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Water, Wastewater and Energy in Smart Cities

Energy from Landfill Gas as an Example of Circular Economy

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Abstract. Landfill biogas becomes an important factor in elimination of fossil fuels as a result of fast- growing use of renewable energy sources. The article presents an analysis of operation of the plant where landfill biogas was utilized for energy production. The average annually (gross) productions of electric energy and heat at the plant were 1217 MWh and 1,789 MW, respectively. The average calorific value of biogas was 17 MJ/m^3, which corresponds to 4,8 kW/m^3. According to the measurements and actual readings acquired during operation of a cogeneration unit, it can be stated that the CHP system has been working within its average operation limits and still has some power reserves to utilize. Therefore, the authors concluded that a landfill can be operated both as a producer and a supplier of prosumer energy.

1 Introduction

According to the Central Statistical Office (GUS) [1, 2] there have been 394 municipal landfills in operation in Poland at the end of 2014. They occupied a total area of over 4762 acres. At the same time, 66 landfills were closed in 2014 with the total area of almost 390 acres. Also, about 10 330.4 thousand tons of municipal waste (an increase by 8.3%, if compared to 2013.) have been collected and 5 978.7 thousand tons (52.6%) were disposed at landfills in 2014. The data show that landfills are still the leading method of solid waste disposition in Poland.

Municipal waste stored in landfills has a high content of organic materials of different humidity. Methane fermentation produces biogas. The composition of biogas is mainly methane (35 - 70%), carbon dioxide (20 - 50%) and other pollutants, among others. nitrogen, hydrogen, hydrogen sulphide, oxygen, carbon monoxide. On average, 150-400 m3 of waste can be recovered from the 1 tonne mass of waste [3 – 5, 6, 7].

Biogas must be cleaned and used for energy purposes or burned in a torch. The most common way of managing landfill gas is to burn it in specially prepared torches or heat-generating plants that supply heat to adjacent plants or housing estates. However, it is best to use landfill gas as a fuel for generating sets equipped with heat exchangers. Not only does it have "clean" ecological electricity as well as warmth that can be used freely.

A general problem with biogas resources is their local nature. The EU policies concerning renewable energy systems (RES) have set forward a fixed goal of supplying 20% of the European energy demands from RES by year 2020. A major part of the renewable energy will originate from European farming and forestry. At least 25% of all bioenergy in the future can originate from biogas, produced from wet organic materials such as: animal manure, whole crop silages, wet food and feed wastes, etc. [6 – 9].

The worldwide biogas production is unknown, but the production of biogas in the European Union was estimated to be around 69 TWh in 2007. To arrive at a rough estimate of global landfilling, we started with the known rate of landfilling in the US (220 million tonnes). The European Union (EU), and the rest of the "golden billion" who enjoy a high standard of living generate an estimated 420 million tonnes of MSW of which at least 210 million tonnes (50%) are landfilled. Waste management studies in developing nations, including some in Africa, have shown that the MSW generation is always higher than 0.2 tonnes per capita, most of which is food and yard wastes and is landfilled. This results in the estimate of 1080 million tonnes for the 5.4 billion people in the developing world. Adding up these estimates indicates that the global MSW landfilled is somewhere close to 1.5 billion tonnes of MSW[6, 7, 10].

Optimization of energy consumption at solid waste disposal facilities is a major challenge while managing these objects. Rising operation costs (in particular energy costs) are forcing policymakers to search for new solutions, including new energy sources. Landfill biogas can be considered as such a potential energy source.

2 Waste disposal installations – Waste-to-Energy Units

The landfill, which collects municipal waste with a biodegradable fraction becomes a "bioreactor", where organic matter is transformed into landfill biogas. According to data provided by the GUS, 342 Polish landfills had degassing installations in 2014; they accounted for 86.8% of all active landfills where municipal waste were deposited. The detailed summary of the Polish landfills with degassing installations in –service in 2014 is presented in the table below.

Table 1. Degasification installations and energy recovery systems at the Polish landfills

Year	Landfills with degasification	Landfills with a gas discharge to atmosphere	Landfills with individual burners	Landfills with a flare	Landfills with heat recovery	Landfills with electricity generators
2014	342	159	59	82	16	62
2013	362	199	61	78	15	59
2012	430	244	63	81	13	58
2011	322	225	30	28	5	31

More than 42% of the degassing installations were units that discharge gas directly into the atmosphere (a drop by 6.2%, comparing to 2013) while at 4.2% of the installations the captured landfill gas was neutralized and used for recovery of thermal energy; 16.4% of units use landfill gas for electricity production. As a result of landfill gas burning about 81 415 thousand MJ of thermal energy and about 148 348 thousand kWh of electricity were recovered [6 - 8].

The optimum parameters of landfill biogas, used for energy purposes, reported in the literature should remain within the following ranges: methane 45 ÷ 58%, carbon dioxide 32 - 45% nitrogen, 0 ÷ 5%, hydrogen, 1 ÷ 2%, oxygen 2% and trace amounts of other compounds such as hydrogen chloride, alkaline compounds, hydrogen sulfide 10-200 ppm,

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ammonia, etc.In fact, every landfill is different in terms of a chemical composition of biogas, its performance, humidity and energy potential. Therefore, every degassing installation at landfills should be treated individually, especially while looking into use of biogas for energy.

Currently, cogeneration (CHP) i.e. landfill operation with energy recovery is becoming more popular in Poland. This process can be defined as a thermodynamic process in which chemical energy from landfill biogas is converted into useful energy forms such as electricity and heat (for plant's technological/maintenance needs). The main advantage of cogeneration is overall conversion efficiency achieved in the cogeneration process, which is higher than when electricity and heat are produced in a separate way. The overall process efficiency exceeds 85% [9 - 12].

3 Landfill as a source of renewable energy

Energy from renewable sources it is energy obtained from regular natural processes and extracted from renewable non-fossil energy sources including e.g. landfill biogas. Renewable Energy Sources (RES) are an alternative to traditional, non-renewable primary energy carriers [12 – 15, 16, 17].

The amount of primary energy, exerted from renewable sources, and its share in total amount of energy obtained in individual EU countries varies. In most EU countries, renewable energy and its share in total primary energy acquisition is growing. In Poland, a significant increase in the amount of energy coming from renewable sources was observed in the last 10 years (Table 2).

Table 2. Energy from renewable sources as a percentage of primary energy in UE-27 and Poland [18]

Categories	2008	2009	2010	2011	2012	2013	2014
Energy from renewable sources as a part of primary energy in the EU (total)	16,2	17,9	19,6	20,2	22,3	24,3.	25,1
Energy from renewable sources as a part of primary energy in Poland	7,6	9,0	10,2	10,9	11,7	11,9	11,8

Consequently, a recent increase of renewable energy source utilization is accompanied by a growing role of landfill biogas in elimination of fossil fuels. According to data published by the GUS [18], concerning the amount of electricity produced from biogas in Poland in 2014 (Figure 1), biogas comprises 3,66% of all renewable sources. The data include landfill biogas, biogas from wastewater treatment plants and remaining biogas (from agriculture and fermentation of waste from brewery, food processing and slaughter houses).

Electricity production from biogas can be further divided, as follows [6, 7, 8]:
1) Landfill biogas 225 GWh,
2) Biogas from wastewater treatment plants: 253 GWh,
3) Remaining biogas: 338 GWh

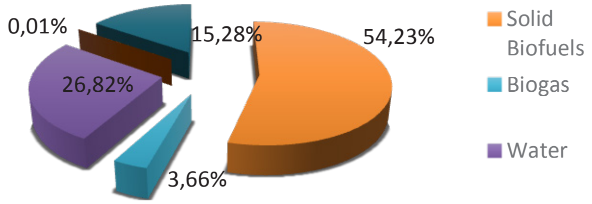

Fig. 1. Renewable energy carriers and their share in electricity production in 2014 [18]

Accordingly, heat production from biogas in 2014 was as follows:
1) Landfill biogas: 69 TJ,
2) Biogas from wastewater treatment plants: 86 TJ,
3) Remaining biogas: 144 TJ.

The lowest heat production attributed to landfill biogas results from a low heat demand at a landfill, compared to other producers[17- 20]. There are some advantages of use of biogas as an energy source. They include: environmental effect coming from discontinued emissions (methane, carbon dioxide), economic benefits due to use of heat and electricity to satisfy user's own needs and the added value of so called "green certificates" [21 - 25].

4 Waste disposal plant – energy prosumer

At most waste disposal plants a landfill is just one of units that comprise a waste disposal system and require a constant supply of energy. Electricity and heat produced from landfill biogas can be primarily spent to satisfy facility's own needs while the surplus can be transferred (sold) to a power grid as "green energy". This is the new role of the facility as an energy prosumer.

While looking into the way electricity is managed in prosumer systems three types of installations can be distinguished:

- directly connected to the network (on-grid) – that transfer the produced energy directly to the grid. The owner of installation benefits from the energy sale. At present, such a solution requires a special license from the President of the Energy Regulatory Office.
- with no connection to the external grid (i.e. off-grid or island systems) - that operate independently; the plant powers a single facility with all its machinery and equipment (e.g. a landfill). In such cases a detailed balance of the energy demand is required for each day and time of year.
- mixed systems - most commonly used systems, combining features of on- and off-grid systems. During peak energy demands and "green energy" scarcity a renewable energy is supplemented by energy from a grid. When more energy is produced than can be utilized its excess can be transmitted to the grid using intelligent energy meters (bidirectional system)[20 – 22, 25].

Electricity and heat generated at landfills make up the external electric power system. Prosumer energy, produced on site, can significantly affect the overall energy balance at the landfill and consequently reduce costs of its operation[23 - 29] as well as its harmful environmental effects.

5 Waste disposal plant and prosumer energy use

The facility (landfill) is located in the Malopolska province in the area of valuable natural assets. The facility comprises 4 installations used for: waste disposal (landfill), mechanical-biological waste treatment, landfill degassing and disposal of landfill biogas and its use for energy.

The landfill, that has been collecting non-hazardous and inert wastes, was put into operation in 1999 and currently it covers the area of about 10 acres; its operational capacity is about 600 000 m^3. Currently, the landfill is filled up to about 70% of its volume. The landfill operates an installation for landfill degassing, which consists of vertical and horizontal degassing wells, biogas transporting pipelines and a station for biogas acquisition and processing with a flare mounted at its roof. An installation for active degassing of the landfill was put into operation in 2009, and in January 2010 the Company

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managing the unit received the licensed to produce electricity from landfill biogas. The energy is produced by burning biogas extracted from the waste in a gas engine or the flare.

A package cogeneration unit (in container) is a part of the installation for a landfill biogas disposal and energy use. The unit produces 365 kW of electric power and 455 kW of heat. The biogas produced from landfill waste deposits is used as fuel to power a piston engine, which drives a synchronous generator and converts mechanical power into electricity. The unit works as a biogas CHP in a CHP (Combined Heat and Power) system, where both electricity and heat are produced. The volumes of landfill biogas collected and disposed at the landfill in the years 2010 - 2015 are presented in the Table 3. Utilization of landfill biogas in a cogeneration system is the optimal way of a chemical energy use in a thermodynamic process. Currently methane, the main component of landfill gas, represents 48 to 50% of its volume. In 2010, when the production of electricity was initiated, a methane content was about 56%. Changes in the methane content in the landfill biogas in the years 2010 - 2015 are shown in the figure below.

Since according to the new regulations non-biodegradable waste cannot be deposited at landfills, it may be assumed that volumes of both biogas and methane produced at landfills will steadily decline in the coming years. Therefore, the installation's managers will face a problem how to optimize production of electricity and heat to power the engines.

Currently, 100% of electricity produced in the installation is distributed through a mixed type system of on - and off-grid. Electricity is mostly used to satisfy plant's own needs and power an electricity generator (process maintenance); its surplus is transmitted to the external power grid for further distribution. The balance of electricity generated from a renewable source (landfill biogas) was presented in the Table 3.

Table 3. Landfill biogas disposal (Authors' elaboration)

Year	Landfill biogas collected and disposed	Biogas burned in an engine	Biogas burned in a flare
	m^3	m^3	m^3
2010	832398	778498	53900
2011	1120998	1072998	48000
2012	1037215	991295	45920
2013	773748	697499	76249
2014	822110	815390	6720
2015	816364	808464	7900
Total	**5402833**	**5164144**	**238689**

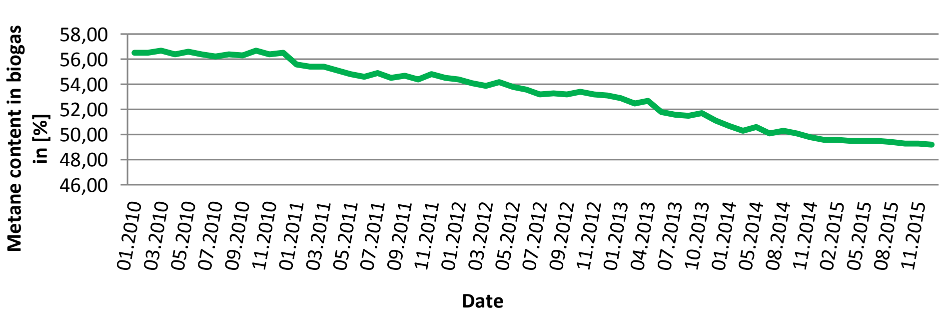

Fig. 2. Methane in the landfill biogas at the installation in years 2010–2015 (Authors' data)

Table 4. Balance of electricity generated and used at the location (Authors' own data)

Year	Electricity generated (gross)	Electricity transmitted to the external grid (net)	Electricity utilized on- site (total)	Electricity utilized for plant's own needs	Electricity utilized for installation maintenance
	MWh	MWh	MWh	MWh	MWh
2010	1223,5	1040,7	182,8	121,4	61,4
2011	1670,3	1417,6	252,7	143,5	109,2
2012	1436,4	1196,0	240,4	143,0	97,4
2013	971,4	775,8	195,6	124,9	70,7
2014	1012,5	802,3	210,2	133,5	76,7
2015	991,7	751,4	240,2	167,4	72,9
Total	**7305,8**	**5983,7**	**1322,0**	**833,7**	**488,4**

Electricity is transmitted to the external power grid, under the terms of the contract with the distributor, at the price per 1 MWh set each year by the President of the Energy Regulatory Office. Production of energy from renewable sources has also the added value. This is a support system that transfers property rights to the produced electricity (green certificates) and enables its sale within the actual financial mechanisms.

Heat generated in a biogas generator equipped with a heat recovery unit is used for every-day operation (heating of a sorting cabin - heat exchanger: glycol/air) and for technological processes (drying of waste in a rotary screen - heat exchanger). Currently, about 25% of the heat is used during a day-to-day operation. The amount of heat generated in a cogeneration system is shown in the Table 5.

Table 5. Heat generated from landfill biogas at the location in years 2010 – 2015

Year	Heat generated (gross)	Heat utilized at the waste disposal plant (net)	
	GJ	**GJ**	**%**
2010	5861	1008	17,2
2011	8440	1806	21,4
2012	7464	1649	22,1
2013	5252	1229	23,4
2014	6139	1523	24,8
2015	5500	1408	25,6
Total	**38653**	**8623**	

The average quantity of heat generated over 6 years was 6443 GJ, which corresponded to 789,789 kW of energy. To increase a heat consumption at waste disposal plant, an internal heating system will soon be constructed and put in operation to heat up a working area and produce hot water on site.

Biogas is not the only renewable energy source at waste disposal plant. The plant has also in liquid solar collectors to convers solar energy and use it for hot water production and as a back-up for a gas boiler. These methods of energy production may serve as good examples of implementation of the idea of prosumer energy in spread systems, using renewable energy sources.

Operation of installation using landfill biogas as an energy source was analysed in the years 2010 – 2015. It showed that about 1217 MWh of electricity and about 1,789 MW of heat was annually produced there (average gross values).

Cogeneration systems should meet the efficiency requirements for electricity and heat cogeneration if they are to work properly and provide a basis for the prosumer energy.

There are several most commonly used indicators describing efficiency of energy conversion in a CHP system with piston engines, which include:

1) Efficiency of electricity generation in a combined cycle: 25÷40% (1),

2) Efficiency of heat generation in a combined cycle: 30÷50% (2),

3) Overall CHP system efficiency (chemical energy utilization factor - EUF): 70÷90% (3),

4) Association index: 0,5÷1,0 (4).

Based on the average annual operating parameters of a cogeneration system with landfill biogas (6-year operation) the above indicators have been calculated. Their values are as follows:

$$el_{EC} = \frac{Eel}{P \cdot Wd} = \frac{1217625kW}{860691m^3 \cdot 4,8kW/m^3} = 0,29 \quad (1)$$

$$\eta q_{EC} = \frac{Q}{P \cdot Wd} = \frac{1789789kW}{860691m^3 \cdot 4,8kW/m^3} = 0,43 \quad (2)$$

$$\eta c_{EC} = EUF = \frac{Eel+Q}{P \cdot Wd} = \frac{1217625kW+1789789kW}{860691m^3 \cdot 4,8kW/m^3} = 0,72 \quad (3)$$

where$\eta el$is a electricpower generated in a combined cycle, $Q$is a heatgenerated in a combined cycle, $P$is a fuel stream and$Wd$is a fuel caloric value.

The average caloric value of biogas was 17 MJ/m^3, which is equivalent to 4,8 kW/m^3.

The input data for the above calculations came from actual measurements and readings acquired during cogeneration unit operation. It can be concluded that they fall within the range of average values so the CHP has been working within the operation limits and still has some reserves to utilize.

Based on the available data on electricity produced from landfill biogas in 2015 and the way it was utilized a prosumer energy balance may be prepared. It shows to which extend the installation serves as an electricity consumer or a producer or a distributor.

The balance of electricity generated at the plant shows that the most electricity (75,78%) was sold to the external grid (distribution) while the plant owns overall needs accounted for 24,83% of electricity: 16,89% of this value represents electricity used to power facilities, machinery and equipment at the landfill and the facility itself, while 7.94% is used by the degassing installation (maintenance works).

Electricity from the external power grid is purchased only in case of planned maintenance services/repairs and failures of the cogeneration unit. In 2015, the waste disposal plant and the installation for degassing and disposal of landfill biogas consumed a total of 240.2 MWh of electricity, while only 7.4 MWh were purchased from an external supplier. The balance of electricity used at the plant in 2015 shows that 3% was bought from the external power grid, while 97% was a prosumer energy

Considering the above data, it should be stated that the plant tries to implement the concept of prosumer energy in a manner consistent with the idea. Since both electricity and heat are produced from waste it can be firmly stated that the process operates in a closed waste-energy cycle where waste becomes a product (energy carrier).

The landfill as a prosumer meets its own energy needs and at the same time acts as a "green energy" provider for households, offices, cities, etc. This way, it contributes to the development of a prosumer energy.

6 Summary

The use of landfill biogas as a renewable energy source enables to utilize local energy resources. Prosumer energy serves as an example of a comprehensive approach, where transition from local issues to global issues in energy conservation is observed. It can be noticed throughout the course of its obtaining, efficient processing, transmission and finally proper utilization.

While looking into basic functions of the landfill as: facility, bioreactor, renewable energy source, consumer and ultimately an energy prosumer one can conclude that in this case the landfill becomes both a producer and a supplier of electricity needed for landfill operation.

It seems appropriate to extend the concept of prosumer energy utilization to waste management companies, which often, as regional installations, utilize energy generated during anaerobic digestion of biodegradable waste. Such examples can be already found in Poland and they should be encouraged to take a comprehensive approach to energy and waste issues, authorized by clear legislations.

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