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Towards thermophilic anaerobic digestion application in Attica, Greece: a feasibility study

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Abstract
The global population growth and the improvement of the life quality of the last 30 years have resulted in a corresponding increase in urban waste. More than 3Gtons/y is produced in Europe. In addition, energy demand shows a new increase. Biogas, produced from waste management, is one of the renewable energy sources and can replace fossil fuels in electricity and heat production. It can also be used as a gas fuel in vehicles. It has been rated as the most energy efficient and environmentally friendly technology that drastically reduces greenhouse gas emissions. This manuscript consists of a techno-economically study of a possible thermophilic anaerobic biological degradation unit installation in Attica, Greece, which will manage the source sorted organic fraction of solid municipal waste (SS-OFSMW). In general feasibility studies of anaerobic digestion units are rare in literature and valuable to the scientific committee because they can verify the validity of lab experiments and small scale applications, while they consist of a necessary simulation tool for possible large scale applications. The thermophilic process can produce on average 194m^3 of biogas per ton of fresh substrate. The anaerobic digestion unit will produce almost 13150MWh$_{el}$/y. The pay back of the investment will be around 4 years. Biogas production from municipal waste is an alternative interdisciplinary efficient solution. It can be a part of an integrated waste management plant while at the same time anaerobic digestion units can be combined with other renewable energy technologies (e.g. photovoltaic energy supply facilities).

Keywords: *anaerobic digestion, source-sorted organic fraction of solid municipal waste, dry digestion, thermophilic anaerobic degradation.*

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I. INTRODUCTION

The anaerobic biological degradation is the complex process of organic matter decomposition in the presence of microorganisms and in the absence of oxygen. The process produce renewable energy (biogas) and exploit the rich fertilizer remaining ingredients (except for the production of biogas for energy use, the anaerobic digestion process destroys pathogens and produce stabilized material (compost), which can be used as fertilizer in agriculture) [1][2].

The term biogas refers to the flammable mixture of gases produced by the anaerobic degradation. The mixture contains 55-65% methane, carbon dioxide and traces of other gases. Biogas has good calorific value and can be used directly as a fuel or indirectly for electricity generation [3].

The global population growth and life quality improving for the last 30 years has resulted in a corresponding increase in human waste. Consequently million tons of garbage produced each year, which must be removed safely without any negative impact on the environment. Alongside the economic and social development is intertwined with the production of energy to efficient and sustainable levels. But the mode of production, distribution and use of energy can cause environmental problems such as water soil and air pollution, or even climate change. Anaerobic digestion as a pre-processing step before waste composting or landfilling has many advantages, such as minimizing mass and volume, neutralization of biological and biochemical processes to avoid odour and gas emissions in the next stages of waste management, reduction of landfill sites and produce energy in the form of biogas. So the anaerobic biological process of biodegradable part of waste is considered an alternative environmentally friendly method of waste management, while an important renewable energy source. Therefore, anaerobic digestion is a method of reducing environmental pollution from agricultural, urban, industrial waste and gaseous pollutants, while contributing to energy independence from fossil fuels [3] [4]. Further anaerobic digestion has zero impact on CO2 emissions, because the emitted CO2 originates from the CO2 substrates have absorbed from the environment. So, the emitted CO2 is released in the atmosphere and will be again absorbed by plants, which are going to be used for biogas production starting another carbon cycle.

The various anaerobic biological process techniques and technologies are distinguished by their respective operational factors (e.g. operation continuity: batch-continuous, operating temperature: psychrophilic, mesophilic, thermophilic,), the design of the reactor (e.g. Plug-flow, complete-mix, covered lagoons) and the solid content of the waste (wet-dry (liquid-solid substrate)) [5][6][7].

The dry substrate anaerobic digestion regards waste solids content higher than 15%. Unlike the wet substrate anaerobic digestion manages substrates with solid content concentration of 0.5% to 15%. Manure, mud and waste food industry generally treated by wet anaerobic digestion. The organic fraction of municipal waste and lignocellulosic biomass (agricultural waste and energy crops) are treated by dry techniques. The technique of the dry substrate is advantageous in the reactor size (smaller and consequently smaller reactor capacity requirements), the lower energy requirements for heating the reactor and stirring the content. In European Union dry substrate anaerobic digestion reactors dominate except the period 2005-2006. The last five years 63% of the facilities that were built are dry substrate anaerobic digestion units [8][9][10].

The industrial anaerobic digesters in Europe can operate at mesophilic and thermophilic temperatures. In the beginning all the facilities were mesophilic mainly because the mesophilic process was considered more stable and required less heat consumption. The thermophilic digestion was developed in the 1990s. During the period 2000-2005 many mesophilic plants were built mainly of wet substrate but after the thermophilic plants are increased significantly [8][9].

The thermophilic operation results in approximately 50% greater organic matter decomposition, particularly with substrates rich in fats, better microbial activity and thus higher methane profit. Also in operation above 55 ° C for more than 23h, no further heating to destroy pathogens is needed. Even oxygen is less soluble in the thermophilic region and therefore the optimum operating conditions are reached quickly [3].

This paper consists of a techno-economically study of a possible thermophilic 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. Both cases of installing one (Case I) and two (Case II) thermophilic bioreactors operated at high organic loading rate (OLR) are taken into consideration. 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 of anaerobic digestion units are rare in literature. This type of research is valuable to the scientific committee 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. In general feasibility studies include designing, simulation and evaluation of future potential applications and are key tools for understanding the expected anaerobic digestion unit efficiency and output production.

II. MATERIALS AND METHODS

2.1.1 The situation of municipal solid waste in Attica

The composition of the organic fraction of municipal solid waste varies from food waste (vegetable waste and fruit peels) to garden waste (leaves and grass). The strategy for the collection of municipal waste affects the characteristics of urban waste, gain in methane and use (disposal in the fields or in landfills or combustion) of the digested residue. Changes occur in the composition of the source sorted organic fraction of municipal waste according to the season and the geographical location that is collected. In summer, for example, municipal waste containing large amounts of garden waste which reduces the gain in methane.

In Attica, 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. 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) [11](Data on Fig.1 is dated back on 2003, although the numbers are still valid)

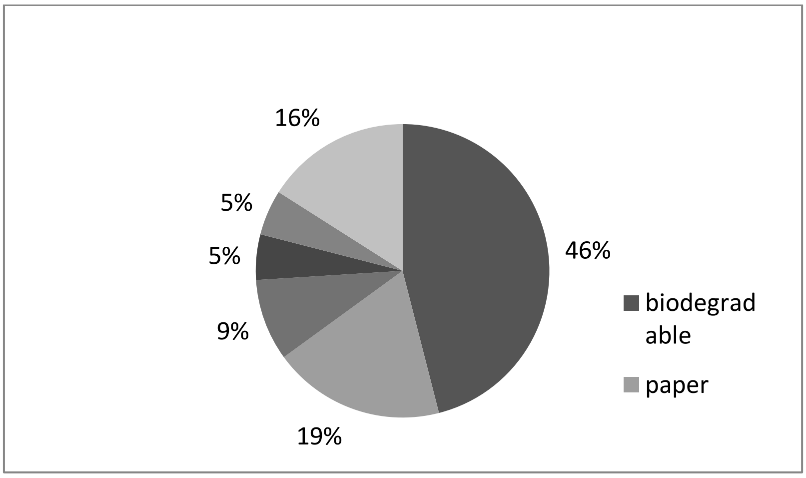

Figure1: Average composition of Attica municipal waste (data from 2003)

The organic fraction of municipal waste is categorized into mechanical sorted, source sorted and hand sorted [12]. 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. Nevertheless for the purpose of this study was assumed that the organic fraction of municipal solid waste consists of source sorted waste.

2.1.2 Kinetic model

For the kinetic study the first-order model was selected [13]

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: $\frac{B_o - SMP}{B_o} = \frac{S}{S_o}$ [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] becomes:

$$(S_o - S)/_S = HRTk \leftrightarrow S_0/_S - 1 = HRTk \leftrightarrow B_o/_{(B_o - SMP)} = HRTk \qquad [5]$$

And finally:

$$\frac{1}{SMP} = \frac{1}{B_o} + \frac{1}{B_o kHRT} \qquad [6]$$

2.2 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), 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 (Case I) or two (Case II) bioreactors, where anaerobic treatment of the organic fraction of waste, biogas production and its use for electricity generation will take place.

2.2.1 Pre-processing unit

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

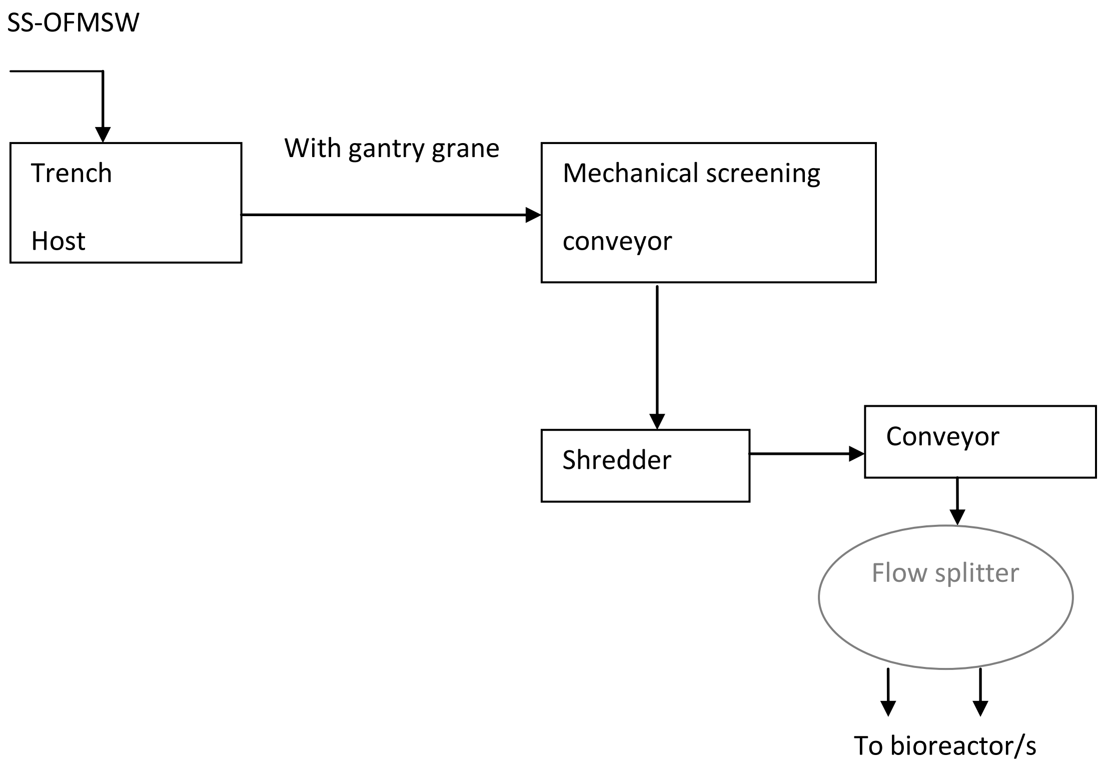

Figure 2: Pretreatment unit flowchart, the flow splitter (gray line) is for Case II where the anaerobic digestion unit is composed of two bioreactors

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 $2\,d \times 35\,\frac{t}{d} \times {}^{1}\!/_{d_{waste}}$ plus 10% tolerance (with $d_{waste} = 0.55 - 0.67\,{}^{ton}\!/_{m^3}$.) So the trench will have a capacity of $115 - 140 m^3$. 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, where hand screening of contaminants (plastics, glass, metals, paper) will take place. The contaminants are removed to avoid hindering the process of anaerobic biological degradation. The metal film concludes feeding 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).

2.2.2 Anaerobic Digestion Unit

The anaerobic digestion unit will be supplied by the preprocessing unit. It will consist of:
Case I: pumps mixing of substrate and recycling of leachate, one dry substrate bioreactor, biogas storage tank, and a heat and electricity generator (Fig. 3).

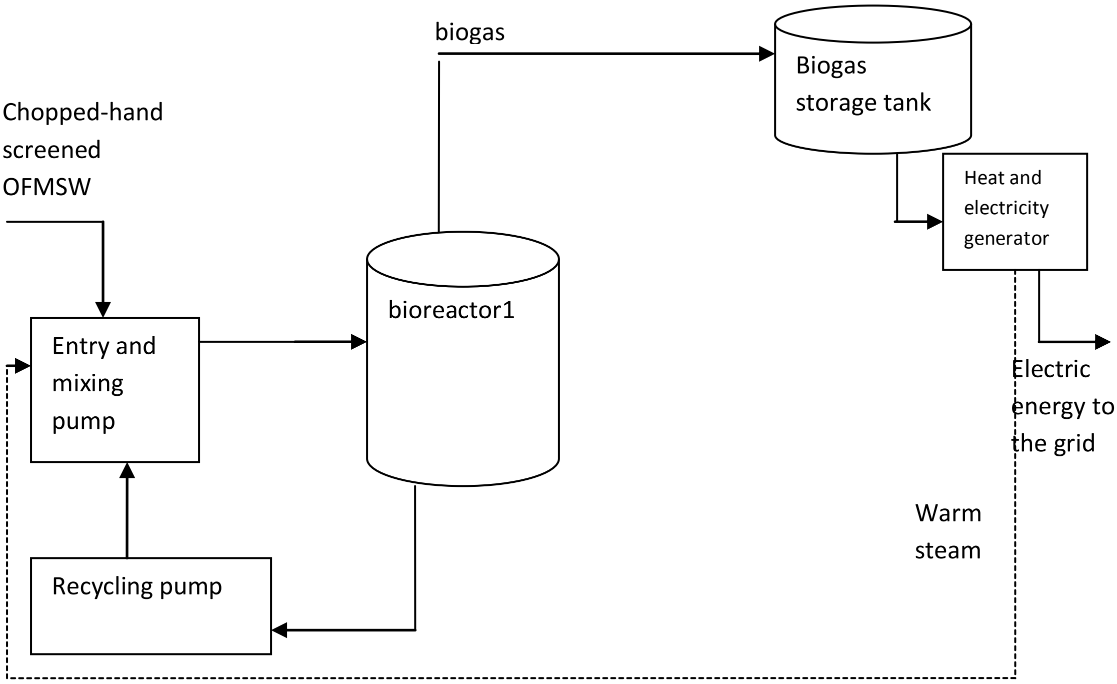

Figure 2: Schematic diagram of the anaerobic biological treatment plant, Case I

Case II: pumps mixing of substrate and recycling of leachate, two dry substrate bioreactors, biogas storage tank, 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. 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:

$$V(m^3) = (substrate\ \ volume)(\frac{m^3}{d}) \times HRT\ (d) + 25\ \%\ tolerance \qquad [7]$$

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 and it will be capable of storing biogas for 8-7h.

The electricity and heat production unit power

$$P_{el}(kW) = \frac{(anual\ \ mehane\ \ production\ \ in\ m^3) \times 10\ \frac{kWh}{m^3}}{anual\ \ operation\ \ hours} \times (unit\ \ electric\ \ efficiency) + 25\ \%\ tolerance \qquad [8]$$

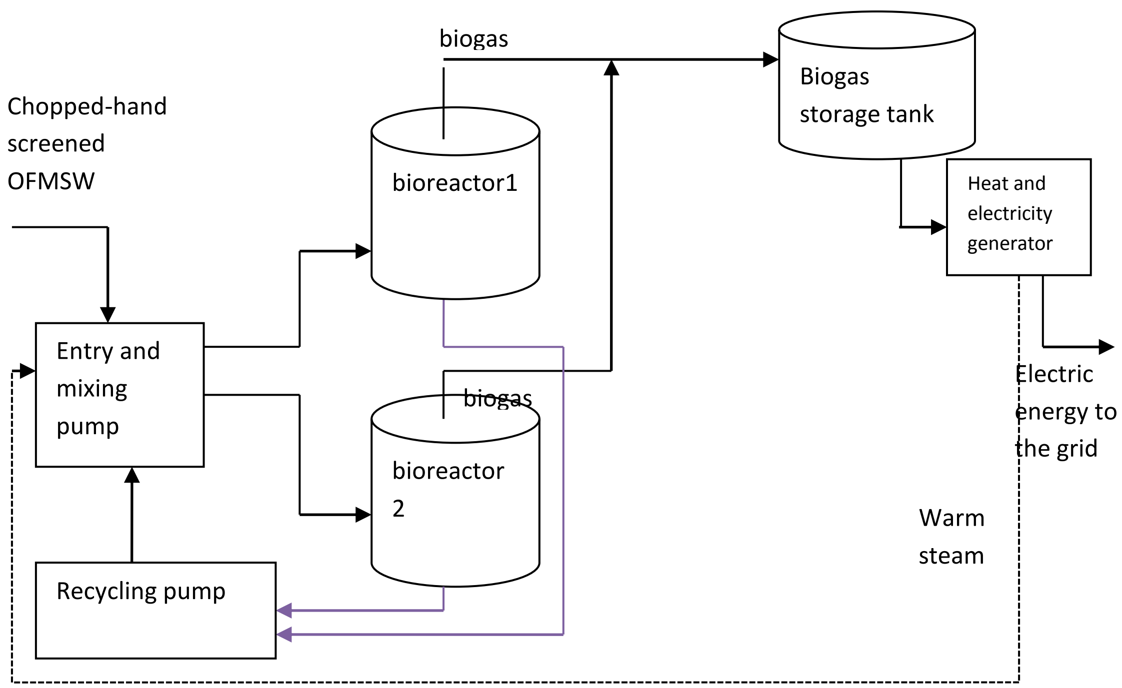

Figure 3: Schematic diagram of the anaerobic biological treatment plant, Case II

2.2.3 Assumptions

For the thermophilic 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. The composition of SS-OFSMW will be 70-80% food waste with $d_{fw} = 0.75\, {}^{ton}/_{m^3}$ and 30-20% garden waste with $d_{gw} = 0.3\, {}^{ton}/_{m^3}$). So SS-OFSMW density is $d_{SS-OFSMW} = 0.67\, {}^{ton}/_{m^3}$
3. The average density of the substrate is $d_s = 0.86\, {}^{ton}/_{m^3}$ ($d_{sludge} = 1.02 - 1.06\, {}^{ton}/_{m^3}$)
4. Substrate with 35%TS and VS=81%TS
5. Methane potential: $0.44 m^3 CH_4/kgVS_{in}$ (STP)
6. First order kinetic model with constant $k = 1.61d$
7. HRT=16d
8. Biogas methane content 62%
9. $T_{reactor}$=55°C
10. $VS_{reduction}$=67%
11. Annual CHP operation hours 7500h/y
12. Unit electric efficiency 0.83%
13. Methane value 10kWh/m^3

III. RESULT AND DISCUSSION

In Table 1 the technical characteristics of the anaerobic digestion unit, for both Case I and II are presented.

Table 1: Technical characteristics of the proposed anaerobic digestion unit for both Case I and case II.

Technical characteristics	Case 1	Case 2
Bioreactor capacity (m^3)	2326	1163 (x2)
Biogas storage tank capacity (m^3)	430	
CHP power (MW)	2.5	

Table 2 shows thermophilic anaerobic biological process input-output data, which process is going to treat 100ton/d of substrate, with 35%TS. For Case II each bioreactor will treat 50ton/d so its input-output data is half the values presented in Table 2.

Table 2: Technical characteristics of the proposed anaerobic digestion unit for both Case I and case II.

Effective capacity (m^3)	1861 (total 2326)		
Mass input (kg/d)	100000		
VS input (kg/d)	28350		
TS input (kg/d)	35000		
Biogas mass (kg/d)	26653		
Methane mass (kg/d)	8618 (CO_2 around 15035)		
Output mass (kg/d)	76347		
TS output (kg/d)	16006 (to compost)		
VS output (kg/d)	9356		
Retention time (d)	16		
Loading rate (kgVS/m^3d)	11.7		
Biogas yield (average) (m^3/kgVS$_{in}$)	0.684		
Methane yield (average) (m^3/kgVS$_{in}$)	0.424		
Methane content (%)	62		
Methane volume (m^3/d) (STP)	12020		
Biogas volume (m^3/d) (STP)	19388		
CO_2 volume (m^3/d) (STP)	7368		
Methane value (kWh/m^3)	10		
Electric power efficiency (%)	35	Produced Electric power (kWh/d)	42070
Heat value efficiency (%)	50	Produced Heat (kWh/d)	60100
Losses %	15		

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) [14] [15]) [16]).

The assumptions were based on real large-scale experiments conducted in Greece, Italy and Spain [15][16] and we believe that nutritional conditions and culture that have Greeks, Italians and Spanish are similar. Food and garden waste density was assumed to be the average value according to [17]). Further organic waste composition is based on research of Komilis et al [18][19] and the technical report for Tinos municipality [20]). Sludge density was assumed according to the research of Dammel and Schroeder ([21]). The first-order constant for thermophilic applications has been calculated by Cecchi et al for the three categories of municipal waste in the early 1990s [22]. The assumption on the maximum theoretical gain in methane or the ultimate methane production B_o was based on the study of Davidsson et al [23] taking into account that there will be a portion of garden waste and paper on the source sorted organic fraction of municipal waste. Both garden waste and paper decrease methane production.

The use of two bioreactors, in Case II, reduces the possibility of suspending the operation of the entire unit. If the operation of one bioreactor is inhibited the second bioreactor will operate. On the other side 90% of the european full scale anaerobic digestion plants treating OFMSW rely on one-stage system mostly because of its simpler design, which suffers less frequent technical failures and is economical [24]).

According to Table 2 the thermophilic process can produce on average 194m^3 of biogas per ton of fresh substrate. The results of the thermophilic process are consistent with large-scale studies in the European Union where it is produced 100-200m^3biogas/ton [25][26]. In comparison to mesophilic applications can produce almost 20% more amount of biogas/ton.

As far as electric energy production concerns, the aforementioned anaerobic biological treatment unit will produce almost 13147 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 4500-3000 households in the Municipality of Athens. So by treating the 10% of annual organic waste produced in Athens it can be covered the 1.4-2% of Athens municipality electric energy demand. Which means, that the specific anaerobic digestion unit is capable to supply with electricity an area of 15000 habitants.

3.1.1 Economical Aspects

The investment cost of the anaerobic digestion plant for Case I is estimated around 7.3M€. This value includes the turn-key anaerobic part, with the treatment of the biogas by means of biogas engines and the necessary civil works. It does not include the cost of the pretreatment unit of the waste. However taking into account that the pretreatment unit cost stands for the 40% of the total investment cost, the anaerobic digestion unit of case 1 will have an investment cost around 10.22M€. For Case II the estimated investment cost rises 20% higher than Case I so it is going to cost around 12.3M€.

The anaerobic digestion unit will produce 42070kWh/d, which means 13146875kWh/y. If this energy is sold to the national grid then the annual profit of energy production will be around 3300000€/y (assuming a selling price of 0.25€/kWh that is valid now in Greece for biogas units treating agricultural and dairy waste [26] Operational cost of the unit will be around 700000€/y. So the net profit will be approximately 2600000€/y and the pay back of the investment will be around 4 years for Case I and 5 years for Case II.

IV. CONCLUSION

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. Both cases of installing one and two thermophilic bioreactors are taken into consideration. The thermophilic process can produce approximately 200m3 of biogas per ton of fresh substrate and almost 13150 MWh/y. The pay back of the investment will be around 4-5 years.

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