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Analysis of Energy Generation Efficiency and Reliability of a Cogeneration Unit Powered by Biogas

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Abstract: Landfill gas recovery and utilisation is a solution which reduces the adverse environmental impact of the landfill. Combined heat and power (CHP) generation improves the energy balance of the facility and enables the optimal management of energy generated from a renewable source. This article aims to analyse the operation of the CHP unit in two aspects, that is, in terms of energy generation efficiency and operational availability. Energy ratios were calculated and the analysis was based on the Weibull distribution in order to assess the CHP unit's operational reliability to minimise costs and maximise energy production. The results of the investigations and analyses demonstrated an increase of the gas yield by 29.5%, an increase of energy production by approx. 42%, and the reduction of downtime by 28.2% from 2018 to 2022. Studies related to the efficiency and reliability of operation of the cogeneration unit showed an increase in all the main parameters analysed, which resulted in greater energy and operational efficiency. The research which has been conducted is a significant scientific contribution to the optimisation of the "waste-to-energy" process for cogeneration units with the capacity of up to 0.5 MW.

Keywords: biogas cogeneration system; landfill gas; reliability; Weibull distribution

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1. Introduction

The process of municipal solid waste neutralisation at landfills is among the least recommended in the waste-handling hierarchy. This notwithstanding, the process is commonly used in many countries worldwide. When banning biodegradable waste storage at landfills, the European Union had in mind, among other factors, the adverse impact of landfills in terms of the atmospheric emissions of methane and carbon dioxide as primary greenhouse gases [1,2]. As a consequence of waste storage, waste waters come into being in the landfill bed. If these waste waters are not managed correctly, they may pose a hazard to human health if they penetrate into surface or groundwaters [3,4]. Landfill monitoring aims to check the quality of waters in the landfill area and, in particular, to protect individual and common water intakes [5,6]. In the waste bed, physical and chemical processes occur whose intensity depends on the morphology of waste being deposited including, in particular, the biodegradable fraction content [7]. As a consequence of these processes, the landfill as a civil structure becomes a bioreactor in which landfill gas (LFG) is generated, with methane and carbon dioxide being its main components [8,9]. This gas becomes a problem for landfill operators, in particular, in terms of an odour nuisance in the landfill area due to emissions into air. The solution most commonly used at landfills is the construction of a degassing plant to recover and neutralise this gas [10]. As LFG contains mainly methane

(45–55%), it may be utilised for heat generation or in a combined process (combined heat and power or CHP) to generate electricity and heat [11,12]. LFG recovery and utilisation in a CHP system is the optimal solution, which reduces the environmental impact of the landfill as a facility [13]. This issue may be analysed in two aspects: in terms of energy, as the utilisation of a renewable fuel for energy generation and its use immediately at the landfill, and in terms of the environment, as a reduction of the emissions of a greenhouse gas, that being methane [14,15]. Municipal infrastructure facilities at a landfill, which are a waste neutralisation facility, as well as power engineering infrastructure, should be supervised to be ready to fulfil their function in the context of energy generation reliability. The extension and modernisation process must take place with the use of materials holding relevant certificates, and waste generated in the process should be managed in accordance with the waste disposal hierarchy pertaining to waste of a given type [16,17].

CHP systems at landfills should be subject to ongoing inspection and monitoring for the efficiency of energy generation and utilisation directly at the landfill. The lack of suitable supervision, operation records, and appropriate biogas combined heat and power plant personnel results in the plant's inappropriate operation which, as a consequence, translates into the low efficiency of the conversion of landfill gas in a CHP and into small energy production [18,19]. The correct approach to the operation of such a system consists in the development of a correct procedure which governs the basic activities concerning the amount and quality of biogas recovered from the landfill, along with the monitoring of the basic energy ratios. The implementation of such a procedure will result in the reliable operation of the cogeneration system [20].

Research aimed at optimising the efficiency of energy production from renewable sources in CHP units is part of the environmental footprint and life cycle assessment (LCA) methodology in the context of climate change. The key element is to ensure the quality of the input data for the optimisation process, described by the authors of paper [21], who presented a pragmatic approach that can help identify areas such as energy processes and their efficiency.

The Weibull distribution is a recognised statistical model in machine reliability assessment. The Weibull distribution is the generalisation of the exponential distribution. The applicability of that distribution comprises phenomena where damage intensity is a variable with a monotonic pattern. That distribution is used to describe, for example, the fatigue life of materials and mechanical structures [22]. System data needed for the ratio analysis may be obtained from difference sources, namely laboratory tests or the record of events in the course of facility operation [23]. It is therefore important that the users of the biogas cogeneration system be equipped with simple "tools" for the assessment of the facility's operation [24]. The Weibull distribution has been successfully used, for example, to assess the operational reliability of waste water treatment plants [25] and photovoltaic systems [16] as well as to determine pseudo-components and the kinetic analysis of the pyrolysis of the selected combustible solid wastes [26]. The authors of [27] applied the Weibull distribution model to the analysis of wind velocity and power density distribution. A similar issue was examined by the authors of [28]. They analysed the option to apply the Weibull distribution to determine the energy performance of wind. The authors of [29] used the parameters of the Weibull distribution to assess the wind power potential and calculated the prospective annual revenues for Gdańsk if the city had municipal wind turbines in its centre. In work [30], damage assessment was conducted and life expectancy of the end superheater tubes of power plant boilers was measured. The Weibull distribution model was used to obtain a trend in the changes in the cumulative risk of failure as well as to assess and predict the safety status of the entire system of pressure components of the power plant boilers [31].

In this article, reliability analysis according to the Weibull distribution is used to estimate the reliability of a cogeneration unit. Understanding the distribution of reliability indicators will allow the reader to develop an appropriate device management strategy to minimise maintenance costs and maximise energy production.

In the literature, mention is mainly made of research work on CHP units equipped with gas engines in large cogeneration units with the electrical power above electricity of 1 MW.

The results of research presented by the authors of the work [32] showed that for cogeneration systems based on biogas, the efficiency of electricity production ranges from 16% to 83%, and heat production ranges from 18% to 90%. These values result from the power range of cogeneration units and the type of biogas.

The research results showed that the use of CHP units for biogas installations is recommended mainly because of the use of renewable energy.

The technical and economic analysis of a cogeneration unit powered by agricultural biogas was described in work [33]. Its authors demonstrated the electrical efficiency of the cogeneration unit at the level of 22% and the thermal efficiency of 65%. The parameters of the CHP unit defined in this way indicate the priority in heat generation with low efficiency of electricity generation without taking the reliability aspects into account.

Most of the literature focuses on the energy efficiency of the energy generation process in large biogas-fired CHP plants with the capacity of more than 1 MW.

The novelty of research presented in this article is the focus on small CHP units up to 0.5 MW and the correlation of such research with reliability.

In the literature, there are no publications concerning small biogas-powered CHP installations based on gas engines. Therefore, the aim of this work is to fill this gap and demonstrate the synergy between energy efficiency and energy production reliability.

2. Object of Research

The object of research is the biogas combined heat and power plant (a CHP system) in a containerised design with the electric capacity of 440 kW and the thermal capacity of 520 kW, which has been operated at a municipal landfill since 2010. Waste after mechanical and biological treatment is deposited at the landfill. The landfill is part of the Waste Processing Company (WPC), which comprises the mechanical and biological waste processing system, RDF (refuse-derived fuel) preparation station and construction waste processing plant. The gas piston engine driving the generator is supplied with biogas obtained from the landfill degassing plant with the use of vertical degassing wells. Biogas sucked by a blower with the capacity of up to 280 m^3 h^{-1} is then directed to the processing station, where biogas is conditioned and thus prepared for combustion in the gas engine. The containerised cogeneration unit with basic equipment is shown in Figure 1.

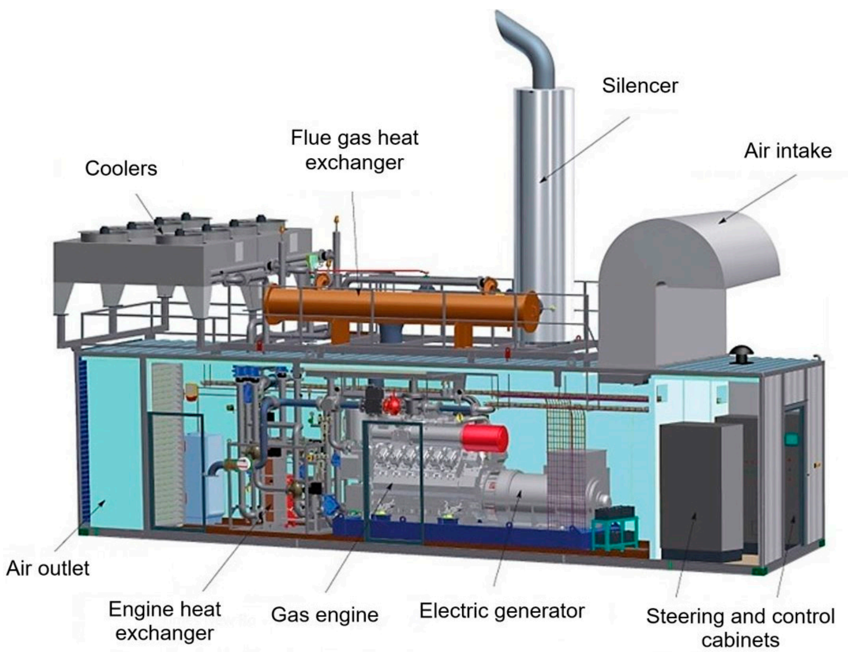

Figure 1. General view of the cogeneration unit [34].

The engine is a v-shaped, four-stroke, turbocharged, 12-cylinder engine with a supercharged mixture cooler and is factory-adapted to run on biogas with a variable methane content from 35% to 65%.

The cogeneration unit is built in a container and consists of the following main components:

- Biogas engine;
- Synchronous power generator;
- Heat recovery block (the engine and exhaust gases);
- Backup cooling system with an external cooler;
- Electricity, metering and export system;
- Control and visualization system.

The technical parameters of the cogeneration unit are presented in Table 1.

Table 1. Technical parameters of the cogeneration unit.

Parameter	Value
Electrical capacity	440 kW
Thermal capacity	520 kW
Electrical efficiency	37.6%
Thermal efficiency	42.8%

Landfill biogas recovered from the waste bed is treated in a plant comprising a carbon filter and condensate settling tank. Before feeding into the gas engine, biogas is measured with the use of a flow meter.

In the period from plant construction in 2010, until 2017, the plant was only supervised by a third party on-line, and only planned inspections were conducted. Such a situation resulted in frequent breaks in the operation of the plant, which were caused by, for example, the following:

- CHP shutdown due to a low methane level (measurements were not conducted and the output of the various gas wells was not optimised);
- Operation interruption caused by the lack of power supply (temporary power failures and lightning strikes);
- Oxygen meter failure (excessive biogas moisture content, no biogas drying plant);
- Inadequate biogas yield (silting-up of gas wells and pipelines at the landfill);
- Excessive reaction time (up to 48 h) of remote service staff to the causes of plant downtime;
- Exceeding permissible air temperature in the container (a fan failure);
- Exceeding permissible exhaust gas temperature (exhaust gas exchanger blockage);
- Gas blower stopping as a result of the limit pressure being exceeded (flooding of wells and gas pipelines with water);
- Lack of ongoing measurements of biogas quality, including the content of hydrogen sulphide, which is reduced in the active carbon of the landfill gas filter.

The average methane content of landfill gas between 2012 and 2017 was 47.4% (the calorific value of 16,548.7 $kJ \cdot m^{-3}$), which was the result of the lack of monitoring the quality of gas extracted from the landfill and landfill gas optimisation on control valves in the suction and regulation station.

Table 2 shows the basic performance data recorded in the CHP control system for 2012–2017.

In view of the frequent downtime of the CHP plant, an electrician has been employed since 2016 on the degassing system and biogas utilisation plant at the landfill, who was seconded only to the plant, and a relevant procedure was implemented to optimise and ensure reliable operation of the cogeneration plant. The implemented internal procedure consists in the detailed monitoring of the degassing plant, along with optimising cogeneration plant operation. As part of the procedure, an operational database was created on the basis of the documentation in place, titled "Operation records for the degassing system and biogas utilisation at the landfill".

Table 2. CHP plant performance data for 2012–2017.

Year	Plant Running Time [h·year^{-1}]	Amount of Biogas Recovered [m^3·year^{-1}]	Amount of Electricity Generated [MWh·year^{-1}]	Amount of Heat Generated [MWh·year^{-1}]
2012	7614	926,732	1135.25	1589.35
2013	7623	936,321	1310.85	1779.01
2014	7436	898,464	1266.83	1646.88
2015	7581	868,451	1083.83	1542.37
2016	7338	956,298	1331.17	1652.48
2017	7342	876,932	1188.42	1485.52
Average	7489	910,533	1219.39	1615.94

The documentation includes, without limitation:

- Landfill gas meter reading sheet;
- Gross electricity production meter reading sheet;
- Net active electricity meter reading sheet for electricity transmitted to the power grid;
- Active electricity meter reading sheet for electricity consumed for the purposes of supplying landfill equipment;
- Heat meter reading sheet for heat generated in the CHP plant;
- Plant operation sheet (failures, downtime, and inspections);
- Gas flare operation record;
- Landfill gas composition measurement sheet (oxygen, carbon dioxide, methane, hydrogen sulphide).

The average methane content in landfill gas in 2018–2022 was 56.6% (the calorific value of 19,635.2 kJ·m^{-3}), which was the outcome of the introduction of corrective measures including full LFG monitoring in terms of quantity and quality. The operational database was maintained on the basis of records in the plant operation documentation by a staff member hired as a power engineer with a relevant licence for plant operation and supervision. All the measurements and readings on the plant were taken three times a day, and monthly schedules were subject to review by the managers. The basic performance data from 2018–2022 for the CHP plant is included in Table 3.

Table 3. CHP plant performance data for 2018–2022.

Year	Plant Running Time [h·year^{-1}]	Amount of Biogas Recovered [m^3·year^{-1}]	Amount of Electricity Generated [MWh·year^{-1}]	Amount of Heat Generated [MWh·year^{-1}]
2018	7876	1,306,298	2327.82	2788.38
2019	7852	1,276,732	2073.41	2863.35
2020	7883	1,286,321	2181.60	2815.28
2021	7687	1,248,464	2128.63	2708.61
2022	7943	1,218,451	1944.65	2821.60
Average	7848	1,291,515	2131.22	2799.44

The data in Table 3, completed with the results of biogas quality measurements and with the calculated biogas calorific values, are the input data for the calculation of the basic energy ratios for the CHP plant.

3. Research Methodology

The input data for the analysis of energy generation efficiency in the CHP system is the operating data from 2012–2022. These are the results of meter readings, measurements, and calculations. As the assessment of energy efficiency of the combined heat and power generation process differs from single-purpose processes, the efficiency of the individual processes was assessed on the operation manuals for energy cogeneration systems. The difference in these systems lies in the fact that all the cogenerated products have a useful value, and their production and management are conducted to the expectations of energy consumers.

The results were statistically analysed with the use of Statistica v 13.3 by TIBCOI Software Inc. [35]. To analyse the impact of the amount of biogas recovered for conversion into electricity and heat in a CHP system, 3 W scatter plots were used to visualise the interdependence between the three variables representing the X, Y, and one Z (vertical) coordinates of each point in three-dimensional space.

In turn, to analyse the impact of plant running time on the amount of electricity and heat generated in the CHP system, categorised 3W surface plots were used for the three variables corresponding to the sets of X, Y, and Z coordinates, i.e., for data subsets defined by the selected categorisation method suitable for the surface and defined by the smoothing method.

The analysis of the efficiency of energy generation in the CHP unit was conducted with the use of calculations based on indicators characterising the efficiency of the fuel chemical energy conversion process in the cogeneration system. The variable values taken for the calculations according to Formulas (1)–(3) were the average figures for the periods under analysis.

Electricity generation efficiency:

$$\eta_{el\_EC} = \frac{E_{el}}{\dot{E}_{ch}} = \frac{E_{el}}{\dot{V} \cdot W_d} \tag{1}$$

Heat generation efficiency:

$$\eta_{t\_EC} = \frac{Q}{\dot{E}_{ch}} = \frac{Q}{\dot{V} \cdot W_d} \tag{2}$$

Total efficiency:

$$\eta_{total} = \frac{E_{el} + Q}{\dot{E}_{ch}} \tag{3}$$

where:

$\dot{E}_{ch}$—LFG chemical energy yield
E_{el}—amount of electricity produced
Q—amount of heat produced
$\dot{V}$—annual LFG yield
W_d—LFG calorific value

As a tool for analysing the conversion of the chemical energy contained in landfill gas [36], these energy ratios pertain to CHP generation processes.

The availability of the CHP unit for power generation (A_{CHP}) was analyzed by calculating the unit's availability with the use of Formula (4), assuming the maximum annual working time of 8760 h.

$$A_{CHP} = \frac{t_{max} - t_D}{t_{max}} \tag{4}$$

where:

t_{max}—maximum annual working time
t_D—annual downtime

Reliability factors were analysed with the use of the Weibull distribution. As part of the reliability analysis, the following estimates were made:

- Reliability function:

$$R(t) = e^{\left(-\frac{t^{\beta}}{\alpha}\right)} \tag{5}$$

- Damage intensity function:

$$\lambda(t) = \frac{\beta}{\alpha}\left(\frac{t}{\alpha}\right)^{\beta-1} \tag{6}$$

- Cumulative distribution functions of the running time until the first damage:

$$F(t) = 1 - e^{\left(-\frac{t^{\beta}}{\alpha}\right)} \tag{7}$$

where:

- t—facility correct running time
- α—shape parameter
- β—scale parameter

By solving the system of three equations, the scale parameter β and shape parameter α may be determined.

$$\begin{cases} \alpha \cdot \sum_{i=1}^{\frac{n}{2}} lnx_i - \frac{n}{2} \cdot ln\beta = \sum_{i=1}^{\frac{n}{2}} ln\left(ln\frac{1}{1-h(x_i)}\right) \\ \alpha \cdot \sum_{i=\frac{n}{2}}^{n} lnx_i - \left(n - \frac{n}{2}\right) \cdot ln\beta = \sum_{i=\frac{n}{2}}^{n} ln\left(ln\frac{1}{1-h(x_i)}\right) \\ h(x_i) = \frac{i-0.5}{n} \end{cases} \tag{8}$$

One of the objectives of research and analyses conducted was to assess the operational reliability of the cogeneration unit at the municipal landfill. Between January 2018 and December 2022, a database was maintained which concerned, among other data, the plant running, inspection, heavy repair, and failure time. These data are presented in Figure 2.

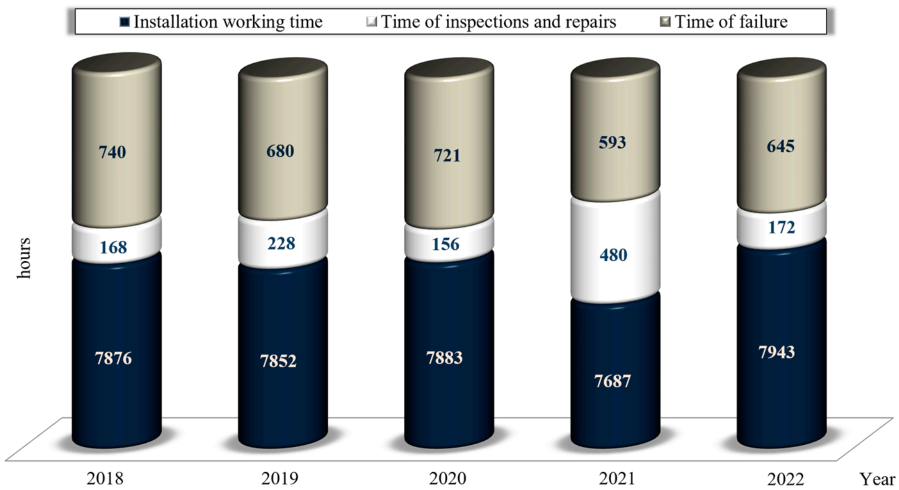

Figure 2. Cogeneration unit's running, inspection, heavy repair, and failure time in the various years of operation.

4. Research Results and Discussion

4.1. Analysis of Energy Generation Efficiency in the CHP System

To analyse the impact of the amount of biogas recovered for conversion into electricity and heat in a CHP system, 3W scatter plots were used to visualise the interdependence between the three variables representing the X, Y, and one Z (vertical) coordinates of each point in three-dimensional space. The operation of the cogeneration plant from 2012 to 2017 was distinguished by no direct plant supervision or the analysis of energy ratios, which resulted in the actual annual running time of 7489 h calculated as an average for the years from 2012 to 2017. As a consequence of this situation, the average LFG yield in that period was 910,533 $m^3 \cdot year^{-1}$, which enabled the generation of the following amounts of electricity and heat, respectively: 1219.39 kWh/year and 1615.94 kWh/year. Figure 3 shows the amount of electricity and heat generated in the CHP unit depending on the amount of recovered landfill gas.

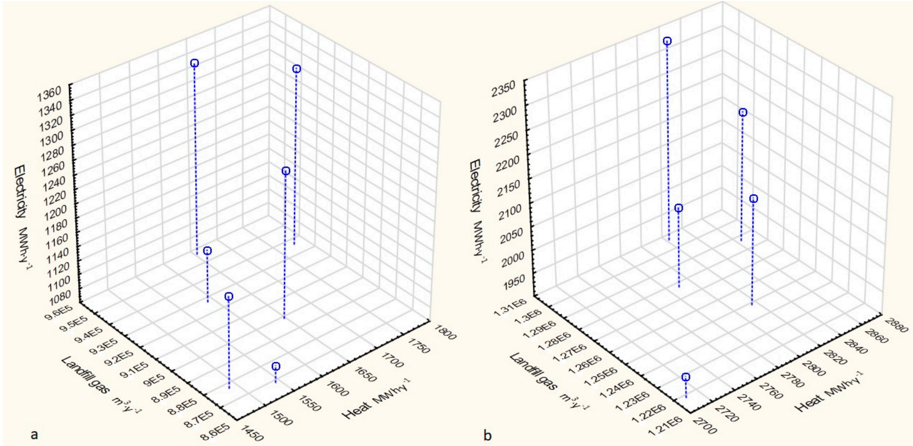

Figure 3. Biogas volume for the generation of electricity and heat in the CHP plant: (**a**) before optimisation, 2010–2015; (**b**) after the introduction of plant operation management, 2018–2022.

The analysis of the data for 2018–2022 showed that the annual average amount of recovered biogas was 1,291,515 $m^3 \cdot year^{-1}$, a figure 29.5% higher than in the previous period under analysis. This LFG yield enabled the CHP unit to produce 2131.22 MWh of electricity and 2799.44 MWh of heat per year.

4.2. Analysis of the Impact of Plant Running Time on the Amount of Electricity and Heat Generated in the CHP System

The impact of plant running time on the amount of electricity and heat generated in terms of energy, as two basic indicators characterising the efficiency of the fuel chemical energy conversion process in the cogeneration system, were calculated with the use of Formulas (5)–(8) [37], i.e., the efficiency of electricity and heat generation. The calculated availability of the cogeneration unit, including energy generation efficiency, is presented in Table 4.

Table 4. CHP plant performance data for 2012–2020.

Years	CHP Plant Running Time [h]	Downtime [h]	Availability	Electricity Generation Efficiency	Heat Generation Efficiency	Total Efficiency
2012–2017	7489	1271	0.854	0.28	0.37	0.65
2018–2022	7848	912	0.895	0.31	0.40	0.71

Calculated electricity generation efficiency after optimisation of CHP plant operation was higher by 6.66% and heat generation efficiency increased by 5.12%. These values indicate that the optimisation measures taken by the plant owner have a positive effect.

The volume of electricity production in the two periods under analysis is presented by means of categorised 3 W surface plots for the three variables corresponding to the sets of X, Y, and Z coordinates, i.e., for data subsets defined by the selected categorisation method suitable for the surface and defined by the smoothing method. Figure 4 comprises the comparison of the amount of electricity and heat generated in the two periods of CHP plant operation under analysis.

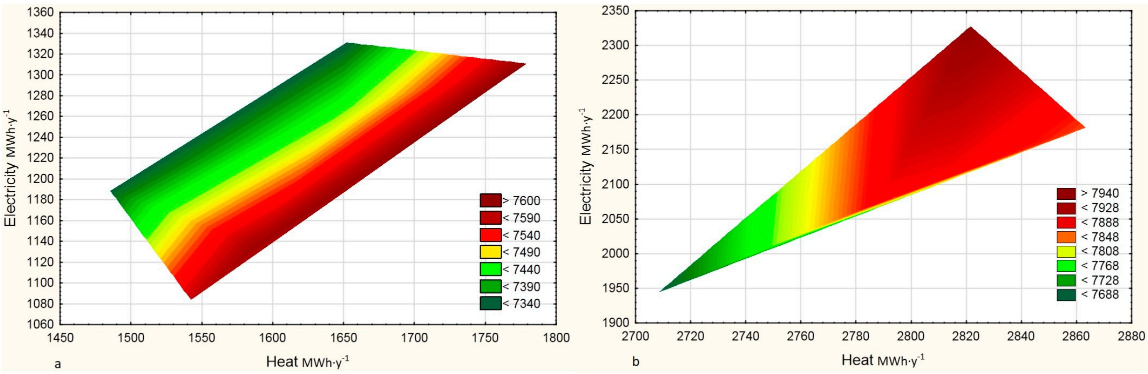

Figure 4. Energy production depending on CHP running time: (**a**) before optimisation, 2012–2017; (**b**) after the introduction of plant operation management, 2018–2022.

Figure 4 shows the amount of energy produced before and after optimisation depending on plant running time.

Higher energy parameters were achieved because of an increase in the generation unit's running time by 4.6%, which resulted in the availability of the CHP unit at the level of 0.895. These parameters and the higher LFG calorific value made the cogeneration unit generate more energy in 2018–2022 than in 2012–2017.

4.3. Assessment of the Technical Condition and the Analysis of the CHP Reliability Factors

During the CHP plant operation period, i.e., between 2018 and 2022, repeated technical inspections were conducted. Worn-out parts were replaced and the necessary maintenance work required by the documentation was performed. For example, the flywheel, combustion temperature sensors, spark plugs, and ignition cables were replaced. Observations of the combustion chambers were also conducted. The sample results of the observations are shown in Figure 5.

a b

Figure 5. Sample results of the videoscopic observations of combustion chambers: (**a**) siloxane layer on the inner surfaces of a cylinder piston and piston liner and (**b**) sulphur deposits in the gas engine [38].

The effect of a carbon deposit build-up is a drop in compression pressure in the specific cylinders. Table 5 presents the measured values of compression pressure.

Table 5. Compression pressure in cylinders [MPa].

Cylinder No.	Measured Value	Correct Value
1	1.65	1.90
2	1.65	1.90
3	1.75	1.90
4	1.65	1.90
5	1.70	1.90
6	1.60	1.90
7	1.80	1.90
8	1.60	1.90
9	1.75	1.90
10	1.85	1.90
11	1.80	1.90
12	1.60	1.90

The results of the measurements and observations demonstrated that the gas engine installed in the cogeneration unit did not operate at its rated load, which resulted in underburning of the mixture and in the formation of a carbon deposit in the engine components. The main source of the resulting contaminants in the engine are sulphur and silicon compounds (siloxanes) present in landfill gas, resulting in the formation of silica in the engine combustion chamber. When decomposing in the combustion process, silica causes damage to the engine cylinders and pistons [39,40].

Operating an engine when such contaminants are present most frequently leads to mechanical damage to the assembly of the crankshaft, pistons, and connecting rods as well as to the development of fretting wear in the components of an internal combustion engine [41,42]. Such a situation has a negative impact on the reliability of gas engine operation, which directly affects the efficiency of heat and electricity generation. Therefore, the key issue is to control the landfill gas treatment process and replace the gas filter in order not to exceed the permissible gas parameters allowed by the gas engine manufacturers [43,44].

In the period under analysis, the database was maintained, which included information on the type of damage following from plant operation. The irregularities and their numbers are compiled in Table 6.

Table 6. Type and cause of failures of the CHP plant.

No.	Element	Cause of Inoperability of the System	Number of Occurrences of Damage in the Period Under Analysis
1	Cylinder head	Bridge microcrack Water jacket crack	2
2	Turbocharger	Oil leak	2
3	Flywheel	Tooth breaking	1
4	Starter	Rack bearing damage	1
5	Exhaust manifold	Contamination with oil	4
6	Cooling system	Cooling liquid tube crack	3
7	24 V battery charger	No electric voltage	1
8	Battery	Total discharge	1
9	Actuator on the gas path to the engine	Mechanical damage	2
10	Engine block	Leaks, gasket	3

This information was used for the preparation of CHP plant reliability factors. Table 7 shows the calculations needed for the determination of the reliability function R(t), damage intensity function λ(t), and the cumulative distribution functions of the running time until the first damage F(t). The CHP plant running time until inoperability was marked t.

Table 7. CHP plant performance data for 2016–2020.

No.	t	ln(t)	h(t)	1/[1−h(t)]	ln{1/[1−h(t)]}	ln{ln{1/[1−h(t)]}}	Σln{ln{1/[1−h(t)]}}	Σln(t)
1	1680	7.426549072	0.025	1.025641026	0.025317808	−3.676247258	−15.11099783	94.0869
2	5623	8.634620608	0.075	1.081081081	0.077961541	−2.551539632		
3	10,850	9.291920359	0.125	1.142857143	0.133531393	−2.013418678		
4	14,374	9.573176298	0.175	1.212121212	0.192371893	−1.64832484		
5	15,189	9.628326761	0.225	1.290322581	0.25489225	−1.366914374		
6	17,459	9.767610554	0.275	1.379310345	0.321583624	−1.134497663		
7	19,313	9.868533723	0.325	1.481481481	0.393042588	−0.933837306		
8	20,118	9.909370216	0.375	1.60	0.470003629	−0.755014863		
9	21,586	9.979800235	0.425	1.739130435	0.553385238	−0.591700887		
10	22,180	10.00694626	0.475	1.904761905	0.644357016	−0.439502333		
11	23,548	10.06679617	0.525	2.105263158	0.744440475	−0.295122383	3.846541555	103.536
12	24,187	10.09357058	0.575	2.352941176	0.85566611	−0.155875037		
13	26,500	10.18490001	0.625	2.666666667	0.980829253	−0.019356889		
14	29,377	10.28796733	0.675	3.076923077	1.23930097	0.116831558		
15	32,501	10.38902614	0.725	3.636363636	1.290984181	0.255404859		
16	33,474	10.4185243	0.775	4.444444444	1.491654877	0.399886159		
17	34,250	10.44144184	0.825	5.714285714	1.742969305	0.555590156		
18	36,555	10.50657325	0.875	8.00	2.079441542	0.732099368		
19	38,945	10.56990567	0.925	13.33333333	2.590267165	0.951761023		
20	39,241	10.5774774	0.975	40.00	3.688879454	1.305322741		

With the use of information in Table 7 and Formula (4), the scale parameter β and shape parameter α were calculated. These values are as follows:

$$\alpha = 2.006231;\ \beta = 714504251.9$$

The shape parameter α has the value greater than one, and therefore the damage intensity function should be expected to grow.

If the value of the scale and shape parameters is known, the various reliability factors may be determined by means of Formulas (5)–(7). It is on that basis that the pattern of the reliability function R(t), damage intensity function λ(t), and the cumulative distribution functions of the running time until the first damage F(t) were determined, and their distributions are presented in Figures 6–8.

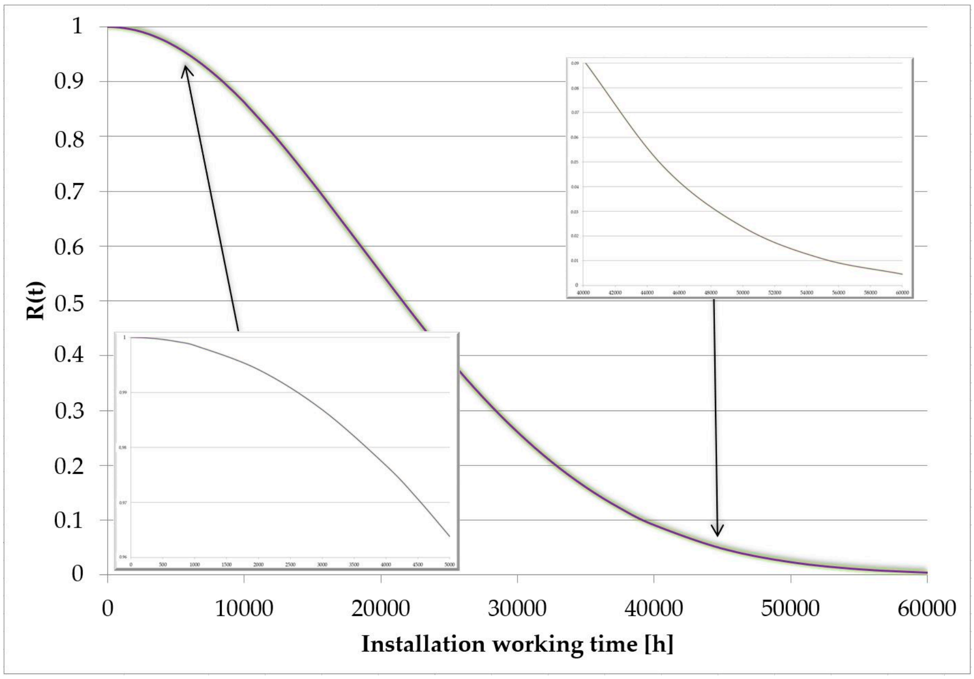

Figure 6. The distribution of the reliability function R(t) of the CHP plant in time.

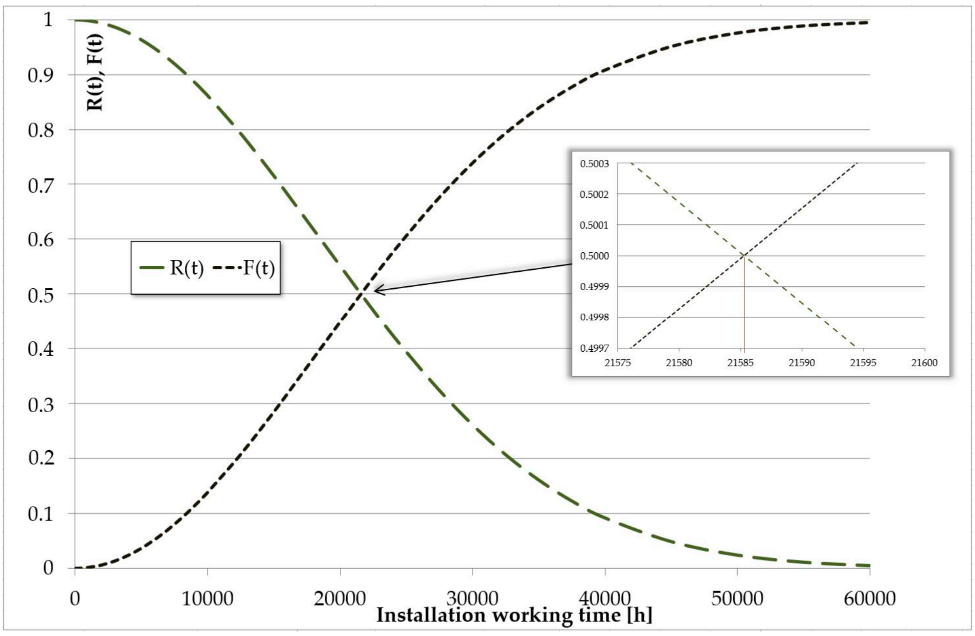

Figure 7. Distribution of the reliability function R(t) and the cumulative distribution functions of the running until the first damage F(t) of the CHP plant in time.

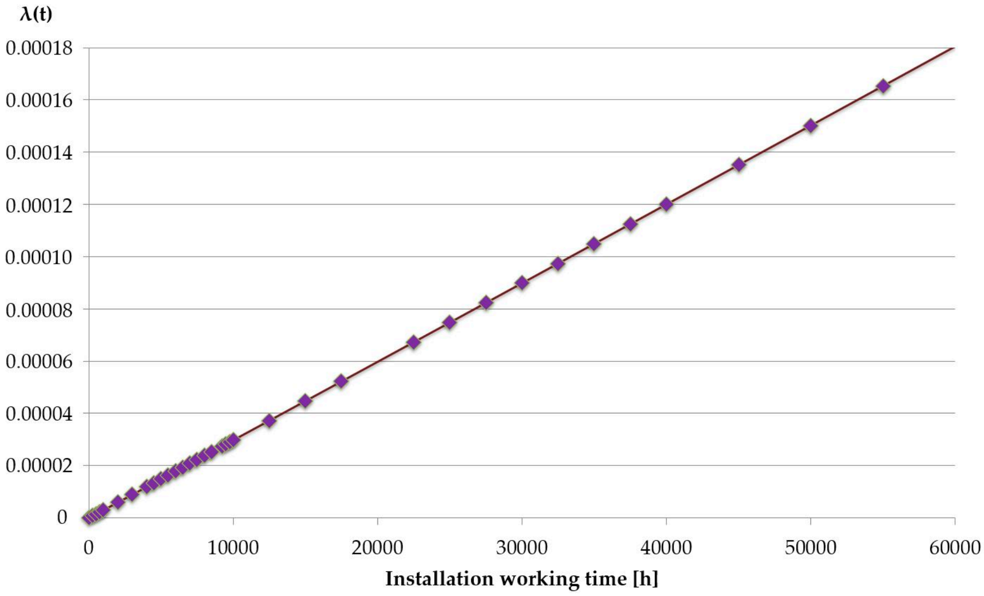

Figure 8. Distribution of the damage intensity function λ(t) of the CHP plant in time.

It may be estimated on the basis of Figures 6 and 7 that the CHP plant reaches 50% efficiency after approx. 21,500 h of operation. The plant reaches 90% efficiency after approx. 39,000 h of operation.

The calculations resulting in the diagrams shown above make it possible to estimate effectively the current increase in the risk for the CHP plant in the future and the timing of an intensive failure. On the basis of the risk situation and the consequences of the failure, it is possible to prioritise planned maintenance of the high-risk system to avoid unplanned downtime and thus effectively reduce operating costs by predicting the probability distribution and risk density of plant failure.

The comparison of the optimisation parameters is presented in Table 8.

Table 8. Comparison of optimisation parameters.

Parameter	Unit	Parameter Value	
		Before Optimisation	After Optimisation
Biogas stream	m^3/year	910,533	1,291,515
Electricity production	MWh/year	1219.39	2131.22
Heat production	MWh/year	1615.94	2799.44
CHP unit operating time	h/year	7489	7848
Downtime	h/year	1271	912
Availability	%	85	89
Efficiency of electricity generation	-	0.28	0.31
Heat generation efficiency	-	0.37	0.40
Total efficiency	-	0.67	0.70

Based on the analysis of parameters after optimisation of the CHP unit, their increase in relation to the values of the initial parameters can be observed. The key issue in this process is to increase the production availability of the unit as a result of the implemented technical and organizational processes, which directly translates into the energy efficiency of cogeneration.

Energy production is closely linked to the organic matter content in waste which, as a consequence, translates into the quantity and quality of biogas produced and into the availability of the energy generation unit. The efficiency of the energy generation process, which determines the efficiency of the conversion of biogas energy into electricity and heat [45], is directly linked to the question of biogas post-treatment quality and energy self-sufficiency of the waste water treatment plant.

Comparing the results of the research conducted in this work with the literature data, it should be noted that access to these data is limited due to the lack of research for CHP units in the power range up to 0.5 MW.

The few available test results of units operated in Greece showed the efficiency of electricity generation in the range of 30–35%. The total efficiency of these units was 70–75%. These data were not related to the period of technological availability [46].

Biogas-powered CHP installations up to 1 MW operated in Sweden showed electrical efficiency in the range of 20–50%, while their total energy generation efficiency was 70–80% [47].

Increasing the efficiency of the use of chemical energy in fuel (biogas) for the purposes of electricity and heat generation is recommended at the EU-level by the European Commission.

Biogas utilisation in a cogeneration unit (CHP) is regarded as an added value, reducing the costs of electricity production [48,49].

Due to the fact that the research conducted in this work aimed at increasing the energy efficiency and reliability of the CHP unit powered by landfill gas and is in line with the general trend of optimisation of manufacturing processes, this research can be transferred to other industries, not only those related to the municipal economy.

Research results in this area are presented by [50], with the author emphasising that the electrical efficiency of cogeneration units is a major factor in the commercial viability of electricity generation from biogas. Eight CHP units fuelled with biogas from sludge digestion were analysed. Research results demonstrated that the highest engine efficiency was achieved only in the case of units with a full service package including heavy repairs.

5. Conclusions

The analysis of operation of the landfill-gas-fuelled cogeneration unit in two periods, i.e., 2012–2017 and 2018–2022, showed considerable differences in the amount of LFG recovered and energy generated as well as in the availability of the CHP unit.

The period under analysis, i.e., 2012–2017 was distinguished by the lack of the plant operator's integrated approach to the process of energy generation from LFG. The operational and organisational changes introduced in the second period of the unit's operation, i.e., 2018–2022, showed the gas yield increase by 29.5%, the methane content increase by

16.25%, and the reduction in downtime hours by 28.24% compared to the first period. As a consequence of these parameters, energy generation efficiency increased, which resulted in an increase in electricity production by 42.78% and an increase in thermal energy production by 42.27%. The analysis of reliability factors with the use of the Weibull distribution demonstrated that CHP plant would reach 50% efficiency after approx. 21,500 h of operation, while a clear decrease in efficiency by 10% would be reached by the plant after 39,000 h of operation. In view of the indicators presented, further corrective measures need to be undertaken to prevent failures which result in no energy being generated. In the case of the operation of landfill-gas-fuelled cogeneration units, it is crucial to ensure the ongoing supervision of the plant in order to monitor LFG quality and the technical condition of equipment as well as to optimise the management of the energy generated.

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