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Biogas for Electricity Production in Agricultural Facilities: A Case Study

Bruno Teixeira[1], Teresa Nogueira[1] and R. F. Mesquita Brandão[1]

[1] Institute of Engineering, Polytechnic Institute of Porto
Rua Dr. António Benardino de Almeida, 431, 4200-072 Porto (Portugal)
Phone:+351 228 340 500,
e-mail: brunoteixeira87@gmail.com, rfb@isep.ipp.pt, tan@isep.ipp.pt

Abstract. Biogas has become an attractive alternative source of energy as the renewable fuel serves several policy priorities, ranging from increased domestic energy production to the reduction of greenhouse gases and more efficient waste treatment.

It can be produced from many kinds of organic materials but it is closely linked to agricultural activities, integrated into farming processing structures. The primary source is manure from animal production, mainly from cattle and pig farms.

Anaerobic digestion is a natural process that converts animal waste to biogas. The anaerobic facility must be designed to meet the individual characteristics of each dairy farm operation. Biogas is produced when bacteria convert organic matter to methane gas.

A digestor/generator produces two important outputs: it is capable of generating electricity and heat. Electricity can be used for self-comsumption and the surplus can be delivered in the distribuition grid. The generated heat should be used closed to the generator and attains economic value dependent upon how it is used: to heat water or to refeed anaerobic digestion process.

Before a biogas plant is built, a techno-economic assessment should be made. In this study it is done a financial analysis which judges the profitability of a biogas unit from the point of view of the user. The costs and revenues were studied for this particular project considering the known parameters of the technical system.

Key words

Biogas production, anaerobic digestion, agricultural.

1. Introduction

The import oil dependency of almost all European countries and the concerns about long-term sustainability, constantly brought renewable energy sources to the forefront energy policies.

The EU policy has set the goal of supplying 20% of the European energy demands from renewable energy. A great part of this renewable energy can be obtained from European farming and forestry, as biomass conversion to gaseous, liquid and solid biofuels. The gaseous part – the biogas production - has its own, more and more, consolidated platform.

The forecast looks promising. At least 25% of all bioenergy in the future could be originated from biogas, produced from wet organic materials, like animal manure, whole crop silages, wet organic food/feed wastes, etc. [1].

Biogas can be produced from nearly all kinds of organic materials. There are quite a few biogas process volumes at the current waste water treatment plants, landfill gas installations, and industrial biowaste processing facilities. However, the largest volume of produced biogas is closely linked to agricultural activities, integrated into the farming processing structures.

Anaerobic digestion (AD) is the most promising method of treating the organic wastes. In the absence of oxygen, anaerobic bacteria will ferment biodegradable matter into methane gas (CH_4) and carbon dioxide gas (CO_2), a mixture called biogas.

Biogas may be used for Combined Heat and Power (CHP) production. The utilisation of biogas in internal combustion engines (gas engines) is a long established and extremely reliable technology. When used to produce electricity, biogas is introduced into the CHP plant to meet electricity demand on site and the surplus can be injected in the distribution grid.

For many years the purpose of using biogas technology (or anaerobic technology) has been the search for renewable sources of energy. In the meantime, other environmental protection aspects are gaining additional importance: a technology which previously just filled a "niche" is now becoming a key environmental technology for integrated, solid and liquid waste treatment concepts and climate protection, both in industrialised and developing countries.

Around the world, air and water pollution created by municipal, industrial and agricultural operations continues to grow. The emission of CO_2 and other greenhouse gases (GHG) has become an important issue. Governments and industries are therefore increasingly on the lookout for technologies that will allow for more efficient and cost-effective waste treatment, while minimising GHG.

The production of biogas at each agricultural location can, on one hand, reduce the production of energy generated by fossil fuels, resulting in the saving of

resources. On the other hand, the biogas can reduce the emission of GHC emissions to the atmosphere, not only by avoiding the issuance of the three most important gases to the greenhouse effect - carbon dioxide, methane and nitrous oxide (N_2O) produced by the manure of animals - but also by reducing the emission of gases as a result from burning fossil fuels used in utilities to produce electricity [2].
The best use of national indigenous resources is an important tool to further the goals of national energy policy, including the reduction of external energy dependence and harmful gas emissions, particularly those that assume a great importance for climate change. This paper analyses the energy potential of biogas in the agricultural sector in Portugal, introducing a case study based on a particular farm utility in Northern Portugal. The results enhance the economic feasibility of the biogas exploitation in farms with such a dimension.

2. Basics of Biogas Production

For biogas production, four ingredients are needed: organic matter, bacteria, anaerobic conditions and heat. Organic matter is the food source for methane producing bacteria. The primary organic matter source for farm-based biogas production is manure.
The second ingredient is bacteria, necessary to convert the fats, carbohydrates and proteins in the organic matter to simple acids, such as acetic and propionic acid. Then, a second type of bacteria transforms the acids to methane and carbon dioxide. The bacteria are commonly present in manure, and under the right conditions they thrive and multiply.
Another two necessary conditions for the bacteria are anaerobic atmosphere (no oxygen) and the right temperature. Most digesters operate in the mesophylic range of 35-40^{o}C, but others are designed to operate in the thermophylic range of 50-60^{o}C, and even a few are designed to operate at 15-25^{o}C or the psychrophylic range [3].
Digestion of animal manure is probably the most widespread AD application worldwide. It produces a valuable fertiliser – biomass, as well as the biogas, which can be used as fuel to generate electric and thermal energy (fig. 1).

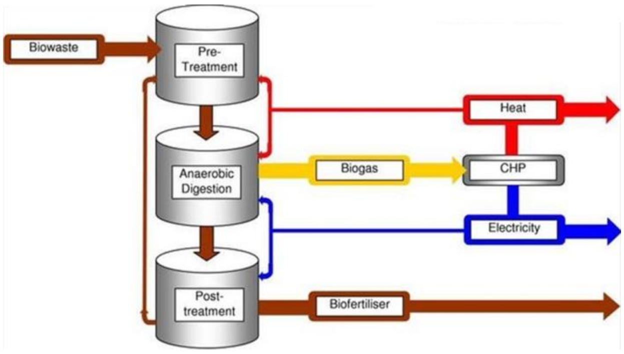

Fig. 1. Anaerobic Digestion Method

Farm scale digestion plants treating primarily animal wastes have seen widespread use throughout the world, with plants in developing and technically advanced countries. In rural communities small-scale plants are frequent, generally used for providing gas for cooking and lighting to a single household. In more developed countries, farm-scale AD plants are generally larger and the gas is used to generate heat and electricity. These farm-scale digestion plants are simple stirred tank designs that use long retention times to provide the treatment required.
For the farm scale biogas digesters, two designs are prevailing throughout Europe: the so-called rubber top digester, and the concrete top digester, usually built in the ground. Both have a cylindrical form with a height to diameter ratio of 1:3 to 1:4. They are intermittently mixed tank reactors with hydraulic retention times of the waste in the digester of 15 to 50 days.
In fig. 2 we can see the different stages of anaerobic digestion process.

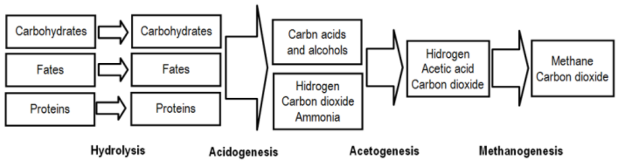

Fig. 2. Stages of anaerobic digestion

Biogas produced in AD-plants or landfill sites is primarily composed of methane (CH_4) and carbon dioxide ($C0_2$) with smaller amounts of hydrogen sulphide (H_2S) and ammonia (NH_3). Trace amounts of hydrogen (H_2), nitrogen (N_2), carbon monoxide (CO), saturated or halogenated carbohydrates, oxygen, and siloxanes [4] are occasionally present in the biogas. Usually, the mixed gas is saturated with water vapor.
The percentage of the biogas composition depends on the nature of the digested residue, and on the conditions under which anaerobic digestion is carried.
In table I we can see the gas composition range, according to three authors [5].

Table I. – Biogas composition according to three authors

Gases	Wheatley, 1979	Hobson et al., 1981	Fox, 1984
CH_4	52 – 95	60 – 70	60 – 70
CO_2	9 – 40	30 – 40	30 – 40
H_2S	0,001 – 5,7	0,007 – 0,2	0,05 – 2
H_2	0,01 – 1,2	2	
N_2	0,1 – 18	4	1
O_2	0,02 – 6,5	0,001 - 1	
Ar (argon)	0,001		
CO	0,001 – 2,1		
NH3 (Ammonia)	traces		

The energetic properties of biogas depend on their constituents percentage, mainly the methane composition. Methane is a colourless and odourless gas that burns with clear blue flame and consists of all the six main gases contributing to global warming. Biogas has a density of 1.13 kg/m^3 [6].

The remaining constituents of biogas, although present in very limited quantities, can affect transport, cleaning and combustion. In fact, it is very important to know the properties of higly variable composition mixtures, and the extent to which they influence their performance. Due to its importance, the following properties of the biogas are of particular relevance [4]:

- Calorific value (kWh/m^3) –the energy released in heat form, not including energy expended in the vaporization of water in the fuel. This parameter provides information about the exact extent of the useful energy content of the fuel;
- Flammable Limits: corresponds to the minimum and maximum percentages of fuel in a fuel/air mixture for which the mixture ignites. They are a critical parameter in the biogas combustion, due to the dilution of methane with carbon dioxide and other inert gases.

Under normal conditions of pressure and temperature, that is, at the pressure of 1 atm and the temperature of 0°C, the pure methane has a calorific value of 9.44 kWh/m^3. The biogas with methane content between 50% and 80% has a calorifc value between 4.72 and 7.55 kWh/m^3. 1 m^3 of biogas with 60% methane has an energy equivalence of 5.5 kWh [5]. On the other hand, some references report that 1 m^3 of dry biogas with a methane percentage of 10% may correspond to an energy production of approximately 1 kWh.

3. Biogas potential in Portuguese livestock activity

The livestock activity is a field with huge potential in terms of energy producing capacity, but most of the times farmers do not have the necessary information to take on any available possibilities. In this paper we studied the biogas potential in terms of energy production capacity in Portugal, based on the agricultural census of 1999 and 2009 data.

Within the agricultural sector, activities that have more potential in terms of biogas production are those related with cattle and pigs, due to the quantity and the chemical composition of wastes produced by those animals.

One important aspect that needs to be studied is the number of animals existing in Portugal and the variation occurred in the last ten years, for the purpose of understanding if there are sufficient and sustainable conditions for energy production. Based on the results presented by the agricultural census of 1999 and 2009 [9, 10] it was possible to know the number of animals and the evolution that occurred - Tables II and III.

Table II. – Number of animals in 1999

	Pigs	Cattle heads
Number of animals	2.418.426	1.415.188

Table III. – Number of animals in 2009

	Pigs	Cattle heads
Number of animals	1.913.000	1.430.000

The number of pigs decreased and the number of cattle animals remained practically constant. However, at a farm level, if the number of animals is too low, exploitation of biogas is not feasible. For that reason we considered only farms with a minimum of 200 pigs or 50 cattle heads [7]. Using these criteria, the number of animals with real potential to produce biogas in Portugal is reduced as presented in tables IV and V, as animals that were part of small agricultural exploitations were removed from data.

Table IV. – Number of animals with capacity to produce biogas in 1999

	Pigs	Cattle heads
Number of animals	1.832.619	794.793

Table V. – Number of animals with capacity to produce biogas in 2009

	Pigs	Cattle heads
Number of animals	1.568.660	980.000

Biogas can be produced from any organic matter by anaerobic bacteria digestion under appropriated conditions. Based on the average quantity of daily wastes produced by pigs, oxen and cows [7], and on the conversion efficiency into biogas [8], the value of biogas produced by each animal was calculated - table VI.

Table VI. –Average biogas produced by animals

	Pigs	Cattle heads
Body weight (kg)	50	500
Daily excrete (% of body weight)	10	5
Total of solids (%)	5,5	8,5
Volatile solids (%)	75	80
Biogas yield (m^3/kg)	0,45	0,28
Biogas (m^3/day/animal)	0,093	0,571

As expected, oxen and cows excrete more organic matter, and because of that cattle farms with those kind of animals have more potential to produce biogas. For this reason capacity to produce biogas is dependent on the number and kind of animals of the farm.

Based on data provided by tables IV and V it is possible to calculate the Portuguese daily biogas capacity evolution between 1999 and 2009.

Results are presented on tables VII and VIII, for 1999 and 2009 respectively.

Table VII. – Biogas capacity production in 1999

	Pigs	Cattle heads
m^3	170.090	454.553

Table VIII. – Biogas capacity production in 2009

	Pigs	Cattle heads
m^3	145.591	559.580

In spite of the decrease on the total number of animals over 10 years, the number of oxen and cows increased, and based on data of table VI the capacity of biogas production increased in 2009.
The next equation was used to calculate the electric energy from biogas [7].

$$E_{elet} = m_{biogás} * PCI_{biogás} * \eta_{biodigestor} * (1 - f_{orgânico}) * \eta_{elet} \qquad (1)$$

where m_{biogas} represents the biogas flow, PCI_{biogas} is the lower calorific value of biogas (5,5 kWh), $\eta_{biodigestor}$ represents the biodigestor efficiency (85%), $f_{orgânico}$ introduces the percentage of organic matter used by bacteria for their own growth (5%), and η_{elet} is the electric efficiency (31%).
Equation 1 was used to calculate the electric energy that could be produced if all biogas were used, resulting in table IX for 1999 and 2009.

Table IX. – Total electric energy production capacity

	1999	2009
Energy (GWh/year)	319	356

We can conclude that in 2009 356 GWh of electric energy from biogas could have been produced, which is 2,5 times greater than the total electric energy produced by photovoltaic systems in Portugal in the same year [12].

4. Case Study

The case study is base on a small farm, located near Braga, in Northern Portugal.
The cattle farm activity started in 1999, for the production of milk. Today the farm holds 80 animals, 60 of which are used for milk production. Based on the work developed in [11], where chemical properties of animal wastes were studied, it was concluded that the diary production of biogas in the farm is 78,4 m^3. Milk collection is made twice a day, with the interval of 12 hours. Usually, first collection starts at 7:30 am, and lasts at least 2 hours.
As a way of studying the electrical energy consumption, and because the energy bills available for analysis were not sufficient, an energy analyzer was put in place, with the objective of measuring the electrical energy consumption of the cattle farm. The results are shown in figure 3.

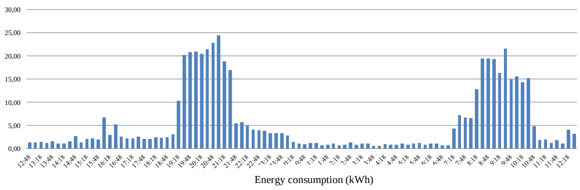

Fig. 3. Electrical energy consumption

From figure 3 it is possible to understand the farm's energy consumption profile, and it is clear that there are two power peaks, related with milk collection periods.

A. Biogas central design

The design of a biogas unit for production of electrical energy is divided in three stages:

- Location and construction of the biodigestor;
- Location and implementation of cogeneration equipment;
- Connection between components and the grid.

Based on data provided by the cattle farm owner, 100 m^3 of animal wastes are produced every two months. Taking into account the necessary space, it was suggested the construction of a biodigestor with the following characteristics:

- Type of biodigestor: continuous supply;
- Length: 25 m;
- Width: 2,5 m;
- Heigth: 2,6 m;
- Construction costs: 8.000 €.

The suggested solution implies the installation of two separate equipments, forming a cogeneration unit. One unit uses biogas to produce electrical energy, and the other unit, attached to the first, uses the exhaust gases produced by the biogas burn.
The equipment chosen for this purpose was the Camda 25kW Biogas Genset KDGH25-GZ model, whose characteristics are presented in table X.

Table X. – General characteristics of Genset KDGH25-GZ

Model	Power(Kw)	Motor	Generator	Biogas flow (m^3/h)	Cost (€)
KDGH25	25	HG4B	LSA42.2L9	16,7	9931

To get use of thermal energy produced by the biogas combustion process it is necessary to attach another equipment to the equipment described before. The selected model was Camda KD-HP-30 Cogeneration System, which has an effective cost of 1.950 €.

The location of the referred equipment was chosen based on terrain characteristics and proximity to the biodigestor.
The monetary values presented include all works needed to the installation and use of equipments.

B. Economic feasibility analysis

Several scenarios were taken into account to study the economic feasibility of the project. The Portuguese legislation takes in two scenarios for this kind of energy production projects: one is aimed at connecting power to the electrical grid, and the other is aimed at self-consumption.
Based on the Portuguese electrical tariff applied to the case study farm, and on the cogeneration system characteristics, it was concluded that:

- average electrical energy tariff: 0,13 €/kWh;
- equipment must work during the milk collection period, which is 4,7 hours a day, according to figure 3.

Biogas production has operation and maintenance costs associated. To this specific case study, annual costs involved were 379 €/year, due to the maintenance and operation of central unit production, biogas network and electrical generator machine. This value will be used in the economic analysis, corrected by the inflation rate over 15 years.
Taken into account all the values, the production of biogas has a cost around 1,03 €/day, for the production of 78,4 m^3/day, which generates a cost of 0,013 €/m^3 for the production of biogas.
The two scenarios will be now analysed as a way to show the best economic approach to this biogas unit.

a. Self-consumption of the generated electric energy

This scenario assumes that biogas produced by the anaerobic digestion of animal waste will be used to generate electric energy to be consumed inside the installation. Assuming that 28.616 m^3 of biogas can be produced every year, knowing the installation characteristics and using the Portuguese tariffs for energy production, is possible to calculate the income money per day, as well as per year, obtained by this installation:

- Income money: 21,42 €/day ------- 7.819 €/year;

With the replacement of electric energy obtained from the grid by the energy produced from the biogas installation, savings in other kinds of energy can also be achieved. An example of this is the savings in diesel used for hot water production, which was determined to be about 250 liters every two months. Using the value of 1,5 €/liter, annual savings of diesel are estimated in about 2.250 €/year.
Having into account all the values previously calculated, an economic analysis for the biogas installation unit can be made. Table X presents the results of the three most popular evaluation criteria used for economic analysis of investments, which are the Net Present Value (NPV), Internal Rate of Return (IRR) and Payback period (PB).

Table XI. – Economic analysis for the self-consumption energy scenario

Evaluation criteria	Value
NPV (€)	90.358,86
IRR (%)	61,62%
PB (years)	2,53

Results shown in table XI suggest the project is very interesting. IRR value is quite high, which means that this is a profitable project for the farm, which has a much lower cost of capital. Payback period is very small, which indicates that the project will "pay for itself" within 3 years. As a summary it is possible to conclude that this scenario is very interesting from the economic point of view.

b. Injection of generated electrical energy into the electrical grid

The other scenario that was considered is the injection of energy generated by the biogas installation into the grid. In such scenario, equipment will work for the heat process during milk collection periods, but the objective is to maximize the production of electric energy, using all available biogas. This means that the equipment needs to work more time during the day than in the case of the previous scenario.
Knowing that daily available biogas is 78,4 m^3 and that cogeneration equipment uses 16,7m^3/h, the period of work time is 4,74 h/day, or 1.714 h/year.
The equipment needed for this scenario is similar to the one of the previous scenario, meaning that investment values are more or less the same, but is necessary to pay a fee for installation licensing of around 4.000 €.
As a result, the total investment on assets to be considered increases to 23.881 €.
According to the Portuguese legislation for renewable energy production units the applicable base tariff is 250 €/MWh, being this value reduced 7% every year. The tariff value varies accordingly to the kind of the primary energy used. For biogas installations the tariff value is 60% of the base tariff value. The resulting economic evaluation generates the results shown in Table XII.

Table XII. – Economic analysis for the grid energy injection scenario

Evaluation criteria	Value
NPV (€)	56.520,86 €
IRR (%)	43,62%
PB (years)	3,43

Again, this scenario suggests that the approach is profitable, and the payback period still short, under 4 years.
Comparing results presented in Tables XI and XII it is possible to conclude that the two scenarios are interesting and have good economic indicators. However, the first scenario – generating energy for self-consumption – is better by all economic measures.

C. Sensibility Analysis

Having selected the first scenario, the production of electric energy from biogas for self-consumption, a sensibility analysis was made, to determine the impact of variations of three factors:

i. variation of biogas availability (less 15% of biogas production);

ii. variation on project discount rate (2% more and 2% less);

iii. increase of VAT tax applied to electric energy. (increase from 6% to 13%, and from 6% to 23%).

Results obtained by this sensibility analysis allow us to conclude that the project is still economically feasible.
The reduction of biogas production in 15%, leads to a reduction of only 13,3% in NPV. A correction of +2% in the project discount rate induces a reduction of 14,6% in NPV, whereas a reduction of 2% in the same discount rate leads to an increase of 17,9% in NPV.
The increase of taxes on energy prices improves the NPV. If VAT is increased to 13% the increase in NPV is 6%; if it is increased 23%, NPV improves 15%.
This analysis stresses the advantages of the project and shows that even for less optimistic scenarios economic feasibility is not at risk.

5. Conclusion

The use of energy generated from biogas has a lot of advantages. It contributes to the reduction of greenhouse gases (GHG) in two ways. Firstly, by avoiding the inherent gases produced from the anaerobic sludge treatment process, and because the energy produced locally does not need to be generated in large and usually pollutant power facilities.
For the purpose of economically evaluating a project of cogeneration, using as primary energy the animal waste produced in cattle farms' installations, two scenarios were considered. One scenario assumed that all energy produced is consumed by the cattle farm installation itself, helping on reducing the amount supplied by the electrical grid – and the respective invoice. The other scenario was focused on generating energy to inject in the electrical grid.
From the economic point of view, both scenarios proved very interesting, though producing energy for self-consumption revealed itself more profitable.
As a way to understand how varying critical parameters impact on the economic indicators, such as the reduction of biogas production or the change in the project discount rate used in the analysis, or even the change in taxes applied to the electric energy tariff, a sensibility analysis was made. Even under pessimistic scenarios, the obtained results still show that producing energy using biogas is a economically feasible.
Taken into account the number of cattle farms existing in Portugal, is possible to conclude that biogas can and should to be more exploited by small cattle farm owners, even considering grouping some of them and creating a big unit for treatment of animal waste and use of the anaerobic sludge treatment process to produce electrical energy.

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