# EVALUATION OF THE OPPORTUNITIES FOR ELECTRICITY AND HEAT GENERATION FROM GENERATED BIOGAS

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**ABSTRACT.** The possibilities for the generation of energy from generated biogas are studied in this article, and the quantities of biowaste that have to be treated are determined. An energy efficiency analysis has been carried out at different bio-waste ratios, whereby the calorific value of the biogas has been assessed. The amount of methane contained therein is determined, as well as that of the other combustible components (including $H_2$), for the purpose of more efficient heat and electricity generation. The lower calorific value or calorific value for methane is determined which is 36 MJ/m³N (8560 kkal/m³N) or 50 100 kJ/kg or 9.7 kWh/m³N. The average calorific value of biogas is about 18 000 kJ/m³N (4 280 kkalm³N) or 5 kW/m³N. The efficiency coefficient of the cogeneration system is determined. An analysis is made and the results for the annual electricity generation are presented, depending on the annual load of the fermenters.

**Keywords**: electricity, heat generation, biogas, cogeneration

**ОЦЕНКА НА ВЪЗМОЖНОСТИТЕ ЗА ПРОИЗВОДСТВО НА ЕЛЕКТРОЕНЕРГИЯ И ТОПЛОЕНЕРГИЯ ОТ ГЕНЕРИРАНИЯ БИОГАЗ**

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**РЕЗЮМЕ.** В настоящия научен труд са проследени възможностите за производство на енергия от генериран биогаз, като са определени количествата биоотпадъци които подлежът на обработка. Направен е анализ на енергийната ефективност при различни съотношения на биоотпадъците вследствие на което е направена оценка на калоричността на биогаза. Определено е количественото съдържанието на метан в него, определени са и другите горими компоненти (в това число и $H_2$), с цел по – ефективно генериране на топлинна и електроенергия е определена долната топлина на изгаряне или калоричност за метана, която е 36 MJ/m³N (8560 kkal/m³N) или 50 100 kJ/кг или това са 9.7 kWh/m³N. Средната калоричност на биогаза е около 18 000 kJ/m³N (4 280 kkal/m³N) или 5 kW/m³N. Определен е коефициента на ефективност на когенериращата система. Направен е анализ и са представени резултати за годишно ел. производство в зависимост от годишното натоварване на ферментаторите.

**Ключови думи:** електроенергия, топлоенергия, биогаз, когенератор

## Introduction

Natural decomposition or degradation of organic material results in the production of biogas by microorganisms under anaerobic conditions. Anaerobic digestion converts organic material into biogas, a renewable fuel that could be used to produce electricity, heat, or as vehicle fuel. In recent years, Anaerobic Digestion (AD) of waste and residues from agriculture and industry, municipal organic waste, sewage sludge, etc. has become one of the most attractive ways of generating renewable energy. The energy and climate policies in the EU and the introduction of various support schemes for promoting the utilisation of renewable resources have encouraged the development of biogas plants for energy production. The energy efficiency of different biogas systems, including single and co-digestion of multiple feedstock, different ways of biogas utilisation, and waste-stream management strategies have all been evaluated (Pöschl et al., 2010). The input data were derived from the assessment of the existing biogas systems, present knowledge on the management of anaerobic digestion processes, and technologies for biogas system operating conditions in Germany. The energy balance was evaluated as Primary Energy Input to Output (PEIO) ratio, to assess the process energy efficiency, hence, the potential sustainability. Results indicated that the PEIO corresponded to 10.5–64.0% and 34.1–55.0% for single feedstock digestion and feedstock co-digestion, respectively. The energy balance depended on the biogas yield, the utilisation efficiency, and the energy value of the intended fossil fuel substitution. For example, the obtained results suggest that the upgrading of biogas to biomethane for injection into the natural gas network potentially increased the primary energy input for biogas utilisation by up to 100%; also, the energy efficiency of the biogas system improved by up to 65% when natural gas was substituted instead of using electricity. Energy balances have been analysed from a life-cycle perspective for biogas systems based on 8 different raw materials. The analysis was based on published data and relates to Swedish conditions. The results show that the energy input into the biogas systems (i.e. large-scale biogas plants) corresponds to 20–40% (on average, to approximately 30%) of the energy content in the biogas produced. Large variations exist in energy efficiency among the biogas systems studied. These variations depend both on the properties of the raw materials studied and on the system design and the allocation methods chosen. The net energy output from biogas systems based on raw materials that have high water content and low biogas yield (e.g. manure) is relatively low. When energy-demanding handling of the raw materials is required, the energy input increases significantly. For instance, in a ley crop-based biogas system, the ley cropping alone corresponds to approximately 40% of the energy input. Overall, the operation of the biogas plant is the most energy-demanding process, corresponding to 40–80% of the energy input into the systems. Thus, the results are substantially affected by the assumptions made about the allocation of a plant's entire energy demand among raw materials, e.g. regarding the biogas yield or the need of additional water for dilution (Berglund et al., 2006). From the point of view of the application, what is unfavourable for the internal combustion engines (ICE) operating on biogas instead of on natural gas, is hydrogen sulphide and moisture. These ingredients are due to the way biogas is formed and are inevitable. This also determines the need for equipment and technologies to reduce emissions. Concentration of hydrogen sulphide depends on the type of waste and the time of biogas formation, i.e. these factors cannot be influenced. In the bioreactor, the timing of creating biogas conditions for the generation of biogas is about 21 days. Moisture removal will use a cycle equipped with heating.

## Energy capacity (calorific value) of biogas

The calorific value of biogas is determined by the content of methane in it. Other combustible components (including $H_2$) are in small quantities and do not affect its calorific value. According to the literature and observations of such installations, the biogas composition is given in Table 1.

Table 1. *Average composition of biogas*

| NAME | GAS | v/v percent |
|---|---|---|
| Methane | $CH_4$ | 54 |
| Carbon dioxide | $CO_2$ | 42 |
| Ammonium | $NH_3$ | 3 |
| Others | | 1 |

Lower combustion heat, or calorific value, for methane is 36 MJ/m$^3$N (8,560 kkal/m$^3$N) or 50,100 kJ/kg or 9.7 kWh/m$^3$N.

Therefore, the calorific value of biogas is about 18,000 kJ//m$^3$N (4,280 kkal/m$^3$N) or 5 kW/m$^3$N.

The specific weight of the individual components of biogas is:

• methane 0.716 kg/m$^3$N

• carbon dioxide 1.93 kg/m$^3$N

When using anaerobic plants for biodegradable waste, the biogas process is limited to a few-week cycle. This is due to the fact that technologically favourable conditions are created for the biogas generation from biodegradable waste. This produces biogas quantities that are controlled and utilised. The most common way of doing so is the combined generation of electricity and heat. For the implementation of this technology, a system is necessary for the separate collection of biodegradable waste, as well as an anaerobic installation developed in which to generate biogas from the collected biodegradable waste.

From an energy point of view, the biogas from anaerobic plants is a renewable energy source (RES). This means that its use as a primary energy source is a priority. Undoubtedly, the generation and use of biogas from waste brings significant benefits. Despite the obvious benefits to society, it is very important to determine the exact capacity of the installation and the choice of technology, respectively.

The most common way to exploit the biogas generated in bioreactors and used to generate electricity is provided by the following:

□ Spark ignition ICE;

□ Generator;

□ Cooling and heat recovery system;

□ Increasing transformer;

□ Connection to the electricity distribution system.

The difference between the cogeneration scheme and that for the generation only of electricity is that in the latter case, the released heat is taken to the atmosphere.

This recovery scheme has the following advantages:

- It is implemented directly next to the biogas source, i.e. there is no gas transport at a distance;
- Easy transmission and low-loss electricity;
- Small running costs.

The drawbacks of this method are limited to the more difficult realization of the excess heat (especially in summer periods).

## Quantity of biodegradable waste

In the analysis, only the biodegradable waste is considered that can be used as feedstock in an anaerobic treatment plant for biodegradable municipal waste - from food, paper, and green waste. Other biodegradable waste exists, such as that classified as wood waste whose biogas potential for anaerobic digestion is greater, yet the degradation process time is much larger and also, it cannot be used in bioreactors (fomenters) without pre-treatment.

Table 2. *Amount of biodegradable waste by municipalities used as feedstock for the anaerobic installation*

| | | Ruse | Vetovo | Ivanovo | Slivo pole | Tutrakan | TOTAL |
|---|---|---|---|---|---|---|---|
| Nutritional | t/y | 4536 | 114 | 367 | 257 | 434 | 5708 |
| Gardening | t/y | 6142 | 289 | 771 | 714 | 392 | 8308 |
| Timber | t/y | 571 | 19 | 43 | 114 | 40 | 787 |
| Paper and cardboard | t/y | 1147 | 27 | 82 | 45 | 86 | 1387 |
| TOTAL | t/y | 12396 | 449 | 1262 | 1130 | 952 | 16190 |

For the period 2023-2050, the average value of biodegradable waste collected separately and fed to the anaerobic installation will be 17,206 t/y; for the first 10 years of operation it will be 17,045 t/y with a maximum of 17,845 t/y.

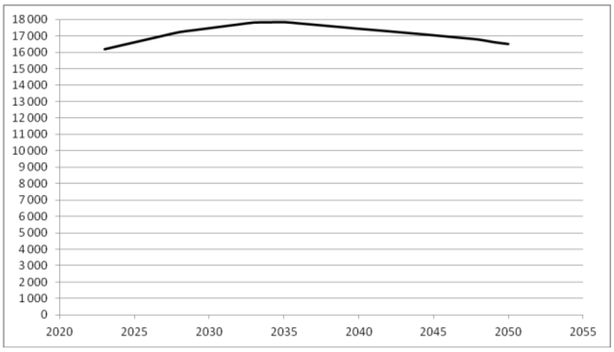


**Fig. 1. Quantities of biodegradable CBT fed to the anaerobic plant in t/y**

Regarding the seasonality of biodegradable waste, Fig. 2 illustrates the change of the individual components by seasons.

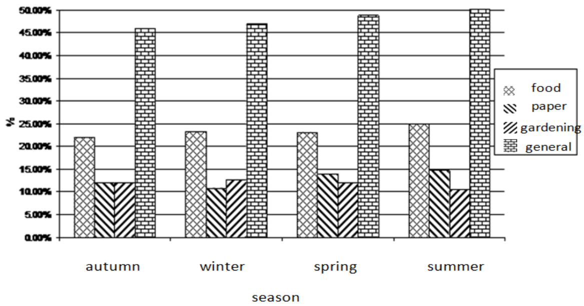


**Fig. 2. Seasonality of biodegradable waste**

There is an obvious seasonality of waste which is easy to explain. For this reason, the design of the plant should allow it to operate over a wide load range, with a minimum capacity of 30%.

Figure 3 shows the main flows in the adopted flow diagram according to the requirements of the "National Technical Requirements for Biodegradable Anaerobic Biodegradation Facilities (Guidance on Good Practices)".

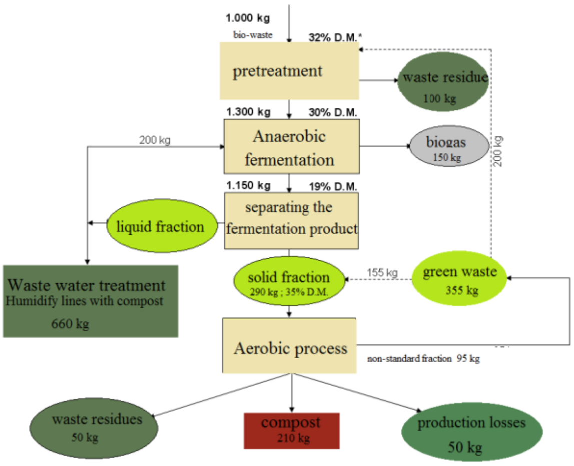


**Fig. 3. Material balance of the technology for dry, continuous fermentation of biodegradable waste**

From the data presented, the following capacity of the anaerobic installation for biodegradable waste collected separately can be determined.

□ Maximum installation capacity - 17,845 t/y;

□ Maximum capacity of biodegradable waste to fermenters - 13,934 t/y;

□ Type of installation - modular with 3 fermenters, dry type;

□ Capacity of 1 digester/fermenter - 6,040 t/y;

□ Operating range of the installation - from 30% to 100% of the maximum load;

□ Permissible waste: Biodegradable collected separately - food, paper and cardboard, green, garden.

To accelerate the biodegradation processes, especially for the slowly degradable components, primary treatment of the incoming material will be carried out in order to eliminate the retarding action of the cellulose on the biodegradation process.

Before the material enters the fermenter, it undergoes ultrasonic treatment (US). The purpose of this operation is the easier degradation of the cellulose and other constituents of the waste and, accordingly, the increase of the biogas yield.

Using ultrasound is another bio-waste pre-treatment technology that has not been used in anaerobic bioreactors so far. With wave frequencies above 20 kHz, cavitation and destruction of microbial cell walls is induced in the liquid. This leads to an increase in the yield of biogas of up to 25%. The substrate thus obtained is transported to the bioreactor where mesophilic or anaerobic fermentation is carried out at a temperature not exceeding 35-37˚ Celsius.

Figure 4 illustrates the principle of operation of ultrasound waste treatment.

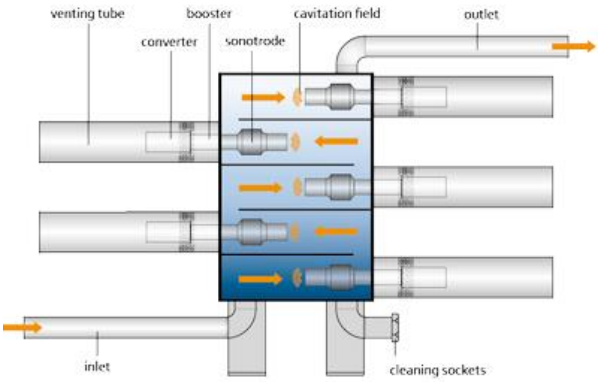


**Fig. 4. Principle of operation of US waste treatment**

In addition, the material that has undergone US treatment has the following advantages:

• Reduced viscosity of the material; therefore, less technical water needs to be added, which reduces the transport costs and the volume it occupies in the fermenter;

• Increased methane yield by up to 10%;

• Increased concentration of methane by 1-2%.

The expected effect of the use of US is an increase in the generated electricity and heat by about 12%, while reducing electricity costs for transporting bio-waste and for separating the liquid from the solid fraction of the fermentation product.

The energy consumption for the US treatment of a cubic meter of waste is 4 kWh/m$^3$.

The resulting biogas is a function of the amount of waste that is fed to bioreactors.

Figures 5 and 6 illustrate the various technological diagrams.

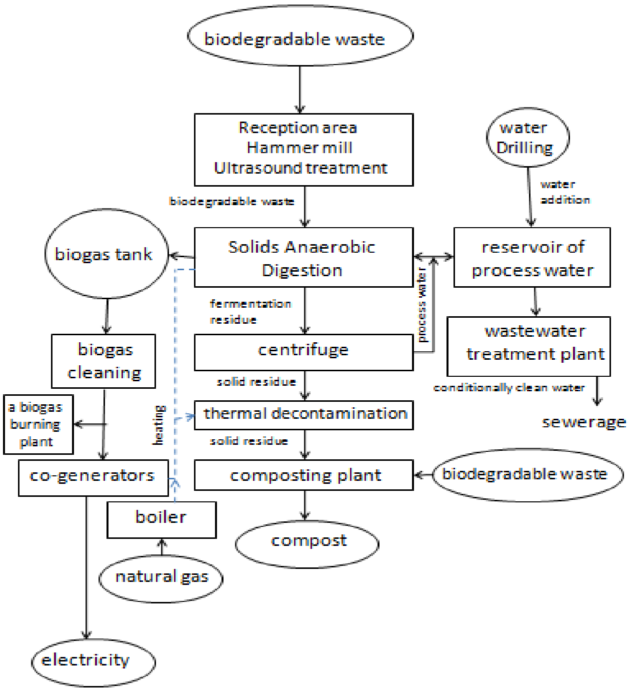


**Fig. 5. Technological diagram of an anaerobic facility with one fermenter and one co- generator**

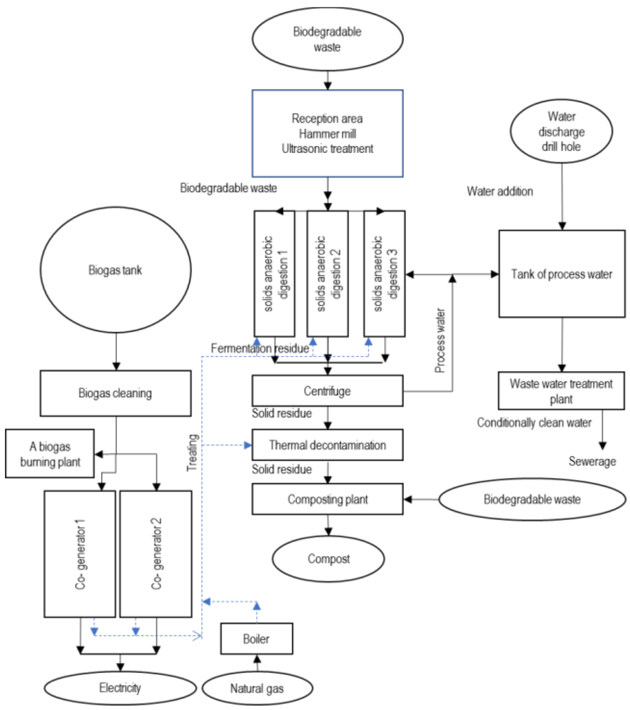


**Fig. 6. Technological scheme of an anaerobic facility with three fermenters and two co-generators**

## Selection of bioreactors

### With regard to bioreactors

An analysis has been carried out of the similar installations existing in Bulgaria and a literature reference has been made for such installations in the EU countries.

Installations with one bioreactor have advantages at constant amounts and composition of the feedstock due to the relatively more compact overall facility. The deficiencies of anaerobic facilities with one bioreactor are significant because any maintenance action, fermenter repair or a compromised mixture means stopping the anaerobic process, and the cycle to restore the biogas production is about a month long; therefore, the amount of unprocessed biogas is significant; respectively, the non-generated electricity, plus the additional costs of natural gas for heating and maintaining the temperature in the bioreactor. In other words, from the operational point of view, each stop of the anaerobic installation from being able to generate biogas, respectively electricity and revenues from its realization and at the same time the additional costs of natural gas within one month. Another feature of single bioreactor plants is that much of the equipment needs to be reserved.

### With regard to multiple bioreactor plants

The proposal is for the anaerobic installation to be with three bioreactors, each with a capacity of 1/3 of the total load. What are the benefits of this scheme? The use of the anaerobic installation is significantly more flexible because, due to different seasonal loads, the installation will be able to work with one, two or three fermenters, depending on the available raw material. This allows organising and performing maintenance and repairs of the fermenters to be carried out without disturbing the production of biogas. In the installation with three fermenters, even if a problem arises in one of the reactors, that is associated either with the equipment or with the mixture, the production biogas will be, in the worst case, about 2/3 of the nominal one and will not necessitate natural gas supply. In other words, there will be no period when the installation will not generate revenues. The following table presents the comparison of the two variants of electricity sales revenues for a period of one year with a single bioreactor shutdown.

Table 4. *Comparison of variants with one and three bioreactors with one hypothetical reactor shutdown in a given year*

| | | 1 bioreactor | 3 bioreactors |
|---|---|---|---|
| Amount of biowaste to bioreactors | t/y | 12000 | 12000 |
| WITHOUT bioreactor shutdowns | | | |
| Generated biogas | $m^3/y$ | 1365181 | 1365181 |
| Electricity produced | kWh/y | 3559518 | 3559518 |
| Revenue from electricity | BGN | 833248 | 833248 |
| With ONE bioreactor shutdown | | | |
| Generated biogas | $m^3/y$ | 1023886 | 1296922 |
| Electricity produced | kWh/y | 2669639 | 3381542 |
| Revenue from electricity | BGN | 624936 | 791585 |
| Decrease in revenue | BGN | 208312 | 41662 |
| Decrease in revenue | % | 25% | 5% |

Table 5. *Comparative table of variants with one bioreactor and with three bioreactors*

| № | Criterion | 1 Bioreactor | 3 Bioreactors |
|---|---|---|---|
| 1 | Amount of the investment | 36244774.25 BGN | 31517195.00 BGN |
| 2 | Staff costs per shift per year | 306800.00 BGN | 306800.00 BGN |
| 3 | Capacity of the installation | 17845 t/y | 17845 t/y |
| 4 | Electricity produced, kWh/r | 2669639 | 3381542 |
| 5 | Minimum amount of bio-waste required | 5500 t/y | 5500 t/y |
| 6 | Installation time after emergency repairs | 1 month | 0 month |
| 7 | Time to restart the installation | 2 months | 0 month |
| 8 | Revenue from electricity | 624936.00 BGN | 791585.00 BGN |
| 9 | Service shutdown - times per year | 1 | 0 |

From the table above, it is clear that the 3-bioreactor option is the one that is appropriate, both in terms of maintenance and service.

## Selection of generating modules

The main consideration for choosing the number of generators is that they should be able to provide a continuous generation of electricity. The generators can operate at a mode of 50 to 110% of the nominal load. In addition, this kind of generators usually operates up to 7,000 hours/year. The other option is used for maintenance and repairs. In other words, with the right choice of power of the generator, the maximum utilisation of the works can be achieved. It should be noted that the seasonality of collected biodegradable waste is determined by the different amount of biogas to be generated. The practice of choosing such type of power equipment is to select one generator that has a rated output of 35-40% of the total load, and another one that has 60-65%.

From the examined alternative technologies, a conclusion is drawn that the Rousse anaerobic installation will be constructed with three bioreactors, each of which having a capacity of 1/3 of the maximum, and with two generators, one at about 40% and the other at about 60% of the nominal value of the one offered by the manufacturers.

## Efficiency / efficiency ratio

Spark-ignition ICE is used as an engine.

The efficiency in the generation of energy is the efficiency obtained by the flywheel of an ICE multiplied by the efficiency of the generator. Generally, an ICE has better electrical efficiency than gas turbines, especially for small capacities. It depends on the type of ICE used.

The presented study is based on the data provided by the major manufacturers of such equipment: GE Jenbacher - Austria, Tedom - Czech Republic, Accorroni - Italy and ENER G - Great Britain.

The electrical efficiency of the generating installations depends on the power of the engine and is shown in Figure 7.

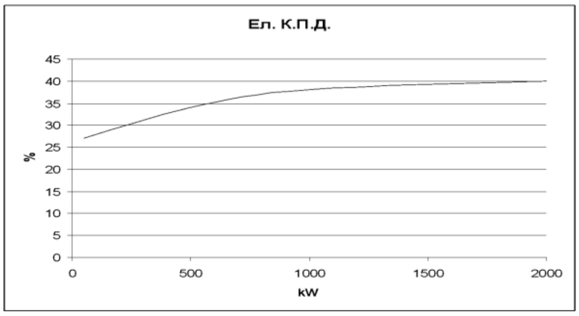


**Fig. 7. Efficiency ratio of generators with Otto engines**

The efficiency factor ranges from 27% for low-power plants, normally reaching 34-36% for those with a power output of 500 to 1000 kW.

If the system is co-generating, the thermal efficiency ratio is usually about 1/3 greater than the electrical efficiency. The total efficiency factor (thermal + electric) is about 80-85%. For the purposes of the preliminary analysis, an average electrical efficiency ratio of 28% and a thermal efficiency of 52% can be adopted. The efficiency factor of the generator should be taken into account, which can be assumed as 96% for the purposes of this analysis.

From the calculations made on the basis of the forecast data on the biowaste entering the installation, the extraction of biogas and methane at different installation loads has been obtained and is given in Table 6.

Table 6. *Methane obtained at different installation loads*

| | | Waste to fermenters - t/y | | | | |
|---|---|---|---|---|---|---|
| GAS | dimension | 2,500 | 5,000 | 7,500 | 10,000 | 12,000 |
| $CH_4$ | % | 53.89% | 53.89% | 53.89% | 53.89% | 53.89% |
| $CO_2$ | % | 41.75% | 41.75% | 41.75% | 41.75% | 41.75% |
| $NH_3$ | % | 4.29% | 4.29% | 4.29% | 4.29% | 4.29% |
| $H_2S$ | % | 0.07% | 0.07% | 0.07% | 0.07% | 0.07% |
| $CH_4$ | $Nm^3$ | 28441 | 56882 | 853238 | 113765 | 136518 |

Based on the data in the table, the energy indicators of the generated biogas and the installed generation capacities are set and are presented in Table 7.

Table 7. *Generated biogas and installed generating capacity*

| Parameters of the generated biogas | value | dimension |
|---|---|---|
| Methane - at a nominal load of the fermenters of 12000 t/yr. | 1365181 | $m^3/y$ |
| Energy capacity of the biogas | 13242256 | kWh/y |
| Annual usability of the installation | 8760 | h |
| Heat output received | 1512 | kWh |
| Theoretical installed power | 406 | kW |

## Selection of the type of equipment for electricity generation

It is recommended to install two modules in order to exploit the resulting biogas under a different load of anaerobic installations with capacities of:

• 150 kW;

• 250 kW.

or a total installed power of 400 kW.

The considerations for this choice are as follows:

□ The biogas flow is not constant and depends on the load of the installation, etc.;

□ Each co-generation unit can operate within the range of 50 to 110% of the nominal load. With the chosen configuration, it can cover a working range of 75 to 440 kW.

The theoretical quantities of electricity generated, depending on the annual load of the fermenters, are shown below.

Table 8. *Annual electricity production at different installation loads*

| Biowaste | Electric energy |
|---|---|
| t/yr | KWh |
| 2500 | 741566 |
| 5000 | 1,483132 |
| 7500 | 2224699 |
| 10000 | 2966265 |
| 12000 | 3559518 |

## The produced electricity is bought at preferential prices, determined by the State Agency of Energy Regulations, and is part of the group of renewable energy sources (RES).

**Electrotechnical part**

The development of the project will meet the requirements of Ordinance No. 3 on the Layout of Electrical Systems and Power Lines of 2004. The electrical part covers the following types of installations and facilities to ensure the normal operation of the facility:

- External power supply;
- Area lighting;
- Power supply to all technological consumers;
- Internal electrical installations in the building - motor, lighting and earthing;
- Lightning protection of buildings and facilities.

With respect to the security of the power supply, the object falls into the third category.

**Power supply**

It is planned to build new 20/0.4kV switchgear, which will be located at a suitable place. The required electrical power for the site lighting will be about 610 kW, which means that the power of the switchgear should be 630 kVA. The 20/0.4kV switchgear will consist of the following devices:

- 20kV Distribution system. This will be built with switchgear cabinets and the number of 20 kV cable cabinets will be determined by the power distribution company, cabinet measurement and cabinet for protection of a 20/0.4kV power transformer; 630kVA. The cabinets will be equipped with electric switches, current and voltage transformers, high-power fuses, and electronic protections;

- 20/0.4kVA Power transformer. The transformer will be dry, located in a separate room with natural ventilation. Grounding of the star centre of the power transformer will be provided by means of a grounding system made of two rods of 60/60/6mm galvanised steel bridges and a 40/4mm galvanised steel bus.

**External 20kV power supply**

The 20kV external power supply will be executed in compliance with the requirements of the local power distribution company. Three single-core cables type CXekt - 20 kV will be laid to the CTS (complete transformer station). The cable cross section will be determined according to the current load and to the resistance under short-circuit conditions.

## Conclusion

A three bioreactors system is proposed for the production of energy from generated biogas. An analysis of the composition and quantities of bio-waste has been made, their effectiveness at different bio-waste ratios, and a biogas calorific value is subsequently assessed. The amount of methane in the biogas is determined as well as other combustible components (including $H_2$) in order to more efficiently generate heat and electricity. The average calorific value of the biogas is about 18 000 kJ / $m^3$N (4 280 kkal / $m^3$N) or 5 kW / $m^3$N. The coefficient of efficiency of the cogeneration system is determined. An analysis is made and the results for annual electricity production are presented, depending on the annual load of the fermenters.

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