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Economic feasibility study of a small-scale biogas plant using a two-stage process and a fixed bio-film reactor for a cost-efficient production

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Abstract

European and Italian incentive schemes promote small-scale biogas plant distribution using different types of biological and agricultural wastes as feedstock. A feed in tariff system is used in most of the European Union countries, and the incentive is paid on top of the market price capped at a maximum amount sold.

The proposed study explores the feasibility of two-stage biogas plants for small-scale CHP, based on a two-phase bio-film process partially tested during the Biowalk4Biofuels (B4B) FP7 project implementing an Anaerobic Digestion (AD) based on a rotating biological contactor thus able to combine significant yields and reduced volume. The project developed a small pre-industrial biogas plant implementing a recovered 45 kWel CHP unit with 95 kWth thermal power. In the two-stage process, a high-temperature hydrolysis phase was followed by a continuously stirred methanogenesis bioreactor equipped with a rotating biological contactor. Main process performances were related to Organic Load Rate (OLR) up to 15 kg VS/m3; the overall reactor volume was 70 m3 for expected biogas production of 25 Nm3/h.

Specifically, the aim of the present article is to address the use of the results and outcomes from some laboratory tests verified by the B4B system to model an overall feasibility evaluation. This allows to explore theoretical and economic feasibility of two ideal plants characterized by a 50 and 150 Nm3/h biogas production based on the overall system performances implementing a fixed biofilm for enhancing methanogenesis process. The feasibility study for the 50 Nm^3/h biogas plants (equivalent to 100 kWel) shows profitable results, as well as evaluation of the 150 Nm^3/h plants (300 kWe), that represent the biggest size for Italian incentives aimed at "small size" biogas plants.

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Keywords: RBC; biofilm; anaerobic digestion; hydrolisys; small scale plants; biogas; CHP; feed in tariff

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1. Introduction

Italian legislation has proposed an incentive scheme for the production of renewable energy from biogas that rewards the creation of small size plants [1]. The attention is focused on small- and medium-sized agricultural districts powered by agricultural waste. The aim of the Italian Directive on promotion and incentives for energy production from renewable sources [1] is to mitigate the environmental impact of crop-based energy production pathways of industrial plants from an overall sustainability perspective.

Feed-in tariffs (FIT) are one of the well-known and widely implemented renewable electricity (RES-E) support mechanisms in European countries. Nevertheless, there is a large range of individual FIT policies and ways of applications [2] like:

- Fixed-price vs. premium tariff (Denmark, Cyprus);
- Cost allocation;
- Cost containment (Cyprus, Estonia, Ireland, Latvia, Portugal, and Spain);
- Contract duration;
- Tariff amount;
- Digression rate.

In Latvia, for instance, RES-E is promoted within the feed-in tariff system involving a complex support system, which also includes elements of a quota system and tenders [3]. The FIT is calculated differently depending on the type of RES sources (i.e. biomass, biogas, wind and solar) and type of technology (mainly addressed to maximal capacity limitations). The FIT support level is implicitly considering natural gas tariff approved by the Regulatory Authority of Latvia [4].

The main environmental and economic hot-spots to be mitigated can be identified as follows:

- High consumption of water resources;
- Use of synthetic chemical fertilizers;
- Optimization and lowering of energy footprint for biomass cultivation and harvesting;
- Discharges of nitrogen compounds in areas adjacent to the plant;
- Transition from agricultural crops to energy crops.

Several LCA studies point out that the use of biological and agricultural waste instead of dedicated energy crops is beneficial for the overall environmental sustainability of bio-energy conversion roots [5, 6].

Nevertheless, the technology for these types of installations is not fully exploited in the market; the main problems are related to difficulties encountered when plants are fed mainly by waste biomass instead of conventional energy crops, or very specific wastes, such as cattle manure. Specifically, compatibility problems arise when biomass characterized by high nitrogen content and biomass characterized by high lipid content is used [5, 6].

In order to seriously improve biogas technology with the aim to reduce environmental impacts and to match the needs of small systems to be installed in small to medium size agricultural districts, the key problems of complex biomass disposal must be solved. A possible solution for these needs can be given by the use of technologically advanced systems able to maximize the biological activity and yield of anaerobic digestion processes.

This study presents the results of a system that combines two of the most technologically advanced solutions: two-stage AD process (instead of one stage) and methanogenesis process realized in a Continuously Stirred Tank Reactor (CSTR) equipped with a Rotating Biological Contactor (RBC) [7].

A hydrolytic thermal pre-treatment prior to methanogenesis is beneficial to solubilize suspended solids, reducing the volatile solids from 1.9 % up to 6 % in comparison with the conventional monophasic systems [8]. The effect of a hyper-thermophilic (70 °C) pre-treatment step on the thermophilic (55 °C) anaerobic digestion resulted in a 12 % higher organic suspended solid removal than the one-step thermophilic process [9]. Volatile Fatty Acids (VFA) and dissolved solids are more easily assimilated by methanogenic bacteria with respect to original molecules, increasing the entire biogas production process yield. It has been demonstrated that the two-stage biomethane production process is 11 % higher when treating primary sludge, and up to 37 % higher when treating secondary sludge [10].

A Rotating Biological Contactor (RBC) offers an alternative technology to the conventional activated sludge process. The RBC structure has a very high specific surface (in terms of m^2available surface/m^3digester volume, 250 m^2/m^3 of available surface). Such a large surface offers larger space for bacterial colonies, in fact creating a bio-film. A bigger bacterial population per each reactor's volume unit results in enhanced digester performance, possibly increasing the OLR and reducing the treatment time with an overall economic benefit for the capital costs of the reactor.

Within the Biowalk4Biofuels FP7a fixed biomass contactor rotor was proposed for a pre-industrial demonstration plant; this rotor employs a bio-film based technology, where an internal rotation systems is driven by limited volumes of air blown in beneath the contactor's frame. The turbulence caused by the movement continuously mixes the liquid substrate, promoting contact and exchanges with the biofilm. The usable surface for the development of bio-films is about 250 m^2/m^3 of the rotor volume. The use of a two-step RBCs process can expect criticism due to adhesion of Long Chain Fatty Acids (LCFA) to active biomass washout, microbial communities inhibition and sludge flotation improving process performances in presence of oils [11, 12].

This technology was tested firstly, in a lab-scale 100-liter prototype; subsequently, it was implemented in the Biowalk4Biofuels plant with a total reactor volume of 70 m^3.

Prototypal tests have led to the definition of a mathematical model that was used for the extrapolation of the data, which resulted in an economic feasibility analysis for commercial scale plants.

In this study, the technology is briefly discussed; the experimental phase and the mathematical model obtained are presented. Finally, a case study is reported. It considers two reactors able to power 100 kW and 300 kW CHP engines, respectively: the first is the minimum size that allows an acceptable economic return; the second is the larger size able to access the best incentive conditions according to Italian legislation.

2. Materials & Methods

Tests were carried out in a 100-litre prototype to verify a hyper-thermophile and completely stirred 40 litres hydrolysis pre-treatmet phase at 60 – 70 °C, followed by a 60 litres RBCs bio-film acidification/methanogenesis reactor. The methanogenesis reactor had a total volume of 60 litres and was equipped with an RBC with a total volume of 35 litres and an equivalent surface of 114 m^2/m^3 (available surface is 4 m^2). Once started up, the prototype was continuously fed with 3 litres/day of Olive Mill Wastewater (OMW) that presented a pH of 4.7, COD of 150.000 mg/l, TKN of 460 mg/l and 2.6 g/l of phenols measured according to the Folin Ciocalteau (FC) method and expressed as Gallic acid.

Daily COD input was about 450 000 mg/day with an OLR of 112.500 mg_{COD}/m^2_{RBC}/day. Assuming the following average composition of Fats $C_{57}H_{104}O_6$, Protein $C_5H_7NO_2$ and Carbohydrates $C_6H_{10}O_5$, a simplified conversion factor of 1 between COD and VS has been used. The OLR fed to the methanogenesis RBC is of 112.5 g_{VS}/m^2_{RBC}/day equivalent to 12.8 kg_{VS}/m^3/day [13, 14].

The tests carried out showed that it is possible to reduce OMW COD input from 100 000 mg/l to 16.000 mg/l. Preliminary test performances reached up to 13 kg VS/m^3/day after two weeks of continuous feeding. Prototypal tests lasted more than 60 days, during which a few plant problems were solved (biomass mix, load and fluid dynamics problems): they were fully operational for 15 days.

It would have needed at least two months of continuous feeding to achieve plant regime and maximum load capacity. Nabil Zouari et Al [13] found that intermittent feeding and nitrogen addition are good strategies to promote both the recovery of inhibited reactors due to heavy OMW load and the mineralization of long chain fatty acids (LCFA).

During the tests, the OMW was the only input biomass that leads to reaching a C/N ratio up to 32 that can inhibit AD process. Furthermore, bacterial colonization of the structure rotor occupied only a part of the available surface.

A second experimental step on this technology was performed on the Biowalk4Biofuels pre-industrial scale plant, with a two stage RBC anaerobic digester. The plant was designed for 25 m^3/h biogas production, which was further sent to a 45 kW_{el} CHP unit. The digester was tested with a mix of biomasses, including OMW, manure, algae and corn.

The experiment was useful to determine balanced feed mixes in order to avoid clogging and biochemical instabilities to the process and to define actual equipment costs, operational and maintenance burdens. Those indications led to economic evaluation that is presented in the following paragraphs.

2.1. Mathematical Model

In the examined 2-stage biodigestor, it is possible to identify two main conversion pathways: an initial portion of the biomass is converted into Volatile Fatty Acids (VFA) during the hydrolysis process; further VFA can be easily processed by methanogen bacteria allowing the direct production of biomethane.

A share of the initial biomass is not directly converted into VFA in the hydrolysis process, so it enters the methanogenesis reactor, unprocessed. In the methanogenesis reactor, the conventional conversion of Volatile Solids (VS) into biogas also occurs, with common digestion dynamics.

The set of equations and parameters used in the mathematical modelling follow. Equations and parameters are derived from literature reviews as well as from experimental evidences obtained in the described experiments.

Volatile Fatty Acids production during hyper thermophilic hydrolysis phase:

$$VFA^i = VS^i_{hy} \cdot c_{hy} \tag{1}$$

where

VFA^i daily Volatile Fatty Acids production rate in the *i*-stage of the hydrolysis [kg_{VFA}/day];

VS^i_{hy} daily amount of Volatile Solids introduced in the *i*-stage of hydrolysis reactor [kg_{VS}/day];

c_{hy} conversion rate of Volatile Solids in Volatile Fatty Acids [kg_{VFA}/ kg_{VS}].

Conversion of Volatile Solids into Biogas in methanogenesis phase reactor:

$$BG^{VS}_{met} = VS_{met} \cdot Y^{BG}_{met} \tag{2}$$

where

BG^{VS}_{met} daily biogas production from Volatile Solids conversion [m^3_{BG}/day];

VS_{met} daily amount of Volatile Solids introduced in methanogenesis reactor [kg_{VS}/day];

Y^{BG}_{met} biogas yield in methanogenesis reactor [m^3_{BG}/kg_{VS}].

Conversion of Volatile Fatty Acids into Biogas in methanogenesis phase reactor:

$$BG^{VFA}_{met} = VFA_{met} \cdot c_{met} \tag{3}$$

where

BG^{VFA}_{met} daily biogas production from Volatile Fatty Acids conversion [m^3_{BG}/day];

VFA_{met} daily amount of Volatile Fatty Acids introduced [kg_{VS}/day];

c_{met} conversion rate of Volatile Fatty Acids in biogas [m^3_{CH4}/kg_{VFA}].

Table 1. Parameters used in the paper.

Parameter	Value	Source
c_{hy}	0.05 [kg_{VFA}/ kg_{VS}];	[15, 16]
Y^{BG}_{met}	0.55 [m^3_{BG}/kg_{VS}];	[17, 18]
c_{met}	0.67 [m^3_{CH4}/kg_{VFA}]	[16, 19, 20]

Goncalves [20] in batch experiments found that the ratio between LCFA degraded and produced methane is in the range of 0.58 and 0.91; while LCFA concentration was in a range between 0.16 and 0.20 $g_{COD\text{-}LCFA}$/g/VS. Kivaisi and Mtila [21] experienced 100 % conversion efficiency of the VFA. Biogas produced was as with a methane content that varied from 36 % (steady-state reactor) to 80 % in an Upflow Anaerobic Sludge Blanket (UASB) reactor. They found that with an OLR of 15.4 g_{VS}/l/d, the yield of VFA is 8.34 mmolg. Considering that more than

70 % of VFA is composed by acetic acid with a molecular weight of 60.05 g/mol, it is possible to assume a conservative estimation of 60.05 g/molx 8.34 mmol/g that is equal to 0.5 g VFA/g VS.

Assuming a conservative estimation of 100 % conversion efficiency of VFA in biogas with 70 % methane content, 10 % less respect to Kivaisi results [21], it is possible to assume that: 1 kg_{VFA}=1 kg of biogas.

At 40 °C and 110 mbar (reactor internal pressure) biogas density corresponds to 1.04 kg/mc equal to 0.96 mc biogas per kg of VFA. Considering 70 % methane content, it is possible to assume a production of 0.67 m^3_{CH4}/kg_{VFA}.

2.2. Mass Balances

On the basis of the theoretical model, an economic evaluation has been performed for two plant sizes: double (50 Nm^3/h) and six times (150 Nm^3/h) bigger than the B4B plant prototype fed by: manure; OMW and Olive Pomace (OP).

Based on the analyses carried out during the B4B project, the typical hen manure to be fed to the plant has the following characteristics: DM 23.8 % of which 70.59 % VS; TKN is 16.300 mg/kg; Organic Carbon is 7.9 % by weight and inorganic fraction is 7 % by weight determined by APHA-2540G/12 standard method. The fraction of water-soluble phosphorus P_2O_5 is about 3.0 % of DM content derived from primary data collected from the pilot plant on March 2013.

OMW is characterised by a dry residue that varies between 5 % and 25 % (6 – 20 g/l), represented by 80 to 90 % organic matter and 10 – 20 % inorganic salts that represent the 0.4 – 1.5 % of dry weight of which phosphates, sulphates and chlorides represent the 80 % [22].

The following parameters were considered for this study: D.M. 8 % of which 86 % VS; TKN and phosphate are respectively about 1% and 0.2 % of DM content by weight.

The Olive Pomace (OP) is a solid by-product obtained during olive oil extraction process; it exhibits high variability depending on the type of process. OP moisture content varies from 24 up to 80 %, while residual oil content can range from 3.5 to 8 %. Whereas C/N ratio is in a range from 45 up to 70.

The following parameters were considered for this study: DM 35 % of which 80 % VS; TKN and phosphate are respectively 1 % and 0.4 % of DM content by weight (average pilot plant values).

Based on the biomass characteristics, the following mass balance for a 100 kW_{el} and 300 kW_{el} plant were determined.

Table 2. Biomass mix to fed the plants.

Plant size	Hen manure	OMW	OP	Resulting mix	C/N ratio	Humidity content
	Ton/day	Ton/day	Ton/day	Ton/day	-	%
100 kW_{el}	2.3	16.7	3.2	22.4	23	88
300 kW_{el}	8.5	33.4	8.2	50.1	20	86

Feeding needs for the 50 Nm^3/h (100 kW_{el}) and 150 Nm^3/h (300 kW_{el}) plants are respectively met by: 3 medium-sized olive mills and a poultry farm of 16 – 20,000 hens; and 9 medium-sized olive mills and a poultry farm of 58 – 60,000 hens.

On the basis of the process described above (RBC and hydrolysis pre-treatment) with a maximum OLR of 40 kg $VS/m^3/day$, it is possible to define the following volumes for 50 and 150 mc/h biogas plants: 63 m^3 and 150 m^3 with regard to the methanogenesis section; 47 m^3 and 112.5 m^3 with regard to the hydrolysis section.

2.3. Economic Evaluation

The economic evaluation has been done through a Net Present Value Analysis taking into account a cost-benefit perspective.

The two-phase fixed biofilm plant costs can be considered in line with market prices and sum up at about 7,500 €/kW installed for turn-key plants with capacity up to 100 kWe, and 6,800 €/kW for turn-key plants with capacity up to 300 kWe (comprehensive of the safety and water treatment system).

Technical economic evaluations take into consideration the following parameters: feed-in tariff 236 €/MWh (for biogas plants of less than 300 kW_{el}); from the sixteenth year onward, energy is dispatched in the free energy market with an average cost of 0.08 €/kWh. Internal consumption lump-sum equal to 11 % of production; equivalent operational time is considered 8200 annual working hours.

Plant revenues are provided by selling net electricity with feed in tariffs and 40 % of solid digestate (20% DM) at 15 €/ton. Table 3 reports the main economic information implemented in the study.

Table 3. Input data for the economic evaluation.

Description	M.U.	100 kWe	300 kWe
Biogas production	m^3/h	50	150
Investment cost	€	742’500	2’033’200’
Equity	€	163’350	447’304’
Inflation	%	6	6
Actualization rate	%	3	3
Net energy production	MWh/year	722	2’182
Compost sold	Ton/year	277	769
Energy price (years 1–15)	€/MWh	0,236	0,236
Energy price (years 16–20) [19]	€/MWh	0,08	0,08
Compost price	€/tonn	15	15
Revenues from energy (years 1–15)	€/year	170’510	514’976
Revenues from energy (years 16–20)	€/year	57’800	174’568
Revenues from compost	€/year	4’154	11’532
O&M costs	€/year	58’472	149’954
Installation cost	€/year	86’615	237’182
Cumulative Cash Flow	€	726’11	2’703’523
PBT	years	8	7
EBITDA	€/year	116’192	376’554
NPV (i=3 %, 20 years)	€	430’103	1’726’789

3. Results

Plant with a biogas yields of 50 m^3/h and 150 m^3/h biogas plants are able to power, respectively, 100 kW_{el} and 300 kW_{el} CHP engines.

Operational costs are related to: loading/unloading of biomass; supplying biomass from the district to the plant, run the plant, regular maintenance, insurance, personnel and handling costs. For both plants, the investment costs are composed of 80 % bank loan and 20 % equity with 6 % interest rate and 9 % depreciation cost. Economic results are shown in Fig. 1.

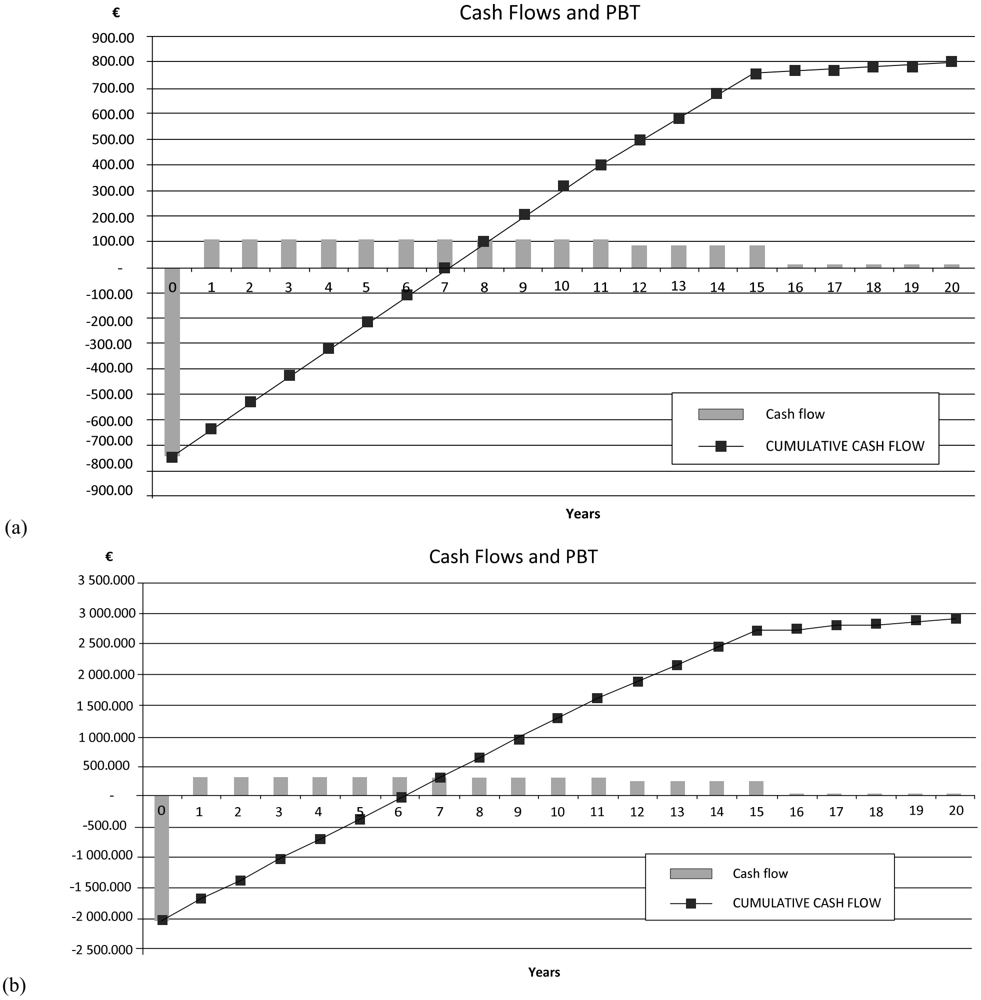

Fig. 1. Economic performance for a 100 (a) and 300 kW_{el} (b) plant (discounting rate not considered in these figures).

4. Conclusion

The experimental testing of a two-stage AD prototype of 100 l capacity, fed by OMW with a rate of 13 kg $VS/m^3/day$, has shown a COD reduction of approximately 84 % respect to input COD that indicate good bio-film acclimation to OMW. The literature review proposed in this study underpins effectiveness of the use of biofilm and hydrolysis pre-treatment for enhancing methanogenesis process.

On the other hand, fixed bio-film technology also appears to be proficient, increasing the effectiveness of the methanogenesis digester equipped with an RBC. Effectiveness is clearly showed by reduced volumes: 70 m^3 digester volume for a 45 kW_{el} CHP engine, as installed in B4B plant, is an extremely low and cost-effective result. Conventional single-stage digester, not equipped with RBC, needs ten times higher volume. The achievement is synthesized in the parameter OLR, that indicates the amount of degradable biomass the digester is able to treat daily. The present technology could be able to reach an OLR 40 gVS/l/d, which is 5 times higher than alternative technologies, however more research is required to prove this hypothesis.

Based on some results validated within the implementation of the pilot plant of Biowalk4Biofuels project, it has been possible to obtain a cost-benefit mathematical model in order to evaluate Net Present Value (NPV) and PBT of two theoretical two-stage AD processes based on RBCs' biofilm technologies.

The results obtained in the study, assuming that the biogas is used to power CHP units of 100 kW_{el} and 300 kW_{el}, show a payback time of 8 years and 7 years and a NPV of 430’103 € and 1’726’789 €, respectively.

The scenario is economically conservative, since it is based on the assumption of excluding revenues both from thermal heat and from incentives related to the nitrogen recovery from wastes.

The use of the two-stage biofilm-based reactors together with hydrolysis pre-treatment represents an innovative and feasible solution to reduce plant footprint and enhance treatment performances of by-products with high concentration of lipids.

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