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A Feasibility Study of a Mesophilic Anaerobic Biological Process Unit Installation in Attica, Greece

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***Abstract*— A feasibility study is presented of a possible mesophilic dry anaerobic digestion unit installation in Attica, which will manage 35600ton/y of fresh substrate of the source sorted organic fraction of solid municipal waste (SS-OFSMW). It consists of a pre-processing step (mechanical screening -cutting) and the main dry anaerobic biological treatment. For the main anaerobic digestion unit two configurations are taken into consideration. This study focuses on the calculation of the main characteristics of the biogas unit (reactor volume, biogas tank volume, CHP power) and gives average values of the unit input-output data. Results show that the mesophilic process can produce approximately 160m^3 of biogas per ton of fresh substrate, which is consistent with large-scale studies in the European Union. Also, a rough economic analysis of the unit is attempted. The investment cost will be around 9 -11M€ and the pay back of the investment about 5-7 years.**

***Index Terms*— anaerobic digestion, source-sourted organic fraction of solid municipal waste, dry digestion, mesophilic anaerobic degradation**

I. INTRODUCTION

Biogas production from agricultural, livestock, municipal and/or industrial waste is an alternative environmentally friendly energy solution. Biogas belongs to the renewable sources of energy and can replace fossil fuels in the electric and thermal energy production. It can also be used as fuel in vehicles. Biogas energetically is rated as the most efficient and environmentally beneficial technology because it reduces greenhouse gas emissions (Capetanios, 2012).

Anaerobic digestion is a process in which the organic matter with the aid of microorganisms, under anaerobic conditions, is converted to biogas (60-70% methane). Three main groups of microorganisms involved: fermenting bacteria, oxidation of organic acids bacteria and methanogens. The microorganisms decompose organic matter through a series of biochemical conversions for the production of methane and carbon dioxide. The determination of the theoretical and practical energy release rate of the produced methane is an important factor in optimizing the design of an installed anaerobic biological process and the efficient evaluation of economic benefit. There are numerous applications of anaerobic digestion in the case of wastewater, sludge, solid waste, agricultural applications and livestock waste. These use different types of reactors and different operating conditions in order to maximize the energy effect, reduce fermentation time and achieve anaerobic digestion system stability (Angelidaki et al, 2011).

The various anaerobic biological process techniques and technologies are distinguished by their respective operational factors (eg continuity of operation: batch-continuous, operating temperature: psychrophilic, mesophilic, thermophilic,), the design of the reactor (eg Plug-flow, complete-mix, covered lagoons) and the solid content of the waste (wet-dry substrate) (Deublein and Steinhauser, 2008, Weiland, 2010).

The dry substrate anaerobic digestion regards waste solids content higher than 15%. On the contrary the wet substrate anaerobic digestion manages substrates with solid concentration of 0.5% to 15%. Manure, mud and food industry waste generally are treated by wet substrate anaerobic digestion. The organic portion of municipal waste and lignocellulosic biomass (agricultural waste and energy crops) are processed through dry substrate technology. The technique of the dry substrate is advantageous in the reactor size (smaller thus smaller reactor capacity requirements), the lower energy requirements for heating the reactor and stirring the contents. In 2011 the dry substrate anaerobic biological process facilities occupied 54% of the total anaerobic digestion facilities in Europe, a number that has gradually been increased since 2005 (Abbasi et al, 2012, De Baere and Mattheeuws, 2010, Lissens et al, 2001, Vandevivere et al, 1999).

The global population growth and continuously improving quality of life for the last 30 years has resulted in a corresponding increase in human waste, mostly municipal. It is estimated that the annual increase in waste amounts to 2-3%. Indeed in Europe it is produced more than 3Gtons/year of waste. Landfilling applied as the main method of waste management is a source of aesthetic (odors), health (skin infections, respiratory problems, etc.) and environmental (water pollution, soil erosion, greenhouse gases) problems (European bioplastics, 2010).

Anaerobic digestion as a preprocessing step before waste composting or landfill has many advantages, such as minimizing mass and volume, neutralization of biological and biochemical processes in order to avoid gas and odor emissions in the next stages of waste management, reduction of landfill sites and energy production in the form of biogas (Capetanios, 2012).

This paper consists of a techno-economically study of a possible mesophilic anaerobic biological degradation unit installation in Attica, which will manage 35600ton/y of fresh substrate of the source sorted organic fraction of solid municipal waste (SS-OFSMW). It consists of a pre-processing step (mechanical screening -cutting) and the main dry anaerobic biological treatment. Two cases are presented. In Case 1 the main anaerobic treatment consists of

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one bioreactor. In the second configuration (Case 2) the preprocessed substrate is fed to two bioreactors. Case 2 is chosen to be studied because reduces the possibility of failure of the entire unit. The anaerobic digestion unit is planned to be near an existing compost unit in Attica region. The compost unit will treat the digestate, so this study focuses only on the anaerobic biological degradation unit operation.

In general feasibility studies are valuable because they can verify the validity of lab experiments and small scale applications, while at the same time consists of a necessary simulation tool for possible large scale applications. So every feasibility study concerns a specific possible event taking into account the specific characteristics of the application.

II. Materials and Methods

2.1 The situation of municipal solid waste in Attica

Household waste varies in composition and quantity. The factors affecting these variables are the standard of living, consumption patterns, mobility of the population and the seasons of the year. It should be noted that commercial sources of waste are primarily packaging material.

The substantial changes in the composition of the waste from the 80s to today is the reduction of biodegradable materials and the increase of plastic and paper (EEDSA website). The largest percentage of Attica municipal waste still consists of biodegradable materials, although to a lesser extent now. Waste is estimated to contain at approximately the same levels as in 80s glass, metals, aggregates, leather, wood, rubber, while the remainder is composed of various other materials (Fig.1)

The organic fraction of municipal waste is categorized into mechanical sorted, source sorted and hand sorted. In Attica there is no policy to separate the organic fraction of municipal waste at source, as it happens in the European Union, although such approach is now under consideration (Athens biowaste website). Nevertheless for the purpose of this study was assumed that the organic fraction of municipal solid waste consists of source sorted waste.

2.2 Kinetic model

For the kinetic study the first-order model was selected (Mace et al, 2003).

The first-order model assumes that the concentration of biodegradable substrate S decreases according to the relation:

$$\frac{dS}{dt} = -kS \qquad [1]$$

where k the first order constant. Considering the relationship between S and the amount of methane produced (Chen-Hashimoto:

$$\frac{B_o - SMP}{B_o} = \frac{S}{S_o} \qquad [2],$$

where B_o the theoretical produced quantity of methane after infinite residence time in the bioreactor, SMP the quantity of methane in $m^3/kgVS_{in}$, S_o the initial substrate concentration), then the relationship [1] is transformed:

$$\frac{B_o - SMP}{B_o} = e^{-kt} \qquad [3]$$

The conservation of mass in a continuous bioreactor system with capacity V , that is fed with pace Q is written:

$$QS_o - QS = VkS \qquad [4]$$

Given that $HRT = V/Q$ (Hydraulic Retention Time) then eq.[4] is become:

$$\frac{1}{SMP} = \frac{1}{B_o} + \frac{1}{B_o kHRT} \qquad [5]$$

2.3 Design of the anaerobic digestion unit

It is assumed that the anaerobic biological treatment unit in Attica will manage an average of 100ton/d of fresh substrate from the source-sorted organic portion of municipal waste (household waste, food waste, garden waste, paper waste), which will be collected and subsequently be led to the anaerobic treatment plant.

This facility includes:

- The pre-processing unit, where undesirable constituents will be removed with mechanical screening. The chopping of the organic fraction will follow and the end product will be fed to the bioreactor/s.
- The processing unit includes one or two bioreactors, where anaerobic treatment of the organic fraction of waste, biogas production and its use for electricity generation will take place.

2.3.1 Preprocessing unit

The preprocessing step consists of a trench host, gantry crane for transferring material from the trench in a conveyor, mechanical screening and metals removal, shredder and a conveyor that will lead the product in the bioreactor/s (Fig.2).

The trench host

The garbage trucks will collect and transport solid waste from appropriate bins filled with biodegradable material that will meet the specifications (purity as regards impurities with unwanted materials). The discharge of garbage trucks will be in a trench host of biodegradable waste. It will be made of concrete and will receive load for at least two days. The capacity of the trench host will be $2d \times 100\frac{t}{d} \times {}^{1}\!/_{d_{waste}}$ plus 10% tolerance (with $d_{waste} = 0.55 - 0.63\,{}^{ton}\!/_{m^3}$.) So the trench will have a capacity of $400-349m^3$. The base of the trench will have little inclination so that the anticipated quantities of liquids end up on a grate in the center of the trench. Below the grate a plastic pipe leading to a well of will be installed. From there a pump will automatically feed the bioreactor.

Waste supply-Chopping

The feed will be made by a gantry crane, which will lead to a metal conveyor belt, followed by a mechanical screening of contaminants (plastics, glass, paper). After the screening, metals removal will take place. The contaminants are removed to avoid hindering the process of anaerobic biological degradation. Then through a metal film the waste concludes to a shredder, which applies a mild cutting (80-40μm) to the biodegradable material. The shredded biodegradable material will be fed to the bioreactor (or through a flow splitter that receives the output of the shredder unit collection, will be fed to the bioreactors).

2.3.2. Anaerobic Digestion unit

The anaerobic digestion unit will be supplied by the preprocessing unit. It will consist of:

Case 1: pumps mixing of substrate and recycling of leachate, one dry substrate bioreactor, biogas storage tank, biogas compressor and a heat and electricity generator (Fig. 3).

Case 2: pumps mixing of substrate and recycling of leachate, two dry substrate bioreactors, biogas storage tank, biogas compressor and a heat and electricity production unit (Fig.4). The organic substrate from the sorting line is mixed with hot steam and leachate from the bioreactor/s to achieve adequate solids concentration. Subsequently with the aid of the pump inlet the mixture is driven in the bioreactor/s. The produced biogas is stored in the tank, while part the biogas is compressed and injected into the bioreactor/s for stirring the content. Biogas from the storage tank is led to an electric power production unit. Part of the heat generated will warm the substrate and the bioreactor/s. The generated electricity will be fed into the national grid.
The technical characteristics of the anaerobic biological processing unit were calculated according to:

Bioreactor dimensions

The capacity of the bioreactor $V(m^3)$ was based on the equation:

$$V(m^3) = (substrate\ volume)(\frac{m^3}{d}) \times HRT(d) + 25\%\ tolerance \qquad [6]$$

Biogas storage tank

Given that there is an electricity and heat production unit installed, the capacity of the storage tank will not exceed 20-50% of the daily biogas production.
The electricity and heat production unit power

$$P_{el}(kW) = \frac{(anual\ mehane\ production\ in\ m^3) \times 10 \frac{kWh}{m^3}}{anual\ operation\ hours} \times (unit\ electric\ efficiency) + 25\%\ tolerance \quad [7]$$

2.3.3. Assumptions

For the mesophilic anaerobic digestion application the following assumptions were made:

1. The anaerobic biological processing unit will treat 36500 ton/y of fresh substrate of SS-OFSMW
2. Substrate with 33%TS and VS=78%TS
3. Methane potential: $\frac{0.4m^3 CH_4}{kgVS_{in}}$ (STP)
4. First order kinetic model with constant $k = 0.2 - 0.4d^{-1}$
5. HRT=26d
6. Biogas methane content 56%
7. TS reactor 23-25%
8. $T_{reactor}$=35°C
9. $VS_{reduction}$=51%
10. Annual CHP operation hours 7500h/y
11. Methane value 10kWh/m^3

RESULTS

In Table 1 the technical characteristics of the anaerobic digestion unit, for both case 1 and 2 are presented.
Table 2 shows input-output data of the mesophilic anaerobic biological process, that is going to treat 100ton/d of substrate with 33%TS. For case 2 each bioreactor will treat 50ton/d so its input-output data is half the values presented in Table 2.

DISCUSSION

The climate of Attica is ideal for mesophilic anaerobic biological degradation application. By this way the heat consumed for warming the substrate and the bioreactors will be reduced. Further thermophilic anaerobic biological degradation of the organic fraction of municipal waste may be inhibited due to high concentration of ammonia and fatty acids depending on the content of municipal waste in food waste.
The choice of a first order kinetic model was based on its simple and easy application. Also the first order model is used in the case of complex substrate like the case of the organic fraction of municipal waste and dry anaerobic biological degradation. Besides, this model has been successfully applied for biogas plants in Spain and Italy (Italy: Bassano, Treviso, Treni, Spain: Barcelona) (Bolzonella, 2006a, 2006b). The first-order constant and the maximum theoretical gain in methane have been calculated by Cecci et al for the three categories of municipal waste in the early 1990s (Cecci et al, 1991, Mata-Alvarez et al, 1992). The assumption of kinetic constant for source-sorted OFMSW is also consistent to (Mata-Alvarez et al, 2000). Actually the mean value between 0.2 and 0.4 d^{-1}, namely 0.3d^{-1} was used in this study. In general waste composition is the crucial factor in designing any anaerobic digestion unit. The proportions of food waste, garden waste and paper waste play an important role in simulating or calculating the biogas unit output result. Also nutritional habits determine food composition in fat, carbohydrates and proteins. All these affect biomethane output. The assumptions on waste composition were based on real large-scale experiment conducted in Italy (Bassano) in

2006 (Bolzonella, 2006b) and we believe that nutritional conditions and culture that have Greeks and Italians are similar.

Moreover the use of two bioreactors, in case 2, reduces the possibility of suspending the operation of the entire unit. If the operation of one bioreactor is inhibited the second bioreactor will operate.

According to Table 2 the mesophilic process can produce approximately 160m^3 of biogas per ton of fresh substrate. The results of the mesophilic process are consistent with large-scale studies in Italy and Spain. In Bassano, (Italy) reported biogas profit of 200m^3 per ton of fresh substrate in the mesophilic anaerobic digestion of the organic fraction of municipal waste (16ton/y, HRT:40-60d, 33% TS, 78% VS, OLR :4-6kgVS/m$^3_{reactor}$d). In Spain (Barcelona) Ecopark 2, produces approximately 157m^3 biogas per ton of fresh substrate (ECOPARK 2).

As far as electric energy production concerns, the aforementioned anaerobic biological treatment unit will produce almost 11641 MWh/y. Assuming an average electricity consumption of 3-4MWh/y/household$_{Athens}$ the annual produced electric energy from the anaerobic digestion unit could supply almost 4000-3000 households in the Municipality of Athens. So by treating the 28% of annual organic waste produced in Athens it can be covered the 1.3-1.8% of Athens municipality households electric energy demand. This percentage of energy cover seems small because Athens municipality population is about 665,000 people. In an area of 60,000 people the aforementioned covered households energy demand is translated to range between 15-20%.

So anaerobic digestion has a twofold benefit: solves the problem of waste management and produces energy from waste. Moreover compost is produced which is of a very good quality and can replace unhealthy chemical fertilizers.

4.1 Economical Aspects

For the economic analysis, concerning investment and operational cost of the anaerobic digestion unit presented in this paper, two mathematical formulas were taken into account:

Vallini et al (Bolzonella et al, 2005):

$$EC = 0.426V^{0.85}x10^{4}\ € \quad [8]$$

$$CC = 0.235V^{0.916}x10^{4}\ € \quad [9]$$

Where EC is the electro-mechanical equipment capital cost, CC the cost of civil work and V the bioreactor capacity in m^3. The total investment cost $EC + CC$ must then be increased a further 20% to consider the major costs for heat exchangers.

Tsilemou et al (2006):

$$Total\ investment\ cost = 34500x^{0.55}\ € \quad [10]$$

$$Operational\ cost = 17000x^{-0.6}\ €/ton \quad [11]$$

Where x the annual input substrate mass in tons. Equations [10] and [11] are valid when $2500 \leq x \leq \frac{100000ton}{y}$

Table 3 presents some economic data derived from the above formulas for both Case 1 and Case 2. Inflation effect from 2004 was taken into account. As it can be seen from Table 3 both formulas have similar results as far as total investment cost concerns.

The third column of each Case of Table 3 shows data that have been derived considering Eurozone recession rates and the economic situation in Greece the last four years. According to these the investment cost of the anaerobic digestion unit will be around 9 million euros for Case 1 and 11 million euros for Case 2. Operational cost for Case 1 approximates 32euros/ton and 37euros/ton for Case 2.

The anaerobic digestion unit will produce 31892kWh/d, which means 11640580kWh/y. If this energy is sold to the national grid then the annual profit of energy production will be around 2900000€/y (assuming a selling price of 0.25€/kWh that is valid now in Greece for biogas units treating agricultural and dairy waste (Law 3851/2010)). So taking into account operational cost from Table 3 the pay back of the investment will be around 5 years for Case 1 and 7 years for Case 2.

Conclusions

This paper consists of a techno-economically study of a possible anaerobic biological degradation unit installation in Attica, which will manage 35600ton/y of fresh substrate of the source sorted organic fraction of solid municipal waste (SS-OFSMW). It consists of a pre-processing step (mechanical screening-cutting) and the main anaerobic biological treatment. Two configurations are taken into consideration. Case 1 relies on one bioreactor while Case 2 consists of two small bioreactors. The mesophilic process can produce approximately 160m^3 of biogas per ton of fresh substrate and almost 11641 MWh/y. The pay back of the investment will be around 5-7 years.

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Figure Captions
Figure 1: Average composition of Attica municipal waste (data from 2003)
Figure 2: Pretreatment unit flowchart, the flow splitter (gray line) is for Case 2 where the anaerobic digestion unit is composed of two bioreactors
Figure 3: Schematic diagram of the anaerobic biological treatment plant, Case 1
Figure 4: Schematic diagram of the anaerobic biological treatment plant, Case 2

Figure 1

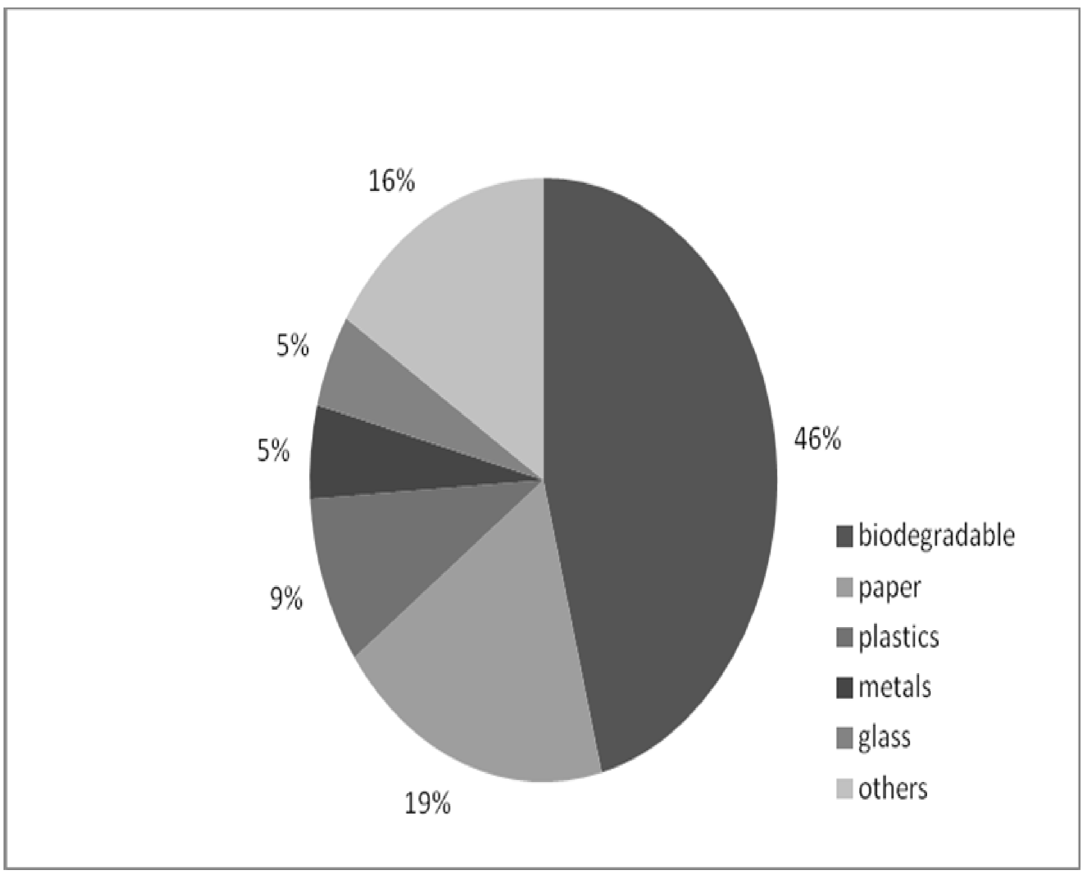

Figure 2

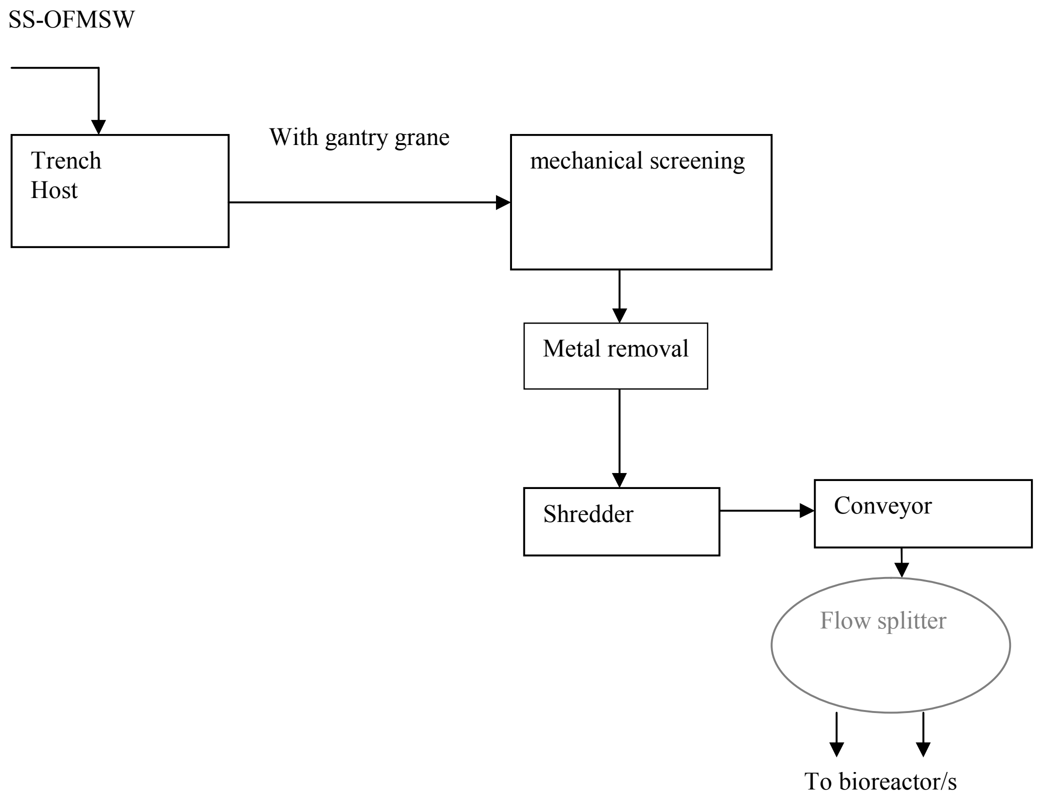

Figure 3

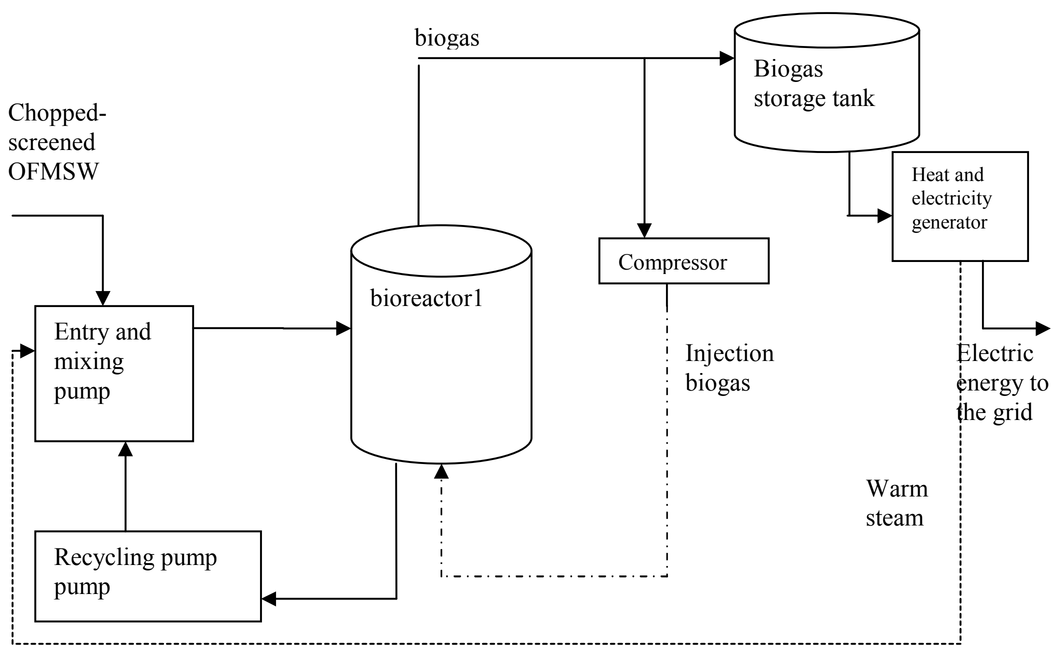

Figure 4

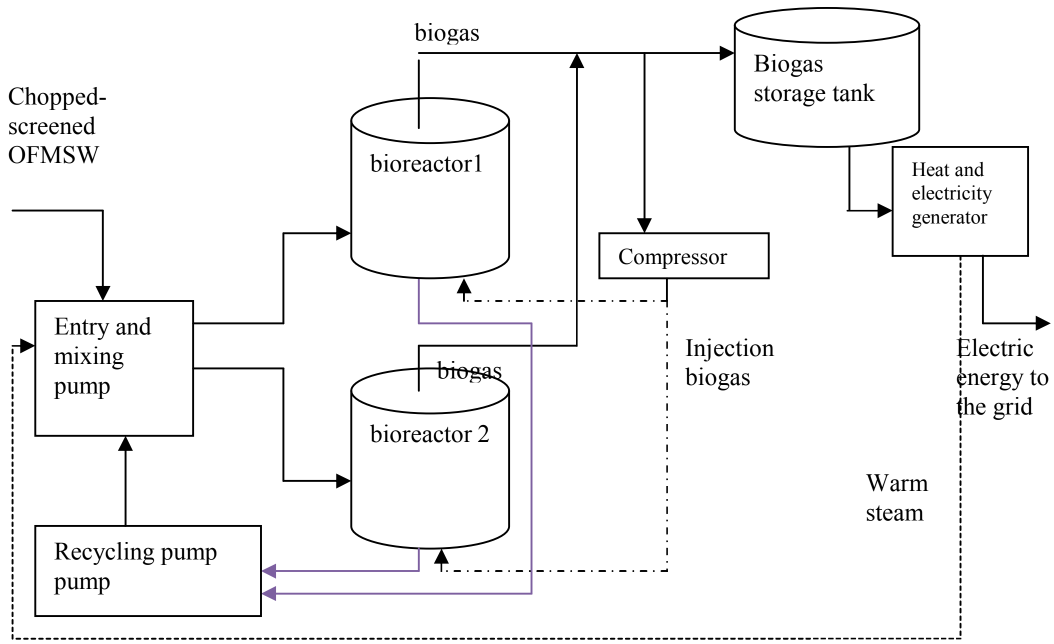

Table Captions

Table 1: Technical characteristics of the proposed anaerobic digestion unit for both case 1 and case 2

Table 2: Input-output data of the mesophylic anaerobic biological process that is going to treat 100ton/d of substrate with 33%TS

Table 3: Investment and operational costs for case1 and case 2

Table 1

Technical characteristics	**Case 1**	**Case 2**
Bioreactor capacity (m^3)	4700	2350(x2)
Biogas storage tank capacity (m^3)	3254	
CHP power (MW)	3.8	

Table 2

Mass input (kg/d)	100000
VS input (kg/d)	25740
TS input (kg/d)	33000
Biogas mass (kg/d)	20571
Methane mass (kg/d)	6509 (CO_2 around 140621)
Output mass (kg/d)	79429
TS output (kg/d)	19857 (to compost)
VS output (kg/d)	12597
Retention time (d)	26
Loading rate (kgVS/m^3d)	6.8
Biogas yield (average) (m^3/kgVS$_{in}$)	0.632
Methane yield (average) (m^3/kgVS$_{in}$)	0.355

Methane content (%)	56
Methane volume (m^3/d) (STP)	9112
Biogas volume (m^3/d) (STP)	16271
CO_2 volume (m^3/d) (STP)	7159
Methane value (kWh/m^3)	10

Economical Data	Case 1			Case 2		
Formulas	Tsilemou et al	Vallini et al	Greek data	Tsilemou et al	Vallini et al	Greek data
Investment cost (million €)	13.4	13.1	9	14.8	14.3	11
Operational cost (€/ton)	36	-	32	40	-	37

Electric power efficiency (%)	35	Produced Electric power (kWh/d)	31892
Heat value efficiency (%)	50	Produced Heat (kWh/d)	45560
Losses %	15		

Table 3