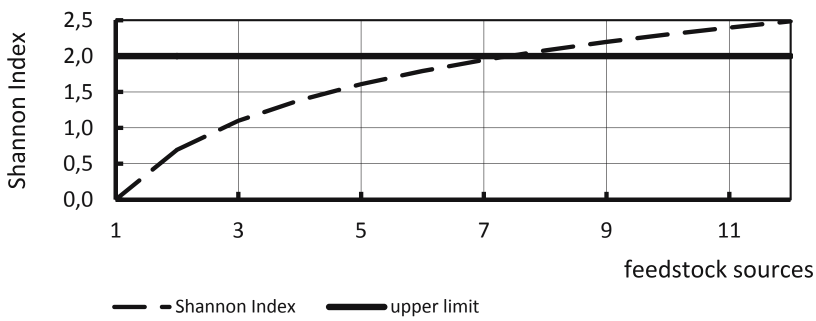

Fig. 12. Shannon Index
Source: developed by authors

The EROEI for biodiesel is taken from different studies conducted in the European Union. The above value depends on feedstock, technology and it ranges from 0.2 to 4.5 (Basset et al. 2010).

The processing of biomass into the biogas has the highest EROEI among biofuels. For different crops the above value ranges from 4.58 to 10.91 (Wajszczuk et al. 2016). Agricultural production systems have substantial influence on the EROEI (Arodudu et al. 2017).

Farm manure has a relatively low EROEI value: from 3.7 (dairy cattle) to 14.7 (chicken). Crop residues have higher energy efficiency for biogas production. Their EROEI ranges from 5.1–10.8 (triticale residue) to 15.7–17.0 (corn residue) (Arodudu et al. 2013).

There is a huge potential to produce liquid and gaseous biofuels from microalgae (Reed 2015). The studies on microalgae biodiesel report that their EROEI is less than 1 (Sills et al. 2012, Milledge 2013, Zhang and Colosi 2013, Chen et al. 2015). Anaerobic digestion of wet microalgae has higher energy efficiency (Milledge 2013, Milledge et al. 2014, Ward et al. 2014, Bohutskyi et al. 2015). Its energy efficiency depends on technology, firstly harvesting methods. The optimal technology endows to reach the EROEI value up to 3.4 (Milledge and Heaven 2017). So biogas production from microalgae may be economically viable.

A number of biomass sources (microalgae, crop residues, and manure) were considered in the study. Figure 13 shows the values for biofuels, average values for biogas from crop residues (the best and the worst crop), and for biogas from manure (the best and the worst feedstock). Therefore, maize residues and chicken manure have the highest energy efficiency. Their values exceed EROEI for biofuels (figure 13).

So the EROEI for biogas production may be calculated as follows

$$EROEI = \frac{EOP}{EIP_{DE} + EIP_{IN}}, \tag{10}$$

where EOP is the energy output, MJ; EIP_{DE} is the direct energy input, MJ; EIP_{IN} is the indirect energy input, MJ.

The energy output depends on its quantity and quality

$$EOP = V_B \cdot Q_B, MJ, \tag{11}$$

where V_B is the biogas production, nm^3; Q_B is the lower heating value of biogas, MJ/nm^3.

Anaerobic digesters produce both biogas and by-product – fertilizer. The biogas upgrading plants produce by-product too which is carbon dioxide. Both by-products are not fuels. That is why in our opinion it is reasonable to determine an energy efficiency ratio for biogas and biomethane production process

$$EER = \frac{EOP + \sum_{i=1} (V_i \cdot \alpha_i)}{EIP_{DE} + EIP_{IN}}, \tag{12}$$

where n is the quantity of by-products; V_i is the volume of i^{th} by-product, nm^3; α_i is the energy equivalent of i^{th} by-product, MJ/nm^3.

Taking into account the formula for the EROEI, the expression for EER could be written as

$$EER = EROEI + \frac{\sum_{i=1}^{n} (V_i \cdot \alpha_i)}{EIP_{DE} + EIP_{IN}}, \tag{13}$$

The above equation establishes a relation between the EROEI and EER for biogas plants.

Biomass energy cost

Different feedstocks have different biomethane yield, costs, etc. The above factors influence feasibility of biogas projects. Let us consider some types of biomass: straw, molasses, maize and grass silage. Their prices have significant fluctuation. For example, CIF Denmark prices for straw range from 5.0 to 6.2 EUR/GJ or from 75 to 93 EUR/t (Bang et al. 2013). According to the Milan Chamber of Commerce, during 2017 the pressed straw price changed from 70 to 88 EUR/t (CLAL.IT 2018).

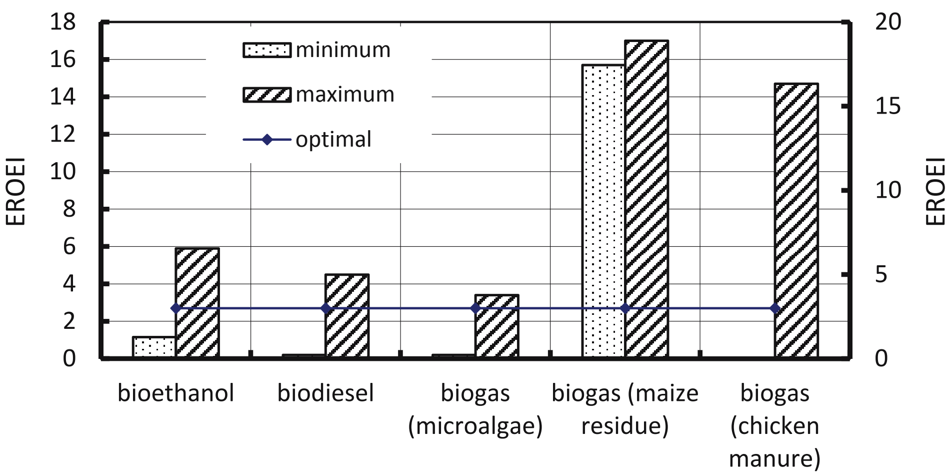

Fig. 13. Energy Return on Energy Invested of bioenergy produced from various sources

Source: adapted from (Wajszczuk et al. 2016, Arodudu et al. 2017, Basset et al. 2010, Arodudu et al. 2013, Milledge 2013, Milledge et al. 2014, Ward et al. 2014, Bohutskyi et al. 2015, Milledge and Heaven 2017)

That is why we propose to get in the use a new indicator for biomass. This as a biomass energy cost

$$BEC = \frac{BPC}{\alpha \cdot Qbm}, \text{ EUR/MJ}, \tag{14}$$

where *BPC* is the cost (production cost) of biomass, EUR/t; α is the biomethane yield, m^3 per ton; *Qbm* is the lower heating value of biomethane, $Qbm = 35.8$ MJ/m^3.

According to our calculations, the most cost-energy effective feedstock is maize silage and straw (table 2).

We have studied the widespread biomass for biogas production: maize silage (Keane and Foley 2014), grass silage (Keane and Foley 2014), straw (Bang et al. 2013, CLAL.IT 2018) and molasses (CLAL.IT 2018). According to our calculations, the most cost-energy effective feedstocks are maize silage and straw (table 2).

Optimal biogas use pathway

Biogas utilization pathways

The best pathway of biogas utilization must be ascertained. It depends on maturity of technology, regional, and national features. The most widespread pathway is the combined generation of heat and power (CHP) (Djatkov 2014). But in Sweden the dominating volume of biogas is utilized as vehicle fuel (Lantz 2012). Biomethane production is immature technology now, but it is a prospect technology (Ravina and Genon 2015). Another promising way is solid oxide fuel cell-based combined heat and power systems for biogas utilization (Trendewicz and Braun 2013, Wongchanapai et al. 2013).

It should be explored which biogas utilization pathway is feasible to be chosen.

The evaluation may be based on a number of different criteria: cost effectiveness (economic criteria) (Börjesson and Ahlgren 2012, Goulding and Power 2013, Kalinichenko et al. 2016), energy efficiency (technical criteria) (Poschl et al. 2010); GHG emission savings (environmental) (Ravina and Genon 2015); green degree (a composite index proposed by X. Zhang based on nine environmental impact categories) (Tian et al. 2011, Yan et al. 2011, Zhang et al. 2008); life cycle assessment (Morero et al. 2015); multi-criteria analysis (Murphy et al. 2004, Dzene et al. 2014, Wua et al. 2016).

The combination of the three indexes (economic, environmental and energetic) is seldom used (Münster et al. 2015).

There are some various biogas-to-energy utilization pathways (figure 14):

1. Biogas to stove (cooking);
2. Biogas to heat;
3. Biogas to electric power;
4. Biogas to heat and power (CHP);
5. Biomethane as vehicle fuel;
6. Biomethane with grid injection to heat;
7. Biomethane with grid injection to combined heat and power generation.

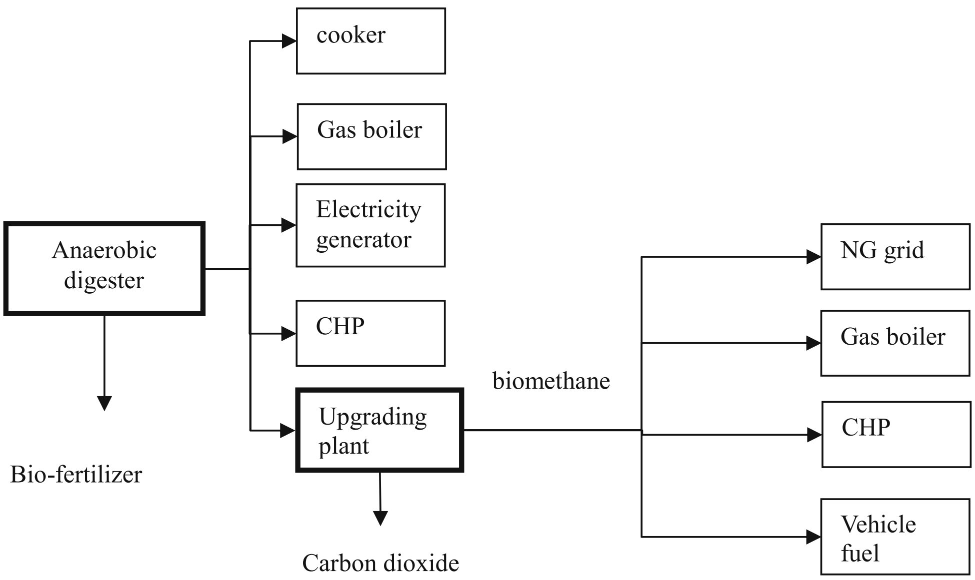

Fig. 14. Biogas utilization pathways
Source: developed by authors

Table 2. Biomass energy costs

Feedstock	Price, EUR · tDM^{-1}/(EUR · t^{-1})	Biomethane yield, m^3 · tDM^{-1}/(m^3 · t^{-1})	Biomass energy cost, EUR · GJ^{-1}
Maize silage	94–133 / –*	205–450 / –	5.83–18.1
Grass silage	120–150 / –*	283–467 / –	7.18–14.81
Straw	– / 70–93 **	242–324 / –	6.03–10.73
Molasses	– / 127–166 ***	– / 193 (moisture 41 %)	18.38–24.02

Source: developed by authors, * – Keane and Foley 2014: ** – Bang et al. 2013; CLAL.IT 2018; *** – CLAL.IT 2018.

As a rule, energy efficiency and economic evaluation methods are widespread.

Energy efficiency evaluation method

The energy efficiency of the biogas utilization systems is different. Until today, the final use of biogas has been its onsite combustion to generate heat or/and electricity. The thermal efficiency of biogas boilers is up to 90%. The efficiency of electricity generation depends on thermal engine type, its power rating and load. The best electrical efficiency is achieved in full load operation. It amounts to 26…27.4% for biogas-powered micro gas turbine engines (Bekker and Oechsner 2010, Brown et al. 2010, Rasul et al. 2015). Their energy efficiency can be increased through using heat recovery system. Thus the total efficiency of Capstone CR65 micro gas turbine engine reaches 70% (Bekker and Oechsner 2010). According to M.G. Rasul, biogas-powered micro gas turbine engines may be solution for small scale provision in remote areas (Rasul et al. 2015).

Biogas utilization systems based on internal combustion piston engines have more high electric and total efficiency (figure 15) (2G 2017, GE 2018). Biogas fuel cells had achieved the highest electric efficiency – up to 49%. They may have up to 90% of total efficiency and be used for combined heat and power generation. By 2015, Fuel Cell Energy, Inc. (USA) has placed 25 direct fuel cells on biogas plants around the world. Their electric output ranges from 250 to 2800 kW (Farooque et al. 2015).

The thermal performance of vehicle internal combustion engines vary in broad range (up to 45%) depending on their type. Thus, boilers and CHP have the highest thermal efficiency, vehicle internal combustion engines and gas turbine engines have the least (figure 16).

Economic evaluation

The economic feasibility of the biogas utilization system is, as a rule, evaluated using the Net Present Value (*NPV*) as a criterion (Kang et al. 2014, Wua et al. 2016). The profitability Index was used for economical analysis of biogas projects (Kalinichenko et al. 2017).

The asset value of one cubic meter of biogas depends on its utilization pathway. Substitution of conventional vehicle fuels (petrol or diesel fuel) has the highest earnings potential. Power generation does not produce high income. The problem of CHP exploitation is that, outside of industrial demand, the market for heat is primarily seasonal.

The asset value of one cubic meter of biogas may be determined as follows

– Substitution of natural gas in a gas boiler

$$EE_b = \frac{Q_b \cdot \eta_b}{Q_{ng} \cdot \eta_{ng}} \cdot PRNG, \text{ EUR/m}^3, \tag{15}$$

– Generation of electric power in engine-generator

$$EE_e = \frac{\eta_e \cdot Q_b}{3600} \cdot PREE, \text{ EUR/m}^3, \tag{16}$$

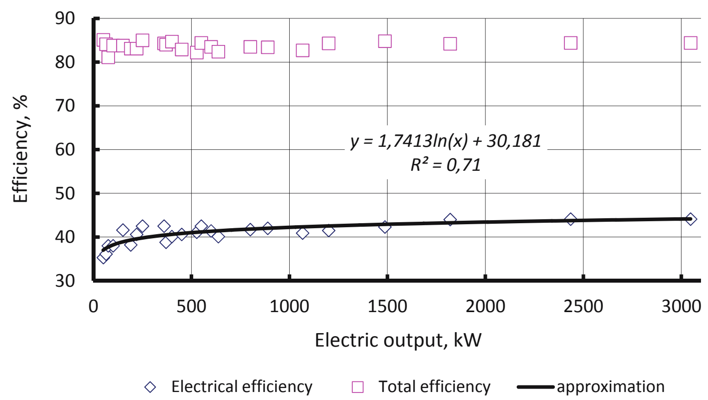

Fig. 15. Electrical and total efficiency of CHP
Source: Adapted from (2G 2017, GE 2018)

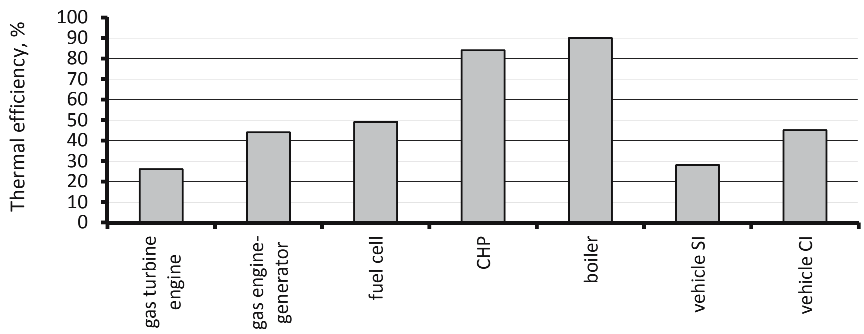

Fig. 16. Thermal efficiency of different technical devices
Source: developed by authors

– Combined heat and power generation

$$EE_{CHP} = \frac{\eta_e \cdot Q_b}{3{,}6} \cdot PREE + \left(\eta_{chp} - \eta_e\right) \cdot \frac{Q_b}{Q_{ng}} \cdot PRNG \text{, EUR/m}^3, \tag{17}$$

– Substitution of conventional vehicle fuel

$$EE_b = \frac{Q_b \cdot \eta_{bv}}{Q_c \cdot \eta_{cv}} \cdot PRCF \text{, EUR/m}^3, \tag{18}$$

– utilization of carbon dioxide (by-product of biogas upgrading process)

$$EE_{cd} = 0.01 \cdot \varphi \cdot PRCD \text{, EUR/m}^3, \tag{19}$$

where Q_{ng} is the lower heating value of natural gas, MJ/m^3; η_b is the efficiency of boiler on biogas; η_{ng} is the efficiency of boiler on natural gas; *PRNG* is the price of natural gas, EUR/m^3; η_e is the efficiency of engine-generator; *PREE* is the price of electricity, EUR/kWh; η_{chp} is the total efficiency of CHP; η_{bv} is the efficiency of engine on biogas; η_{cv} is the efficiency of engine on conventional vehicle fuel; *PRCF* is the price of conventional vehicle fuel, EUR/l; Q_{cv} is the lower heating value of conventional vehicle fuel, MJ/l; η is the content of carbon dioxide in biogas,%; *PRCD* is the price of carbon dioxide, EUR/m^3.

In condition of Ukraine (January 2018), biogas (lower heating value is equal to 21 MJ/m^3 and content of carbon dioxide is equal to 40%) utilization has potential to earn from 0.113 (substitution of natural gas) to 0.770 (substitute of gasoline and carbon dioxide sell) EUR (figure 17).

The economic feasibility of the biogas utilization system is affected by a number of external factors: investment costs; market prices of the end-products and energy resources which are substituted by biogas (biomethane); market prices of by-products (bio-fertilizer and carbon dioxide); economic conditions (including subsidy, green tariff, etc.). All by-products should be used as products. It will increase profitability of the projects (Kalinichenko et al. 2016).

The multi-criteria analysis is used to compare alternatives including optimization of biogas utilization pathway. The core of the multi-criteria analysis is based on a simple multi-objective matrix (Wang et al. 2009, Nzila et al. 2012, Dzene et al. 2014). The multi-criteria analysis covers the technical, financial, social-economic, and environmental perspectives. (Dzene et al. 2014).

To study the optimal biogas distribution by different pathways (heat, electricity, petrol substitute, combined heat and electricity) the economic optimizing model was developed. It takes into account end consumer requirements in energy resources. The linear programming method is applied to solve the problem. The Net Present Value indicator was used as a criterion and an objective function (Pavlov et al. 2015).

Two business configurations for biomethane (biogas) projects are possible. The first one, the producer of biomethane sells renewable energy resource to a distributor. The second one, the producer of biomethane sells its biofuel and by-products to the end consumers. The last configuration is more profitable (Cucchiella et al. 2015). It results in establishing agro-energy verticals in agriculture and food industries (Bilan et al. 2017).

Conceptual flow chart

The conceptual flow chart is outlined in figure 18. The preliminary biogas project assessment covers the following items:

- Preliminary information collection;
- Maturity of biogas technology assessment;
- Feedstock assessment;
- Optimal biogas utilization pathways determination;
- Decision making.

Conclusion

On the first stage of the assessment of a biogas project, the maturity of technology should be examined. The generalized

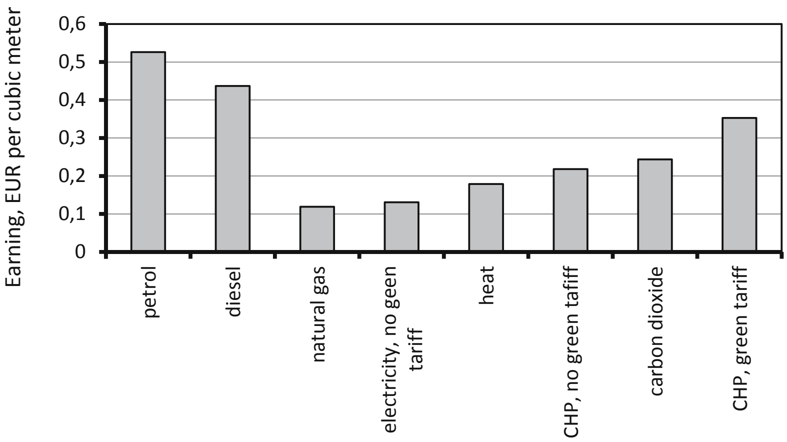

Fig. 17. Potential earnings for different pathways of biogas utilization
Source: developed by authors

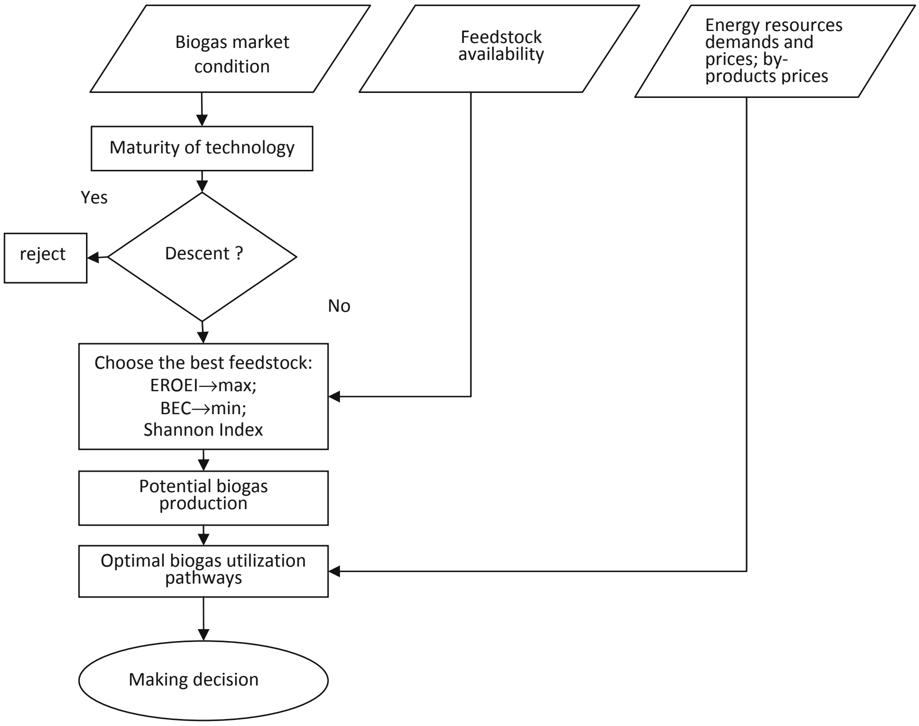

Fig. 18. Flow chart
Source: developed by authors

Weng model is preferable to be used. The simplest method to determine its parameters is the Solver in MS Excel (offered by the authors). The study of technology diffusion gives opportunity to make a short-term prediction. It is of great significance for policy makers to set regulations on a biogas market that reflect reality.

Feedstock supply is an important factor for biogas projects. It is rational to determine biomass available, its energy and economic traits. The crop residues of maize and chicken manure have the highest value of EROEI.

We offered the new energy and economic indicators: energy efficiency ratio for biogas (biomethane) production and biomass energy cost. EER factors in main product (biogas or biomethane) and by-product. BEC gives information about the cost of biomass per unit of biomethane energy.

The feasibility of biogas projects depends on a biogas (biomethane) utilization pathway. The best economic results can be obtained in the following cases:

- The substitution of petroleum vehicle fuels;
- The direct selling of biomethane by a producer to the end consumer;
- The selling of all by-products of both biogas and biomethane producing.

Some agricultural practices or renewable energy resource utilization may be subsidized. Their economic profitability depends on existing market conditions, and governmental regulations. It may be stated that the EU 2020 targets for renewable energy can be met if there are concerted efforts between technologists and policy makers. Suitable policies, management schemes, taxation, and legislation will be a substantial push towards biogas development. The above is a subject for further study.

References

2G (2G Energy AG). (2017). *Product range*, (http://www.2-g.com/module/designvorlagen/downloads/2g_product_range.pdf (06.03.2018)).

Arodudu, O., Helming, K., Wiggering, H. & Voinov, A. (2017). Bioenergy from low-intensity agricultural systems: an energy efficiency analysis, *Energies*, 19(1), pp. 1–18. doi:10.3390/en10010029.

Arodudu, O., Voinov, A. & Duren, van I. (2013). Assessing bioenergy potential in rural areas – A NEG-EROEI approach, *Biomass and Bioenergy*, 58, pp. 350–364. doi: 10.1016/j.biombioe.2013.07.020.

Arodudu, O.T., Voinov, A. & Duren, van I.C. (2012). Assessing bioenergy potentials in rural landscapes, In: *Proceedings of IAIA 12 conference: Energy future, the role of impact assessment: 32nd annual meeting of the International Association of Impact Assessment,* pp. 1–6. (https://research.utwente.nl/en/publications/assessing-bioenergy-potentials-in-rural-landscapes (13.12.2012)).

Atamanyuk, I.P. (2002). Polynomial algorithm of optimal extrapolation of stochastic system parameters, *International Journal* "Upravlyayushchie Sistemy i Mashiny" (*International Journal "Control Systems and Computers"*), 1, pp. 16–19.

Atamanyuk, I.P. (2005). Algorithm of extrapolation of a nonlinear random process on the basis of its canonical decomposition, *Cybernetics and Systems Analysis*, 41(2), pp. 131–139. doi: 10.1007/s10559-005-0059-y.

Bang, C., Vitina, A., Gregg, J.S. & Lindboe, H.H. (2013*). Analysis of biomass prices, future Danish prices for straw, wood chips and wood pellets "Final Report"* – 18.06.2013. Danish Energy Agency's (DEA): Ea Energy Analyses. (http://www.ea-energianalyse.dk/reports/1280_analysis_of_biomass_prices.pdf (08.03.2018)).

Baños, R., Manzano-Agugliaro, F., Montoya, F.G., Gil C., Alcayde, A. & Gómez, J. (2011). Optimization methods applied to renewable and sustainable energy, *Renewable and Sustainable Energy Reviews*, 15(4), pp. 1753–1766. doi: 10.1016/j.rser.2010.12.008

Basset, N., Kermah, M., Rinaldi, D. & Scudellaro, F. (2010). The net energy of biofuels, in: *EPROBIO IP June 2010*. (http://www.iperasmuseprobio.unifg.it/dwn/THENETENERGYOFBIOFUELS.pdf (03.03.2018)).

Bekker, M. & Oechsner, H. (2010). Practical experience of using a biogas-powered micro gas turbine, *Landtechnik*, 65(2), pp. 136–138. (https://www.landtechnik-online.eu/ojs-2.4.5/index.php/landtechnik/article/download/2010-2-136-138/991 (06.03.2018)).

Bilan, Y., Nitsenko, V. & Havrysh, V. (2017). Energy aspects of vertical integration in agriculture, *Rynek Energii*, 5(132), pp. 98–110 (http://rynek-energii.pl/pl/node/3549 (08.03.2018)).

Bohutskyi, P., Ketter, B., Chow, S., Adams, K., Betenbaugh, M.J., Allnutt, F.C.T. & Bouwer, E.J. (2015). Anaerobic digestion of lipid-extracted auxenochlorella protothecoides biomass for methane generation and nutrient recovery, *Bioresources Technology*, 183, pp. 229–239. doi: 10.1016/j.biortech.2015.02.012

Bojesen, M., Birkin, M. & Clarke, G. (2014). Spatial competition for biogas production using insights from retail location models, *Energy*, 68, pp. 617–628. doi: 10.1016/j.energy.2013.12.039

Bojnec, S. & Papler, D. (2013). Biogas energy development in Slovenia, *Annals of the Faculty of Engineering Hunedoara*, 11(1), pp. 77–86. doi: 10.13140/RG.2.1.2542.0644.

Börjesson, M. & Ahlgren, E.O. (2012). Cost-effective biogas utilisation – A modelling assessment of gas infrastructural options in a regional energy system, *Energy,* 48(1), pp. 212–226. doi: 10.1016/j.energy.2012.06.058

BP (2017). *BP Statistical Review of World Energy 2017* (https://www.bp.com/content/dam/bp/en/corporate/pdf/energy-economics/statistical-review-2017/bp-statistical-review-of-world-energy-2017-full-report.pdf (02.03.2018)).

Brandt, A.R. (2010). Review of mathematical models of future oil supply: historical overview and synthesizing critique, *Energy*, 35(9), pp. 3958–3974. doi: 10.1016/j.energy.2010.04.045.

Bravo, M.D.L., Naim, M.M. & Potter, A. (2012). Key issues of the upstream segment of biofuels supply chain: a qualitative analysis, *Logistics Research*, 5, pp. 21–31. Doi: 10.1007/s12159-012-0077-x

Brown, N., Edström, M., Hansson, M. & Algerbo, P.-A. (2010). Evaluation of farm biogas plant with micro turbine for cogeneration production. JTI report Circulation & Waste, no. 46 JTI, Uppsala (in Swedish) (http://www.jti.se/uploads/jti/r-46%20nb,%20med_lag.pdf (08.03.2018)).

Cao, J., Yu, G. & Xie, Y. (2014). The solving method of generalized Weng model parameters based on curve fitting, *Journal of Chemical and Pharmaceutical Research*, 6(12), pp. 734–737.

Carchesio, M., Tatàno, F., Lancellotti, I., Taurino, R., Colombo, E. & Barbieri, L. (2014). Comparison of biomethane production and digestate characterization for selected agricultural substrates in Italy, *Environmental Technology*, 35(17), pp. 2212–2226. doi: 10.1080/09593330.2014.898701

Cerović, L., Maradin, D. & Čegar, S. (2014). From the restructuring of the power sector to diversification of renewable energy sources: preconditions for efficient and sustainable electricity market, *International Journal of Energy Economics and Policy*, 4(4), pp. 599–609.

Chasnyk, O., Sołowski, G. & Shkarupa, O. (2015). Historical, technical and economic aspects of biogas development: Case of Poland and Ukraine, *Renewable and Sustainable Energy Reviews*, 52, pp. 227–239. doi: 10.1016/j.rser.2015.07.122

Chen, H., Zhou, D., Luo, G., Zhang, S. & Chen, J. (2015). Macroalgae for biofuels production: Progress and perspectives, *Renewable & Sustainable Energy Reviews*, 47, pp. 427–437. doi.org/10.1016/j.rser.2015.03.086

Chodkowska-Miszczuk, J., Kulla, M. & Novotný, L. (2017). The role of energy policy in agricultural biogas energy production in Visegrad countries*, Bulletin of Geography. Socio-economic Series*, 35, pp. 19–34. doi: 10.1515/bog-2017-0002

CLAL.IT (Italian Dairy Economic Consulting firm) (2018). *Prices of livestock foods: fodder and by-products* (https://www.clal.it/en/?section=conf_foraggi (08.03.2018)).

CSYD (China Statistical Yearbooks Database). (2015). China agriculture statistical report (1989–2014). China Agriculture Press, ISBN: 978-7-109-21107-0 (http://tongji.cnki.net/overseas/engnavi/HomePage.aspx?id=N2015110269&name=YZGNT&floor=1 (03.03.2018)). (in Chinese)

Cucchiella, F. & D'Adamo, I. (2015). Residential photovoltaic plant: environmental and economical implications from renewable support policies, *Clean Technologies and Environmental Policy*, 17(7), pp. 1929–1944. doi: 10.1007/s10098-015-0913-1

Cucchiella, F., D'Adamo, I. & Gastaldi, M. (2015). Profitability analysis for biomethane: a strategic role in the italian transport sector, *International Journal of Energy Economics and Policy*, 5(2), pp. 440–449.

Dekelver, G., Ruzigana, S. & Lam, J. (2005). *Report on the Feasibility Study for a Biogas Support Programme in the Republic of Rwanda* (http://www.susana.org/en/knowledge-hub/resources-and-publications/library/details/490 (09.03.2018)).

Dell'Antonia, D., Cividino, S.R.S., Gubiani, R., Pergher, G., Monarca, D., Bedini, R. & Cecchini, M. (2014). Preliminary study of biogas production from agricultural waste in friuli Venezia Giulia (Nord-East of Italy), *Environmental Sciences*, 2(1), pp. 1–11. doi: 10.12988/es.2014.411

Delzeit, R. & Kellner, U. (2013). The impact of plant size and location on profitability of biogas plants in Germany under consideration of processing digestates, *Biomass and Bioenergy*, 52, pp. 43–53. doi: 10.1016/j.biombioe.2013.02.029

Dereli, R.K., Yangin-Gomec, C., Ozabali, A. & Ozturk, I. (2012). The feasibility of a centralized biogas plant treating the manure produced by an organized animal farmers union in Turkey, *Water Science & Technology,*66(3), pp. 556–563. doi: 10.2166/wst.2012.203

Djatkov, D., Effenberger, M. & Martinov, M. (2014). Method for assessing and improving the efficiency of agricultural biogas plants based on fuzzy logic and expert systems, *Applied Energy,* 134, pp. 163–175. doi: 10.1016/j.apenergy.2014.08.021

During, F.F.A., de Souza, J., Rossini, E.G. & Beluco A. (2017). Pre--feasibility study for the development of a biogas plant, *Revista Espacios*, 38(18). (http://www.revistaespacios.com/a17v38n18/a17v38n18p25.pdf (28.03.2018))

Dzene, I., Romagnoli, F., Seile, G. & Blumberga, D. (2014). Comparison of different biogas use pathways for Latvia: biogas use in CHP vs. biogas upgrading, *The 9th International Conference "ENVIRONMENTAL ENGINEERING"* 22–23 May 2014, Vilnius, Lithuania. doi: 10.3846/enviro.2014.017

EC (European Commission) (2017). *Optimal use of biogas from waste stream. An assessment of the potential of biogas from digestion in the EU beyond 2020*. (https://ec.europa.eu/energy/sites/ener/files/documents/ce_delft_3g84_biogas_beyond_2020_final_report.pdf (04.03.2018))

Fallde, M. & Eklund, M. (2015). Towards a sustainable socio-technical system of biogas for transport: the case of the city of Linköping in Sweden, *Journal of Cleaner Production*, 98(1), pp. 17–28. doi: 10.1016/j.jclepro.2014.05.089

FAO (Food and Agriculture Organization of the United Nations) (2008). Forests and energy, key issues. FAO Forestry Paper 154. ISBN: 978-92-5-105985-2. (http://www.fao.org/docrep/010/i0139e/i0139e00.htm (03.03.2018))

Farooque, M., Leo, A., Rauseo, A. & Wang, J. (2015). Efficient and ultra-clean use of biogas in the fuel cell – the DFC experience, *Energy, Sustainability and Society*, 5, pp. 246–256. doi: 10.1186/s13705-015-0041-0

Gagnon, N., Hall, C. & Brinker, L. (2009). A preliminary investigation of the energy return on energy investment for global oil and gas production, *Energies*, 2, pp. 490–503. doi: 10.3390/en20300490

GE (General Electric power) (2018). *Reciprocating Engines*. (https://www.gepower.com/gas/reciprocating-engines (04.03.2018))

Gebrezgabher, S.A., Meuwissen, M.P., Prins, B.A. & Lansink, A.G.O. (2010). Eco-nomic analysis of anaerobic digestion – a case of Green power biogas plant in The Netherlands, *NJAS-Wageningen Journal of Life Sciences*, 57(2), pp. 109–115. doi: 10.1016/j.njas.2009.07.006

Gong, J. & You, F. (2014). Optimal design and synthesis of algal biorefinery processes for biological carbon sequestration and utilization with zero direct greenhouse gas emissions, *Industrial & Engineering Chemistry Research*, 53(4), pp. 1563–1579. doi: 10.1021/ie403459m

Goulding, D. & Power, N. (2013). Which is the preferable biogas utilisation technology for anaerobic digestion of agricultural crops in Ireland: Biogas to CHP or biomethane as a transport fuel? *Renewable Energy,* 53, pp. 121–131. http://dx.doi.org/10.1016/j.renene.2012.11.001

Gu, L., Zhang, YX., Wang, JZ., Chen, G. & Battye, H. (2016). Where is the future of China's biogas? Review, forecast, and policy implications, *Petroleum Science,* 13(3), pp. 604–624. doi: 10.1007/s12182-016-0105-6

Hall, C. & Klitgaard, K. (2012). *Energy and the Wealth of Nations: Understanding the Biophysical Economy*. Springer Publishing Company, New York 2012. doi: 10.1007/978-1-4419-9398-4

Hall, C.A.S., Balogh, S. & Murphy, D.J.R. (2009). What is the minimum EROI that a sustainable society must have? *Energies*, 2(1), pp. 25–47. doi: 10.3390/en20100025

Hall, C.A.S., Lambert, J.G. & Balogh, S.B. (2014). EROI of different fuels and the implications for society, *Energy Policy*, 64, pp. 141–152. doi: 10.1016/j.enpol.2013.05.049

Havrysh, V. & Nitsenko, V. (2016). Current state of world alternative motor fuel market, *Actual Problems of Economics*, 7(181), pp. 41–52. (http://www.irbis-nbuv.gov.ua/cgi-bin/irbis_nbuv/cgiirbis_64.exe?C21COM=2&I21DBN=UJRN&P21DBN=UJRN&IMAGE_FILE_DOWNLOAD=1&Image_file_name=PDF/ape_2016_7_7.pdf (08.03.2018)).

Hook, M., Li, J., Oba, N. & Snowden, S. (2011). Descriptive and predictive growth curves in energy system analysis, *Natural Resources Research*, 20(2), pp. 103–116. doi: 10.1007/s11053-011-9139-z

Hughes, J.D. (2013). *Drill, Baby, Drill: Can Unconventional Fuels Usher in a New Era of Energy Abundance*? The Post Carbon Institute, Santa Rosa 2013.

IEA (International Energy Agency) (2017). *Key World Energy Statistics 2017* (https://www.iea.org/publications/freepublications/publication/key-world-energy-statistics.html (02.03.2018)).

Igliński, B., Buczkowski, R. & Cichosz, M. (2015). Biogas production in Poland – Current state, potential and perspectives, *Renewable and Sustainable Energy Reviews*, 50, pp. 686–695. doi: 10.1016/j.rser.2015.05.013

IRENA (International Renewable Energy Agency). (2016). *Renewable Energy and Jobs*, Annual Review 2016, ISBN: 978-92-95111-89-9 (http://www.irena.org/publications/2016/May/Renewable-Energy-and-Jobs--Annual-Review-2016/ (02.03.2018)).

IRENA (International Renewable Energy Agency) (2017). *Biogas for road vehicles. Technology brief.* ISBN: 978-92-9260-002-0 (http://www.irena.org/publications/2017/Mar/Biogas-for-road-vehicles-Technology-brief (03.03.2018)).

Jansen, J.C., van Arkel, W.G. & Boots, M.G. (2004). Desigining indicators of long-term energy supply security, ECN-C-04-007. (https://www.ecn.nl/publicaties/PdfFetch.aspx?nr=ECN-C--04-007 (09.03.2018)).

JICA (Japan International Cooperation Agency) (2015). *Simple Pre-Feasibility of Biogas Projects* (http://open_jicareport.jica.go.jp/pdf/12229423_04.pdf (09.03.2018)).

Kalinichenko, A., Havrysh, V. & Perebyynis, V. (2017). Sensitivity analysis in investment project of biogas plant, *Applied Ecology and Environmental Researches*, 15(4), pp. 969–985. doi: 10.15666/aeer/1504_969985.

Kalinichenko, A., Havrysh, V. & Perebyynis, V. (2016). Evaluation of biogas production and usage potential, *Ecological Chemistry and Engineering S.,* 23(3), pp. 387–400. doi: 10.1515/eces-2016-0027

Kampman, B., Leguijt, C., Scholten, T., Tallat-Kelpsaite, J., Brückmann, R., Maroulis, G., Lesschen, J.P., Meesters, K., Sikirica, N. & Elbersen, B. (2016). *Optimal use of biogas from waste streams. An assessment of the potential of biogas from digestion in the EU beyond 2020.* European Commission. (https://ec.europa.eu/energy/sites/ener/files/documents/ce_delft_3g84_biogas_beyond_2020_final_report.pdf (08.03.2018)).

Kang, J.Y., Kang, D.W., Kim, T.S. & Hur, K.B. (2014). Comparative economic analysis of gas turbine-based power generation and combined heat and power systems using biogas fuel, *Energy,* 67, pp. 309–318. doi: 10.1016/j.energy.2014.01.009.

Keane, G. & Foley, J. (2014). Does maize make sense? *Farm Ireland*, (https://www.independent.ie/business/farming/does-maize-make-sense-30017476.html (10.03.2018)).

Kruyt, B., van Vuuren, D.P., de Vries, H.J.M. & Groenenberg, H. (2009). Indicators for energy security, *Energy Policy,* 37(6), pp. 2166–2181. doi: 10.1016/j.enpol.2009.02.006.

Lantz, M. (2012). The economic performance of combined heat and power from biogas produced from manure in Sweden – a comparison of different CHP technologies, *Applied Energy*, 98, pp. 502–511. doi: 10.1016/j.apenergy.2012.04.015

Li, L.D., Wang, Q., Liu, H. & Song, Y. (2008). Calculation and analysis of diversity of domestic primary energy supply, *Journal of North-eastern University,* 29(4), pp. 577–580. (http://en.cnki.com.cn/Article_en/CJFDTOTAL-DBDX200804030.html (09.03.2018)).

Lund, P.D. (2010). Exploring past energy changes and their implications for the pace of penetration of new energy technologies, *Energy*, 35, pp. 647–656. doi: 10.1016/j.energy.2009.10.037

Mansfield, E. (1961). Technical change and the rate of imitation, *Econometrica*, 29(4), pp. 741–766. doi: 10.2307/1911817

Mel, M., Ibrahim, M.M.A. & Setyobudi, R.H. (2016). Preliminary study of biogas upgrading and purification by pressure swing adsorption, *AIP Conf. Proc.*, 1755(1), pp. 130010:1–5, doi: 10.1063/1.4958554

Milledge, J.J. & Heaven, S. (2014). Methods of energy extraction from microalgal biomass: a review, *Reviews in Environmental Science and Bio/Technology*, 13(3), pp. 301–320. doi: 10.1007/s11157-014-9339-1

Milledge, J.J. (2013). *Energy Balance and Techno-Economic Assessment of Algal Biofuel Production Systems*. Ph.D. Thesis, University of Southampton (UK), Southampton 2013 (https://eprints.soton.ac.uk/id/eprint/357074 (18.07.2017)).

Milledge, J.J. & Heaven, S. (2017). Energy balance of biogas production from microalgae: effect of harvesting method, multiple raceways, scale of plant and combined heat and power generation, *Journal of Marine Science and Engineering,* 5(1), 9, pp. 1–15. doi: 10.3390/jmse5010009

Mohammed, M., Egyir, I.S., Donkor, A.K., Amoah, P., Nyarko, S., Boateng, K.K. & Ziwu, C. (2017). Feasibility study for biogas integration into waste treatment plants in Ghana, *Egyptian Journal of Petroleum,* 26(3), pp. 695–703. doi: 10.1016/j.ejpe.2016.10.004

Morero, B., Groppelli, E. & Campanella, E.A. (2015). Life cycle assessment of biomethane use in Argentina, *Bioresources Technology*, 182, pp. 208–216. doi: 10.1016/j.biortech.2015.01.077.

Münster, M., Ravn, H., Hedegaard, K., Juul, N. & Ljunggren Söderman, M. (2015). Economic and environmental optimization of waste treatment, *Waste Manage,* 38, pp. 486–495. doi: 10.1016/j.wasman.2014.12.005

Murphy, J.D., McKeogh, E. & Kiely, G. (2004). Technical/economic/environmental analysis of biogas utilisation, *Applied Energy,* 77(4), pp. 407–427. doi: 10.1016/j.apenergy.2003.07.005

Nzila, C., Dewulf, J., Spanjers, H., Tuigong, D., Kiriamiti, H. & Langenhove, H. (2012). Multi criteria sustainability assessment of biogas production in Kenya, *Applied Energy*, 93, pp. 496–506. doi: 10.1016/j.apenergy.2011.12.020

Palm, R. (2010). *The economic potential for production of upgraded biogas used as vehicle fuel in Sweden*. Report No. FRT 2010:03. Göteborg: Chalmers University of Technology. (http://publications.lib.chalmers.se/records/fulltext/126342.pdf (09.03.2018)).

Pantaleo, A., Candelise, C., Bauen, A. & Shah, N. (2014). ESCO business models for biomass heating and CHP: Profitability of ESCO operations in Italy and key factors assessment, *Renewable and Sustainable Energy Reviews*, 30, pp. 237–253. doi: 10.1016/j.rser.2013.10.001

Pavlov, K., Gavrish, V. & Nitsenko, V. (2015). Biogas complexes: the economic rationale for use in various regions and countries of the world, *Regional economics: theory and practice*, 28, pp. 2–14 (https://cyberleninka.ru/article/n/biogazovye-kompleksy-ekonomicheskaya-tselesoobraznost-ispolzovaniya-v-razlichnyh-regionah-i-stranah-mira (09.03.2018)).

Piwowar, A., Dzikuć, M. & Adamczyk, J. (2016). Agricultural biogas plants in Poland – selected technological, market and environmental aspects, *Renewable and Sustainable Energy Reviews*, 58, pp. 69–74. doi: 10.1016/j.rser.2015.12.153

Poeschl, M, Ward, S. & Owende, P. (2010). Prospects for expanded utilization of biogas in Germany, *Renewable Sustainable Energy Reviews*, 14(7), pp. 1782–1797. doi: 10.1016/j.rser.2010.04.010

Poggi-Varaldo, H.M., Muñoz-Páez, K.M., Escamilla-Alvarado, C., Robledo-Narváez, P.N., Ponce-Noyola, M.T., Calva-Calva, G., Ríos-Leal, E., Galíndez-Mayer, J., Estrada-Vázquez, C. & Ortega-Clemente, A. (2014). Biohydrogen, biomethane and bioelectricity as crucial components of biorefinery of organic wastes: a review, *Waste Management and Research*, 32(5), pp. 353–365. doi: 0734242X14529178

Poschl, M. Ward, S. & Owende, P. (2010). Evaluation of energy efficiency of various biogas production and utilization pathways, *Applied Energy*, 87(11), pp. 3305–3321. doi: 10.1016/j.apenergy.2010.05.011

Pukšec, T. & Duić, N. (2012). Economic viability and geographic distribution of centralized biogas plants: case study Croatia, *Clean Technologies and Environmental Policy*, 14(3), pp. 427–433. doi: 10.1007/s10098-012-0460-y

Rajendran, K., Kankanala, H.R., Martinsson, R. & Taherzadeh, M.J. (2014). Uncertainty over techno-economic potentials of biogas from municipal solid waste (MSW): a case study on an industrial process, *Applied Energy*, 125, pp. 84–92. doi: 10.1016/j.apenergy.2014.03.041

Rasul, M.G., Ault, C. & Sajjad, M. (2015). Bio-gas mixed fuel micro gas turbine co-generation for meeting power demand in Australian remote areas, *Energy Procedia*, 75, pp. 1065–1071. doi: 10.1016/j.egypro.2015.07.476

Ravina, M. & Genon, G. (2015). Global and local emissions of a biogas plant considering the production of biomethane as an alternative end-use solution, *Journal of Cleaner Production*, 102, pp. 115–126. doi: 10.1016/j.jclepro.2015.04.056

Reed, V. (2015). Algal progress report, *Industrial Biotechnology*, 11(1), pp. 3–5. doi: 10.1089/ind.2014.1544

REN 21 (Renewable Energy Policy Network for 21st Century) (2017). *Distributed Renewable Energy Map*, (http://www.ren21.net/wp-content/uploads/2017/06/17-8399_GSR_2017_Full_Report_0621_Opt.pdf (02.03.2018)).

Silalertruksa, T. & Gheewala, S.H. (2010). Security of feedstocks supply for future bio-ethanol production in Thailand, *Energy Policy*, 38(11), pp. 7476–7486. doi: 10.1016/j.enpol.2010.08.034

Sills, D.L., Paramita, V., Franke, M.J., Johnson, M.C., Akabas, T.M., Greene, C.H. & Tester, J.W. (2012). Quantitative uncertainty analysis of life cycle assessment for algal biofuel production, *Environmental Science & Technology*, 47(2), pp. 687–694. doi: 10.1021/es3029236

Sorrell, S. (2010). Hubbert's legacy: a review of curve-fitting methods to estimate ultimately recoverable resources, *Natural Resources Research*, 19(3), pp. 209–230.

Tian, X., Zhang, X., Zeng, S., Xu, Y., Yao, Y., Chen, Y., Huang, L., Zhao, Y. & Zhang, S. (2011). Process analysis and multi-objective optimization of ionic liquid containing acetonitrile process to produce 1,3-butadiene, *Chemical Engineering & Technology*, 34(6), pp. 927–936. doi: 10.1002/ceat.201000426

Trendewicz, A.A. & Braun, R.J. (2013). Techno-economic analysis of solid oxide fuel cell-based combined heat and power systems for biogas utilization at wastewater treatment facilities, *Journal of Power Sources*, 233, pp. 380–393. doi: 10.1016/j.jpowsour.2013.01.017

Trivett, A. & Hall, M. (2009). *Feasibility of Biogas Production on Small Livestock Farms*. UPEI Department of Engineering (http://www.matt-hall.ca/docs/Biogas-Report-Final.pdf (08.03.2018)).

Tverberg, G. (2012). Oil supply limits and the continuing financial crisis, *Energy*, 37(1), pp. 27–34. doi: 10.1016/j.energy.2011.05.049

USDA'S GAIN (United States Department of Agriculture Global Agriculture Information Network) (2017*). EU Biofuels Annual 2017*. GAIN Report Number NL7015, (https://gain.fas.usda.gov/Recent%20GAIN%20Publications/Biofuels%20Annual_The%20Hague_EU-28_6-19-2017.pdf (21.06.2017)).

USEPA (United States Environmental Protection Agency). (2016). *Biogas Facts and Trends. United States Environmental Protection Agency* (https://www.epa.gov/agstar/agstar-data-and-trends#biogasfacts (02.03.2018)).

Wajszczuk, K., Wawrzynowicz, J. & Pepliński, B. (2016). Plant production for biomass into energy: economics and energy efficiency view, *Applied Studies in Agribusiness and Commerce*, 10(1), pp. 65–71. doi: 10.19041/APSTRACT/2016/1/9

Wang, J.J., Jing, Y.Y., Zhang, C.F. & Zhao, J.H. (2009). Review on multi-criteria decision analysis aid in sustainable energy decision-making, *Renewable & Sustainable Energy Reviews*, 13(9), pp. 2263–2278. doi: 10.1016/j.rser.2009.06.021

Wang, X., Lei, Y., Ge, J. & Wu S. (2015). Production forecast of China's rare earths based on the Generalized Weng model and policy recommendations, *Resources Policy*, 43, pp. 11–18. doi: 10.1016/j.resourpol.2014.11.002

Ward, A.J., Lewis, D.M. & Green, B. (2014). Anaerobic digestion of algae biomass: A review, *Algal Research-Biomass Biofuels and Bioproducts Journal*, 5, pp. 204–214. doi: 10.1016/j.algal.2014.02.001

WBA (World Bioenegy Association). (2017). *Global bioenergy statistics 2017* (http://worldbioenergy.org/uploads/WBA%20GBS%202017_hq.pdf (02.03.2018).

Włodarczyk, P.P., Włodarczyk, B. & Kalinichenko, A. (2017). Possibility of direct electricity production from waste canola oil, *E3S Web of Conferences*, 19 (01019), pp. 1–4. DOI: 10.1051/e3sconf/20171901019

Wongchanapai, S., Iwai, H., Saito, M. & Yoshida, H. (2013). Performance evaluation of a direct-biogas solid oxide fuel cell--micro gas turbine (SOFC-MGT) hybrid combined heat and power (CHP) system, *Journal of Power Sources*, 223, pp. 9–17. doi: 10.1016/j.jpowsour.2012.09.037

Wua, B., Zhang, X., Shang, D., Bao, D., Zhang, S. & Zheng, T. (2016). Energetic-environmental-economic assessment of the biogas system with three utilization pathways: Combined heat and power, biomethane and fuel cell, *Bioresource Technology*, 214, pp. 722–728. doi: 10.1016/j.biortech.2016.05.026

Yan, R., Li, Z., Diao, Y., Fu, C., Wang, H., Li, C., Chen, Q., Zhang, X. & Zhang, S. (2011). Green process for methacrolein separation with ionic liquids in the production of methyl methacrylate, *AlChE Journal*, 57(9), pp. 2388–2396. doi: 10.1002/aic.12449

Zhang, X., Li, C., Fu, C. & Zhang, S. (2008). Environmental impact assessment of chemical process using the green degree method, *Industrial & Engineering Chemistry Research*, 47 (4), pp. 1085–1094. doi: 10.1021/ie0705599

Zhang, Y. & Colosi, L.M. (2013). What are we missing by focusing on algae biodiesel?, *Biofuels*, 4(6), pp. 591–593. doi: 10.4155/bfs.13.52

Zuberi, M.J.S. & Fahrioğlu, M. (2015). Application of Hubbert Peak theory to stimulate biogas production, *International Journal of Renewable Energy Research*, 5(1), pp. 61–69. (http://dergipark.gov.tr/download/article-file/148092 (10.02.2018)