Reliability Assessment of Landfill Gas Collection System

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Abstract. The paper conducts a reliability analysis based on the technical scheme of a simple installation of a landfill gas collection system. This kind of installation should be considered as an object of multi criteria problem, because of that, the calculation was carried taking into account economical aspect as well as environmental one, on reliability schemes prepared for each aspect. Based on obtained results, authors made changes in technical structure of the installation which allowed to eliminate its weakest elements which caused lower values of reliability indexes. After recalculations it was possible to compare obtained results and asses, if proposed changes in the structure of this installation, will cause expected improvement of reliability level of the entire system.

1. Introduction
Renewable energy sources can increase energy security and provide adequate standards for protecting the atmosphere and the environment from pollution.

Poland, to become a member of the European Union (EU), was obliged to implement a series of regulations, acts and directives into the national law. One of such document was the Directive 2001/77/EC of the European Parliament and of the Council of 27 September 2001 on the promotion of electricity produced from renewable energy sources in the internal electricity market which considers biogas, generated by the methane fermentation of biomass or biodegradable waste on landfills, as biofuel [1]. Other one is Council Directive 1999/31 / EC of 26 April 1999 on the landfill of waste which also imposes the obligation to recognize and dispose of landfill gas as well The Ordinance of the Minister of the Environment of 24 March 2003 which introduces directly in Poland, the obligation of equipping biodegradable waste landfills in an installation for the discharge and use of energy from landfill gas or its flaring [1,2].

European Union policy has been targeted at alternative sources of energy for several years, and the industry of green energy production is one of the most thriving sectors of the economy. Therefore, investment in landfill installations can bring the organs responsible for their extraction, significant environmental, economic and environmental benefits [1].

Such installations are a key element of the landfill infrastructure, which results in a significant reduction of air pollution emissions with simultaneous economic and social benefits from the production of electricity or heat from landfill gas.

Taking into account the composition of the biogas and the presence of methane in it, as well as the goal of obtaining revenues from the sale of energy, this installation should be characterized by high level of reliability.
Therefore, the article presents an attempt to assess the reliability of a landfill gas collection system with known technical structure, taking into account both environmental and economic factors. The calculation was carried on reliability schemes prepared for each aspect. Based on obtained results, authors made changes in technical structure of the installation which allowed to eliminate its weakest elements. After recalculations it was possible to compare obtained results and assess, if proposed changes in the structure of this installation, will cause expected improvement of reliability level of the entire system.

2. Characteristic of landfill gas

Biogas is a valuable fuel that is a product of a specific disposal method of vegetable and animal waste. The chemical process that converts waste into landfill gas (LFG) is known as waste decomposition or degradation. This process is influenced by several factors such as temperature, moisture content, waste composition and diversity of substrates for microbiological degradation. The phenomena and chemical reactions involved in this process are quite complex and examples of publications describing it are [1, 2, 3]. LFG mainly consists methane (40-60%) and the rest comprises carbon dioxide and trace gases such as hydrogen sulfide, siloxane, nitrogen, hydrogen and oxygen. The first three of them can be incinerated with simultaneous energy releasing, which makes it possible, to use biogas as a fuel.

2.1. Energy potential of landfill gas

The most important factor, which determines the possibility of biogas usage, is gas potential of a landfill. The amount of produced landfill gas can be ranged between 60 and 180 m³/Mg of composed waste. From model laboratory studies and practical measurements of biogas made on landfills it was found that 80-160 m³ of landfill gas is generated from 1 Mg of wet waste collected from households and workplaces. Taking into account the average calorific value of biogas of 4.5 kWh/m³ and the amount of biogas extracted higher than 50 m³/h, it appears that household waste is a viable source of renewable energy [3, 4]. It was estimated that the energetic use of landfill gas is economically viable for landfill sites where the total weight of deposited waste is at least 0.5·10⁶ Mg of waste [1].

2.2. Possibilities of using landfill gas

There are many technologies and ways to use landfill gas, the choice of which is governed by, inter alia, the type of energy in which the region is in demand and its composition (quality) [5, 6].

The methane content of the landfill gas is a crucial aspect for its usage. Knowledge about chemical composition of waste, composed on a landfill, can be used to predict amount of methane and carbon dioxide from mass unit of waste. Some of the most popular applications were listed below [5,6].

2.2.1. Electricity generation from landfill gas. LFG collected at the landfill site is used for electricity generation. The gas is pumped out and then underwent pre-treatment to remove carbon dioxide and yield methane. Combustion for the production of electrical energy is made in gas engines and turbine engines. The generated electricity can be used for the own needs of the landfill and its surplus transferred to the external network. This technology is most common use in Poland [6, 7, 8].

2.2.2. Upgrading to natural Gas Quality. The landfill gas can be distributed through the natural gas distribution network. In this case, the landfill gas need to be mandatory upgraded to natural gas quality. This solution involves high investment costs for a gas purification plant. Prior to delivery of upgraded landfill gas to the natural gas network it is require that the gas must be free from particles and liquid. Furthermore the gas must be odourized. The main step in the upgrading process is the separation of methane and carbon dioxide [8, 9].

2.2.3. Use of gas in Vehicles. In where world there are plants, in which the landfill gas is compressed and used in either compactors, refuse collection vehicles, busses or ordinary cars. The tax system differs in the single country and is important when finding out whether the system is profitable or not.
Furthermore, the profitability depends on the system that is chosen, thus, it will be relatively expensive when investing in a system that is only used for a few numbers of vehicles [8, 9, 10].

2.2.4. Direct combustion for heat production. It's the simplest and cheapest way to use it. Landfill gas is most commonly flared in large industrial boilers, in brick or lime kilns or in cement kilns. It is also used for heating flats, greenhouses or water in boilers. The primary obstacle to the use of landfill gas by direct combustion is that the recipient must be close to the landfill because the transport of landfill gas over long distances is unprofitable [1, 11].

Depending on the quantity, the way of biogas utilization, the biogas technology used, its own fuel properties and the market prices of the energy obtained, the return on investment is 2-10 years [12, 13]. It should be emphasized that the landfill gas is produced intensively for 10-15 years after the operation of the landfill. This is an undeniable argument that the energy use of landfill gas can bring both environmental benefits and measurable economic benefits. In Figure 1 it is shown the scheme of possibilities of usage the landfill gas.

![Scheme of possibilities of usage the landfill gas](image)

Figure 1. Scheme of possibilities of usage the landfill gas [14].

3. Installation of landfill gas collection
Landfill sites are degassed for several reasons, including: prevention uncontrolled landfill gas emissions, to reduce methane emissions to the atmosphere, to obtain biogas for energy purposes, and to reduce odours in the vicinity of the landfill.

Each landfill gas collection system consist of an extraction system described below and utilization system which is different for each of type of utilization [15, 16].

The extraction system can for example consist of vertical perforated pipes, horizontal perforated pipes or ditches. The gas is sucked out of the landfill by means of a pump or a compressor.

The gas extraction takes place through vertical (Figure 2) or horizontal wells with perforated pipes, ditches and in some cases a membrane covering, under which the produced gas is collected. The first type of wells is most common. This might be due to the fact that this is the simplest way of carrying out the system, when the landfill has already been established [14, 15].
However, in a number of sites horizontal suction pipes will be built in when the waste is deposited on the landfill. In this way the gas can easier be extracted from the very beginning of the gas production, as the gas can then be sucked out before closure/covering of the landfill.

Collection system can be also divided to passive or active system. Passive system involves wells similar to groundwater well where gas is drawn to the well because of different pressure between landfill and the atmosphere. Active system incorporated a vacuum on the well to create greater potential in the wells and extract gas from landfill (Figure 3).

Sometimes an impermeable membrane will cover the landfill, and almost all the gas can then be collected and recovered. This, however, is a very expensive solution.

The gas is sucked out of the landfill by means of a gas pump or a compressor leading the gas to the utilization plant by means of pressure in the transmission pipe.

Wells are connected by collectors to the pump station. Single well can be connected by individual line connection to the collecting pipe. In this case, the control valve is mounted on the wellhead. Another solution is when the collector pipes can be laid out individually for each well and connected to the manifolds. The manifolds contain control valves for individual well [16, 17, 18].

Any use of landfill gas involves need to removal of pollutants which devices for its utilization cannot accept. Each manufacturer imposes limitations on the composition of the landfill gas, which exceeds that it does not guarantee trouble-free operation of the equipment, or withdraws from warranty obligations. These limits are mentioned in specifications such as motors and the potential user should perform detailed gas analysis before deciding to use the cleaning process [1, 3].
The final element of each element is a flare, even if the gas is used as a fuel for power generation equipment. The flare fulfills its task in emergency situations or when there is an excess of gas production in relation to the possibility of receiving energy. The Flare should be characterized by specific combustion parameters to ensure full combustion of harmful gases and to minimize the impact of combustion products on the environment [17, 19].

4. Reliability assessment
Reliability is the property that allows the system to meet the ability of a given system to function with the characteristics superimposed on them, under specified operating conditions and within a specific time period. This property is expressed by means of indicators determining the ability to perform the tasks that the system should perform and identifying the components that are most threatening to them.

According to the fact that biogas is a dangerous gas, which threatens both safety and the environment, it is important that the degassing installations for its processing are highly reliable.

This kind of installation is not as complicated installation as water supply network, pumping station or other facilities, but this "simplicity" can pose the greatest difficulty in determining the reliability level and increasing it. In addition, it should be noted that such systems should be considered taking into account two aspects, i.e. environmental impact, as well as the possibility of obtaining financial benefits from its operation. In both of these cases, it should be noticed the hazards like the possibility, for example, of an explosion due to the content of methane in biogas.

The analysis carried out in this article illustrates, how such installation and the estimated reliability level may differ for the two mentioned aspects.

In the first stage of analysis, on the basis of a technical scheme that graphically represents the operation of the system (Figure 4), flow paths were defined for both computational cases. They are sets of system elements, whose operation efficiency determines the efficiency of the whole system. Based on them, reliability diagrams were created. These allows to determine the reliability status of the entire system depending on the states of all the elements included. These diagrams graphically depict the system's reliability structure, i.e. the interrelationships of the components from the impact of their damage on the efficiency of the entire system.

The structure depends on the requirements of the system, so in the cases considered, for one technical scheme may correspond several different reliability schemes.

The schemes allowed to determine both the critical system elements and the K readiness index by using analytical formulas. This indicator determines the probability that, at any time sufficiently far from commissioning, the facility will be operational. On this basis, another technical solution was proposed, which re-created the scheme and calculated its reliability.

4.1. Description of adopted degassing installation
The installation included in the calculation consists of 5 wells in the active system (signed as W1-W5) with the same efficiency and the given K values for each of them. The installation allows the generation of electricity, which is consumed both for the needs of the unit and its excess is sold to the external network. Other equipment includes: a compressor for gas transportation, a leachate collecting device that is precipitated from the gas, filters and gas purification equipment (with given values of the K parameter). This system consist a flare, which burns out biogas in the event of a major failure (elements signed by numbers from 6 to 10 on Figure 4).

Each well is equipped with a control valve to completely shut off the gas supply from the well. In the case of valves (signed by numbers from 1 to 5 on Figure 4), based on the stated work time of the valve – Tp(V) and repair time of the valve – Tn(V), their K parameter was determined, which was compared to the same well parameter, and it was decided whether or not these elements could be omitted. For terminals and main collectors, because they are made of high density polyethylene (PEHD), they are omitted from the calculations. Data for calculations are shown in Table 1.
Figure 4. Scheme of the installation

Table 1. Table for the calculations

| Parameter | Value | Unit |
|-----------|-------|------|
| $K_{\text{well}}$ | 0.9951 | [-] |
| $K_{\text{el.6}}$ | 0.9999 | [-] |
| $K_{\text{el.7}}$ | 0.9995 | [-] |
| $K_{\text{el.8}}$ | 0.9913 | [-] |
| $K_{\text{el.9}}$ | 0.9972 | [-] |
| $K_{\text{el.10}}$ | 0.9972 | [-] |
| $T_{\text{n}}(V)$ | 30 [h] | |
| $T_{\text{p}}(V)$ | 8760 [h] | |

4.2. Calculations according to the environmental aspect

As it was mentioned before, firstly the K value for the valves was calculated to determine the possibility of their skipping. For this purpose, data from Table 2 and Equation 1 are used.

$$K_V = \frac{T_p(V)}{T_p(V) + T_N(V)}$$ (1)

Where: $K_V$ — readiness index of the valve, $T_p(V)$ — work time of the valve [h], $T_N(V)$ — Repair time of the valve [h]

$$K_V = \frac{8760}{30 + 8760} = 0.9966 [-]$$

The value of the K index is similar to K index of well, so it cannot be ignored in reliability calculations.

Taking into account the environmental aspect, it is important that biogas does not get into the atmosphere. Therefore all elements of the system should always be functional. The only exception here is items 9 and 10 of scheme 5. In this case, an accident, in order to disarm the gas, only one of those items in the state of efficiency is sufficient. For this assumption, two efficiency paths are shown in Table 2.

Table 2. Flow path for the environmental aspect

| NUMBER OF FLOW | ELEMENTS |
|----------------|----------|
| I              | W1 W2 W3 W4 W5 1 2 3 4 5 6 7 8 9 |
| II             | W1 W2 W3 W4 W5 1 2 3 4 5 6 7 8 10 |

Based on the flow paths, the reliability diagram shown in Figure 5 was created. It is built of two types of structures: serial and parallel. In this case, Equations 2 and 3 should be used.
4.3. Calculation according to the economic aspect

In the case of economical approach, it is assumed that the minimum efficiency of the installation should cover the whole unit’s own demand for electricity. Due to the fact, that no installation with only 5 wells will not achieve high yields, it is assumed that at least 3 wells of 5 are required for this purpose. One again, the flow paths for these assumptions are presented in Table 3 and a reliability scheme on Figure 6. During determining flow paths, needs to be remembered to include hydraulic contact arisen during gas flow.

Table 3. Flow paths for the economical aspect

| NUMBER OF FLOW PATH | W1 | W2 | W3 | W4 | W5 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---------------------|----|----|----|----|----|---|---|---|---|---|---|---|---|---|----|
| I                   | W1 | W2 | W3 |    |    | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |   | 10 |
| II                  | W1 | W2 | W3 | W4 |    | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |   | 10 |
| III                 | W1 | W2 | W3 |    | W5 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |   | 10 |
| IV                  | W1 | W2 | W3 | W4 |    | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |   | 10 |
| V                   | W1 | W2 | W3 |    | W5 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |   | 10 |
| VI                  | W1 | W2 | W3 | W4 | W5 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |   | 10 |
| VII                 | W1 | W2 | W3 | W4 |    | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |   | 10 |
| VIII                | W1 | W2 | W3 | W4 | W5 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |   | 10 |
| IX                  | W1 | W2 | W3 | W4 | W5 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |   | 10 |
| X                   | W1 | W2 | W3 | W4 | W5 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |   | 10 |

In this case however, there is a difference with respect to the elements numbers 9 and 10. In the previous assumptions, it was assumed that the flare only fulfills the role of protection in case of failure, so this time it is omitted, and the element that must always be functional is the set of devices used for electricity generation.

The resulting reliability scheme consists of components connected to the serial structure, but this time the threshold structure appears. The equations 2 and 4 are again used in the calculations presented below.
Figure 6. Reliability scheme for the economical aspect

\[ K_A = \sum_{k=0}^{M-n} \binom{M}{k} \cdot K^{M-k} \cdot [1 - K]^k = \sum_{k=0}^{M-n} \binom{M}{k} \cdot K^{M-k} \cdot [1 - K]^k \]

\[ K_A = K_{\text{well}}^{5-0} \cdot [1 - K_{\text{well}}]^0 + \binom{5}{1} \cdot K_{\text{well}}^{5-1} \cdot [1 - K_{\text{well}}]^1 + \binom{5}{2} \cdot K_{\text{well}}^{5-2} \cdot [1 - K_{\text{well}}]^2 = 0.9999 \]

\[ K_B = \prod_{j=1}^{n} K_j = K_v^5 \cdot K_{\text{el}1} \cdot K_{\text{el}1.6} \cdot K_{\text{el}1.7} \cdot K_{\text{el}1.8} \cdot K_{\text{el}1.10} \]

\[ K_B = 0.99665 \cdot 0.9999 \cdot 0.9995 \cdot 0.9913 \cdot 0.9972 = 0.9710[\text{\textendash}] \]

4.4. An alternative solution to increase reliability level of the system

As it can be seen from the scheme, the crucial elements of the system are mainly valves. Although the other objects also exist in a serial structure, their internal structure may have some reserve elements, but there is no information about it. Therefore, as an alternative solution for the installation in question, it is proposed to abandon the main collector, for the direct but separate access from each well (Figure 7).

In the case of an environmental solution, it does not change the fact that every element must be fit, so for further consideration the economic aspect were submitted. The flow paths (Table 3) and the reliability diagram are again defined. Figure 8

Figure 7. Scheme for the alternative solution
Table 4. Flow paths for alternative solution

| NUMBER OF FLOW | ELEMENTS |
|----------------|----------|
| I              | W1, W2, W3, W4, W5, 1, 2, 3, 6, 7, 8, 9, 10 |
| II             | W1, W2, W4, W5, 1, 2, 4, 6, 7, 8, 9, 10 |
| III            | W1, W2, W5, 1, 2, 5, 6, 7, 8, 9, 10 |
| IV             | W1, W3, W4, W5, 1, 3, 4, 6, 7, 8, 9, 10 |
| V              | W1, W3, W5, 1, 3, 5, 6, 7, 8, 9, 10 |
| VI             | W1, W4, W5, 1, 4, 5, 6, 7, 8, 9, 10 |
| VII            | W2, W3, W4, 2, 3, 4, 6, 7, 8, 9, 10 |
| VIII           | W2, W3, W5, 2, 3, 4, 5, 6, 7, 8, 9, 10 |
| IX             | W2, W4, W5, 2, 4, 5, 6, 7, 8, 9, 10 |
| X              | W3, W4, W5, 3, 4, 5, 6, 7, 8, 9, 10 |

Figure 8. Reliability scheme for the alternative solution

\[
K_{G} = \left(\binom{5}{0}\right) \cdot K^{5-0} \cdot [1 - K]^0 + \left(\binom{5}{1}\right) \cdot K^{5-1} \cdot [1 - K]^1 + \left(\binom{5}{2}\right) \cdot K^{5-2} \cdot [1 - K]^2 = 0.9999
\]

\[
K_F = \prod_{j=1}^{n} K_j = K_{el.6} \cdot K_{el.7} \cdot K_{el.8} \cdot K_{el.10}
\]

\[
K_S = K_F \cdot K_G = 0.9880 \cdot 0.9999 = 0.9879 [-]
\]

5. Summary and conclusions

In Poland the waste dumps have dominant influence on the methane emission from anthropogenic sources. The methane is the second gas, after carbon dioxide, which is responsible for the greenhouse effect. What is more, it is a valuable source of energy carrier, which is produced from the organic substances. According to the literature data, from 100 m3 of biogas there can be produced about 560÷600 kWh of electric energy. The waste dump of the surface: 15 ha can give from 20 GWh up to 60 GWh of energy during a year if the year-long mass of the deposited wastes is about 180 000 tons [1]. In accordance with the EU requirements, Poland has introduced legislation that requires the installation of landfill gas collection system and/or its disposal facilities. The installation itself is a straightforward installation compared to water pumping stations, water supply and sewage systems but because of high concentration of inflammable methane it should be characterized by high level of reliability. The article presents the reliability calculations of an example of a small installation. Increasing the number of wells would not complicate calculations, because in such installations in Poland, usually each well is connected in the same way to the main collector. However, reliability calculations should be considered with regard to two aspects: environmental and economic. In the first of them, when establishing a reliability scheme, it should be assumed that emissions to the environment can not be allowed. Therefore, elements are locked into a serial structure. For this variant reliability is the lowest. In the
latter case, the performance of the facility is reduced (e.g., when one of the wells fails) but should not fall below 60%, so that the facility's own needs are met. In this case, the object is already more reliable, but the fittings (valves) appearing in the serial structure may underestimate the result. Consequently, in the third option, the solution described in point 3 has been decided, where each well has a separate connection with the valve access. In this way, none of the valves are present in the serial connection. The calculations show that in this way you can get an increase in reliability. It is not high because of the simplicity of installation. In objects such as the water pumping station, such changes may be more apparent because of the fact that such objects try to provide water with several possible flow paths. In this case, for example, for economic reasons, this is not the case. However, for safety and financial gain, even such a change should be considered.

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