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Co-substrate analysis for biogas production enhancement in an anaerobic digestion plant of Argentina

Author

Martin Eduardo Ramirez
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Director/s

Dr. Joan Mata Alvarez
Department of Chemical Engineering. University of Barcelona

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1 ABSTRACT

Anaerobic co-digestion is a feasible option to overcome the drawbacks of mono-digestion and to improve the economic viability of anaerobic digestion plants due to higher methane production. It offer several benefits over digestion of separate materials, such as increased cost-efficiency (one plant for several wastes), increased degradation of the treated materials due to synergistic effects, improve optimal moisture and nutrient content, and also dilution of inhibitive compounds. The TFM was focused on Sudoeste Plant, a WWTP (wastewater treatment plant) from Buenos Aires where the sludge treatment plant is currently being built. The co-substrate selected was the biowaste (fruits and vegetables) from Central Market due to its proximity to the plant. The fruits and vegetables considered were: letuce, banana, apple, pear, potato, tomato, orange, carrot, tangerine, lemon, bell pepper, onion and grass. All the biowastes selected has shown good digester performance in research papers consulted. The calculation methodology of methane and biogas production were taking from Metcalf and Eddy and an heuristic method commonly used by plant operators. The total biowaste generated by Central market (54000 t/day) was considered to be added inside digester plant, and represent a 5% of total sludge flowrate. The biowaste was homogenised by a pulper system. The co-digestion of both wastes generated a biogas and methane enhancement of 28%. The biogas produced was converted into electricity and heat using an CHP engine (Combined Heat and Power). Prior to get the biogas inside the engine a gas treatment was proposed, that included a bioscrubber to reduce the hydrogen sulfide content (H_2S) and water gas separator installation to eliminate water vapor. Finally, the electric and thermal energy generated were enough to supply Sudoeste Plant demands and the economical analysis were positive, therefore, the project was considered beneficial to the company.

2 INTRODUCTION

Anaerobic digestion is a biological treatment performed in the absence of oxygen to stabilize organic matter producing biogas as a consequence (a mixture formed mainly of methane and carbon dioxide). The oldest and more widespread application of anaerobic digestion is the treatment of sewage sludge. Anaerobic digestion is a well known, efficient and environmentally sustainable technology which enables energy production as heat, electricity and/or vehicle fuel, as well as stabilization and volume reduction of sludge (Loustarinen et al., 2008). Typical sewage sludge comprises of primary sludge separated from wastewater during pre-settling and biological excess sludge from the activated sludge system. Characteristics of sewage sludge differ somewhat in different countries and areas due to water consumption and local industry. Total solids content is usually low but sludge volume is high unless some of the water is removed prior to sludge treatment (Einola et al., 2001). The typical values of total solids (TS) and volatile solids (VS) for primary sludge are 3% (TS) and 75% (VS), and 0.8% (TS) and 70% (VS) for biological sludge. The organic load of both sludge are low as the Total Nitrogen (TN) content: 2.5% in primary sludge and 3.8% in biological sludge (Tchobanoglous et al., 2014).

Anaerobic co-digestion is a feasible option to overcome the drawbacks of mono-digestion and to improve the economic viability of anaerobic digestion plants due to higher methane production. It offer several benefits over digestion of separate materials, such as increased cost-efficiency (one plant for several wastes), increased degradation of the treated materials due to synergistic effects, improve optimal moisture and nutrient content, and also dilution of inhibitive compounds (such as ammonia and lipids degradation products), as well as increased biogas production (Mata-Alvarez et al., 2000).

The low organic load of sewage sludge (SS) together with the non-used capacity of the wastewater treatment plants (WWTP) digesters, frequently as much as 30%, is the main driving force behind SS co-digestion. Sewage sludge is characterized by relatively low C/N ratio and high buffer capacity, therefore it is able to stand co-substrates with high amounts of easily biodegradable organic matter and with low alkalinity values. Hence, food wastes are a convenient co-substrate for sewage sludge because it has high organic matter content and, depending which waste, a high nutrient content (Lacovidou et al., 2012). Biowaste is a kind of organic waste that includes food, fruit, vegetable and market wastes together. The biowaste represent a highly biodegradable co-substrate, which, until a certain threshold limit is surpassed, improves the biogas production of the sewage sludge digester just by increasing the organic loading rate (OLR) (Mata Alvarez et al., 2014).

Biowaste, as a main substrate has not been as studied as manures or sewage sludge. That may be a consequence of several factors: the high biogas potential of this kind of waste, the lower number of plants and their location, but above all, the presence of undesired compounds. The last thing makes that the digestate, followed or not by composting, cannot be able to be used in restricted applications (e.g. land reclamation, landfill daily cover, etc.). Apart from these facts, the biowaste could be used as co-substrate for sewage sludge because co-digestion between this two waste has been reflected as a way to reduce significantly the treatment cost of both and it is a good cross-sectorial opportunity (Krupp et al., 2005).

The objective of co-digestion is to enhance biogas generation to produce more electrical energy. Generally, the WWTPs use biogas engine, turbine or micro-turbine to burn the biogas and produce electricity. The engine is the most used technology in wastewater plants, as part of co-generation systems (Arespacochaga et al., 2015). Co-generation is the use of heat produced during biogas utilization. The heat came from engine combustion gases and are obtained using heat exchangers, a device employed to transfer heat from gases to water. Then the heat accumulated in water is used to warm up the sludge digester. This is the most common co-generation configuration in WWTP (Bastian et al., 2011).

2.1 Anaerobic digestion process

The anaerobic digestion (AD) of organic matter includes the following process: hydrolysis, acidogenesis, acetogenesis and methanogenesis as shown in Figure 1. AD is a complex process which requires strict anaerobic conditions to proceed, and depends on the coordinated activity of a complex microbial association to transform organic matter into methane (CH_4). Despite the successive steps, hydrolysis is generally considered as rate limiting (Apeals et al., 2008).

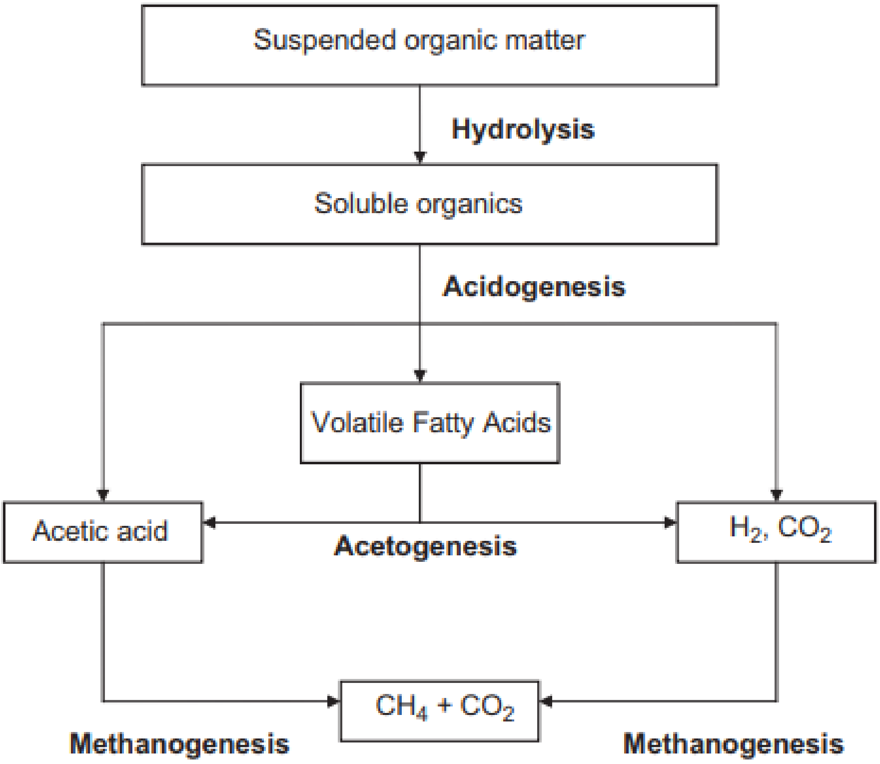

Figure 1: Anaerobic digestion process steps.

The hydrolysis step degrades both insoluble organic material and high molecular weight compounds such as lipids, polysaccharides, proteins and nucleic acids, into soluble organic substances (e.g. aminoacids and fatty acids). The components formed during hydrolysis are further split during acidogenesis, the second phase. At this phase, VFA (volatile fatty acids) are produced by acidogenic (or fermentative) bacteria along with ammonia (NH_3), CO_2, Hydrogen sulfide (H_2S) and other by-products (Apeals et al., 2008). The H_2S is one of the compounds that affects biogas valorisation, due to its corrosive effects (Tchobanoglous et al., 2003).

The third stage in AD is acetogenesis, where the higher organic acids and alcohols produced by acidogenesis are further digested by acetogens bacteria to produce mainly acetate as well as CO_2 and H_2. This conversion is controlled to a large extent by the partial pressure of H_2 in the mixture (Boe, 2006).

The final stage, methanogenesis, produces methane by two groups of methanogenic bacteria: the first group splits acetate into methane and carbon dioxide (acetoclastic reaction) and the second group uses hydrogen as electron donor and carbon dioxide as acceptor to produce methane, called hydrogenotrophic reaction (Boe, 2006).

In anaerobic digestion (AD) various important parameters affect the rates of the different phases of digestion process: pH and alkalinity, temperature, and sludge retention time (SRT).

The pH is an important parameter because there are different optimum pH range for each microorganisms group involved in AD. Methanogenic bacteria are extremely sensitive to pH, with an optimum between 6.5 and 7.2 (Boe, 2006; Turovskiy & Mathai, 2006). The fermentative microorganisms are less sensitive and can work in a wider range of pH between 4.0 and 8.5 (Hwang et al., 2004) with different behaviour: at low pH the main products are acetic and butyric acid, while at a pH of 8.0 mainly acetic and propionic acid are produced (Boe, 2006). Alkalinity is the capacity to resist changes in pH, so it is very important to maintain process stability (Turovskiy & Mathai, 2006).

Temperature influences the growth rate and metabolism of microorganisms and hence the population dynamics in the anaerobic reactor. Acetotrophic methanogens are one of the most sensitive groups to increasing temperatures (Rehm et al., 2000). The temperature has moreover a significant effect on the partial pressure of H_2 in digesters, hence influencing the kinetics of the syntrophic metabolism and also the hydrogenotrophic reaction are less favoured at higher temperatures.

The solids retention time (SRT) is the average time the solids spend in the digester. A decrease in the SRT decreases the extent of the reactions and vice versa. Each time sludge is withdrawn, a fraction of the bacterial population is removed thus implying that the cell growth must at least compensate the cell removal to ensure steady state and avoid process failure (Turovskiy & Mathai, 2006; Appels et al., 2008). The influence of SRT is: (i) retention times shorter than 5 days are insufficient for a stable digestion: VFA concentrations are increasing due to a washout of methanogenic bacteria, (ii) VFA concentrations are still relatively high for SRT of 5–8 days: there is an incomplete breakdown of compounds, especially of the lipids, (iii) stable digestion is obtained after 8–10 days: low VFA concentrations, the breakdown of lipids starts, and (iv) the breakdown curve stabilises at SRT>10 days and all sludge compounds are significantly reduced (Appels et al., 2008).

2.2 Study context

Anaerobic co-digestion has been performed and studied mostly in developed countries (USA and Europe) where the waste management is an important policy to reduce contamination and waste disposal. The majority of undeveloped countries have not encourage the application of an efficient waste management, therefore all the waste generated goes to landfill disposal. This practice is common in countries with available space and low incomes.

Argentina is a country that has been making important investments in infrastructure services in the last 20 years. Most relevant investment are focused on sanitation services like water and wastewater treatment plants and its associated infrastructure (drainage and sewer grid). Nowadays, many WWTP have been built and exist many projects to construct new ones. The majority of these projects are focused in the metropolitan area of Buenos Aires (Capital city and 24 municipalities), where resides the 30% of the population. Moreover, Buenos Aires authorities are implementing a new policy in waste management looking forward to waste valorisation through waste recycling and energy production.

This context is a great opportunity for anaerobic co-digestion implementation: first, most digesters of WWTP in Buenos Aires has an available operational capacity, and second, great part of the organic waste generated by the city were sent to landfill disposal. Therefore, co-digestion could be the best option to achieve energy production and waste valorisation. Additionally, it would report several benefits over separate waste treatments, due to cost efficiency.

One of the most important water treatment projects in Buenos Aires is the construction of the sewage sludge treatment system (anaerobic digestion) in the actual Sudoeste Plant, situated in the Municipality of Ezeiza. This plant treats the wastewater of 850 thousand inhabitants. Currently, this plant doesn't have sludge treatment so in consequence sewage sludge is pumped to another plant. The construction of the sewage sludge treatment is planned to be finished in 2019.

In the surrounding area of the plant is located the Central Market of Buenos Aires (1 km distance). This market sells 106 thousand tonnes of fruit and vegetables by month, besides other products as meat, fish and some processed foods (flavour, bread, oil, etc). It produce 58 tonnes per day of fruit and vegetables wastes, the most important fraction generated by the market (INTI, 2016). Nowadays, all the wastes generated are disposed in landfill without any treatment. CEAMSE, the public company responsible of landfill management, only left 5 years of operation due to space limitation, leaving companies that produce big quantities of waste without any waste management options or expensive ones (private landfill).

Therefore, the construction of the new sludge treatment in Sudoeste Plant (anaerobic digestion), appears as a great opportunity to treat the market wastes and sewage sludge together, reducing transportation and disposal costs of Central Market, and improving methane production for energy generation.

2.3 Sudoeste Plant

Sudoeste Plant is a WWTP located in Buenos Aires, in the Municipality of Ezeiza (3 km from Capital City). This plant has two Modules (A and B) that work separately, as two different plants. Currently, both modules don't have sludge treatment hence all sludge generated is pumped to another treatment plant. Nevertheless, AySA has started the construction of the new sludge treatment for both modules in 2018, and it is expected to be finished at the beginning of 2019.

The **Module A** of Sudoeste Plant is the oldest one, it has a treatment flowrate of 1.97 m^3/s and a treatment capability for 600,000 inhabitants equivalent. The principal processes of this treatment system are:

- Pretreatment (big wastes removal by bars, sand decantation and FOGs removal)
- Primary treatment (settling tank)
- Secondary treatment (Trickling filter and secondary clarifier)

The **Module B** differs from the last one in the secondary treatment configuration (Activated sludge). It has a treatment flow of 0.9 m^3/s and a treatment capability for 300,000 inhabitants equivalent. The principal processes of this treatment system are:

- Pretreatment (big and middle wastes removal by bars, sand decantation and FOGs removal)
- Primary treatment (settling tank)
- Secondary treatment (activated sludge treatment and secondary clarifier).

3 OBJECTIVES AND JUSTIFICATION

3.1 General Objective

- Feasibility and economical analysis of co-digestion in Sudoeste Plant using a co-substrate from Central Market.

3.2 Specific Objectives

- Revision of scientific bibliography about co-digestion experiences.
- Definition of the theoretical methodology to evaluate biogas and methane production.
- Select the best biowastes to use as a co-substrate.
- Definition of the co-substrate composition and feed flow inside the digester.
- Theoretical evaluation of methane production and Energy generation.
- Economical evaluation of the project.

3.3 Justification

Presently, Argentina government is working in two important issues: expansion of water sanitation service and improvement of energy generation. Therefore, co-digestion in WWTP is a great opportunity to accomplish both. It is well known that co-digestion is a good option for enhance energy production but also for cost effective waste management of sewage sludge and others organic wastes. This TFM analyzed the potential improvement of co-digestion in Sudoeste Plant biogas production, offering a better destination to the organic wastes generated in the Central Market and reducing the cost of disposal and waste transportation. The short distance between Sudoeste Plant and Central Market (1 km) makes the co-digestion a very interesting option for this case study.

4 METHODS

This work was focused on making a technical and economical feasibility analysis to evaluate the benefits of adding a co-substrate in the future digesters of Sudoeste Plant to enhance biogas production. Based on the estimated sludge flowrate and sludge characteristics from both existing modules (AySA, 2018), and the quality of the co-substrate chosen, an estimation of potential biogas and methane production were done, following the methodology of Metcalf & Eddy (Tchobanoglous et al., 2014) and an heuristic method used by plant operators.

4.1 Metcalf & Eddy methodology

Metcalf & Eddy methodology (Tchobanoglous et al., 2014) allows to calculate the methane and biogas production using the biodegradable COD (Chemical Oxygen Demand), from now called COD(b). Below is presented step by step how this calculations was made and the meaning of it.

The flowrate of primary and secondary sludge were supplied by the company (AySA, 2018). Based on these values and using the typical COD removal levels of primary and secondary clarifiers (Fr), the $COD(b)_{loading}$ was calculated with the following equation:

$$COD(b)_{loading} = Fr \times Q \times COD(b)_{in} \tag{1}$$

$COD(b)_{loading}$: Biological COD loading to the digester (kg/d)
Fr: COD removal percentage of primary a secondary clarifiers (%)
Q_{in}: Influent flowrate (m^3/d)
COD_{in}: Biological COD influent of the plant (kg/m^3)

The Fr and $COD(b)_{in}$ values can be consulted in Table 1. Once the $COD(b)_{loading}$ was calculated, it was necessary to quantify the mass of VS (volatile solids) produced in the anaerobic reactor corresponded to the biomass of microorganisms generated. It could be done with the following expression:

$$P_x = \frac{Y\,(\mathrm{S_0 - S})}{1 + b(\mathrm{SRT})} \tag{2}$$

P_X: VSS produced in the reactor (kg VSS/d)
S_0: COD(b) loading (kg/d)
S: COD digester effluent (kg/d)
Y: Yield coefficient (kg VS/kg COD)
b: Endogenous coefficient (d^{-1})
SRT: Sludge Retention Time (d)

The kinetic and stoichiometric coefficient given by Metcalf & Eddy (Tchobanoglous et al., 2014) are presented in Table 1. The *S* (COD effluent) was calculated using *E* (solids conversion) that represents the efficiency of COD utilization by anaerobic bacteria. The *SRT* value came from the design construction parameters of AySA (2018), can be seen on Table 1.

The P_x and $COD(b)_{loading}$ allowed the estimation of the methane production (V_{CH4}). The equation (3) relate the COD inverted in methane production after the use of the COD to generate new biomass (P_x).

$$V_{CH4} = Fc[(S_0 - S) - 1.42\,P_X] \tag{3}$$

V_{CH4}: Methane volume generated inside the reactor (m3/d)
Fc: Conversion factor at 35°C (m^3 CH_4/kg COD)
S_0: COD(b) loading (kg/d)
S: COD digester effluent (kg/d)
Px: Biomass inside the reactor (kg VSS/d)

Finally it was possible to estimate the total biogas production assuming the typical % of CH_4 in biogas (60%). The quantity of biogas can be calculated using Eq. (4):

$$V_{biogas} = \frac{V_{CH4}}{\%_{CH4}} \tag{4}$$

V_{biogas}: Total gas volume (m^3/d)
V_{CH4}: CH4 gas volume (m^3/d)
$\%_{CH4}$: Percentage of CH_4 in biogas.

Table 1: Parameters and coefficients for calculate Eq. (1) to (4).

	Units	Value	Reference
Fr 1	%	35	WEF (2010)
Fr 2	%	60	WEF (2010)
COD_{in} (Module A)	kg/m^3	0.157	AySA (2018)
COD_{in} (Module B)	kg/m^3	0.135	AySA (2018)
Q_{in} (Module A)	m^3/s	1.97	AySA (2018)
Q_{in} (Module B)	m^3/s	0.9	AySA (2018)
Y	kg VSS/kg COD	0.08	Tchobanoglous et al. (2014)
b	d^{-1}	0.03	Tchobanoglous et al. (2014)
SRT	d	20	AySA (2018)
E	%	0.8	Tchobanoglous et al. (2014)
Fc (20°C)	m^3 CH_4/kg COD	0.4	Tchobanoglous et al. (2014)

4.2 Heuristic method

This method is most used by plant operators to obtain a quick estimation of the biogas production in sludge digesters. This heuristic uses an empirical conversion factor given by WEF (1998). Biogas production was calculated using the formula below:

$$V_{biogas} = VS \times Fc \tag{5}$$

V_{biogas}: Total gas volume (m^3/d)
VS: Volatile Solids consumed inside digester
Fc: Biogas conversion factor at 20°C and 1 atm (Nm^3/kg VS)

The Fc is the empirical conversion factor from WEF (1998) that convert VS (kg) in biogas (Nm^3). The VS consumed inside digester is assumed in 50% of total VS entered. This methodology, as been told previously, is used by plant operators and also by plant designers. In Table 2 is presented the values of sludge flowrate an its TS and VS content to calculate biogas production.

Table 2: Total flowrate of sludge from both modules (Q_{sludge}), Total Solids (TS) and Volatile Solids (%VS).

	Units	Value
Q_{sludge}	m^3/d	1392
TS	kg/m^3	53.6
%VS	%	72

4.3 Co-substrate addition

The Eq. (3) and (4) allowed to estimate the methane and biogas generated in the Sudoeste Plant. Therefore, to evaluate the improvement in biogas production related to the addition of co-substrate, was necessary to add the co-substrate COD(b) to the total $COD_{loading}$ calculated for sewage sludge alone, and estimate again the biogas production. The co-substrate COD(b) is calculated in Table 3.

5 RESULTS

5.1 Co-substrate addition calculation

The co-substrate is a biowaste (mix of fruits and vegetables) from Central Market of Buenos Aires. The quality characterization of co-substrate were defined using the information of experimentation studies carried out in lab and full scale by other researchers (Buffiere et al., 2006; Arhoun et al., 2013; Catelo et al., 2014; Chao et al., 2017). The flowrate of co-substrate was defined considering two things: i) the maximum Organic Loading Rate (3 kgVS/m^3.d) to assure digester stability (Cecchi et al., 1986; Mata Alvarez et al., 1990; Bouallagui et al., 2004; Fonoll et al., 2014) and, ii) the space availability inside the digester. The Organic Loading Rate (OLR) is the total VS added daily per digester volume. This TFM selected the co-substrates that has shown good digester performance results (in paper works) therefore it was assumed that the nutrient content of the mix will be enough (Viswanath et al., 1992; Hamzawi et al., 1998; Krupp et al., 2005; Bouallagui et al., 2005; Bolzonella et al., 2006; Mata-Alvarez et al., 2014; Fonoll et al., 2014; Chao et al., 2017).

In Table 3 is presented the different market wastes (biowaste) that were chosen to form the co-substrate. These biowastes are generated in big quantities by the Central Market, consequently this biowaste is always available. The total amount of fruits and vegetables generated by Central Market of Buenos Aires is 58400 kg/d (INTI, 2016), so we used a total amount of 54000 kg/d (grass is not included) as a conservative position. The grass was assumed that is provided by the municipality.

Table 3: Quality characterization of fruits and vegetables wastes. The methane production is given in normal conditions.

		Lettuce	Banana	Apple	Pear	Potato	Tomato	Orange	Carrot	Tangerine	Lemon	Bell Pepper	Onion	Grass	TOTAL
TS	%	10.9	12.8	17.1	15.5	19	6.07	17.1	13.5	17.1	17.1	11.4	24.8	31.1	-
VS	%	8.7	10.9	16.7	14.1	17.8	5.56	16.7	12.1	16.7	16.7	10.6	21.1	26.7	-
COD	g/kg TS	127.3	165.8	227.7	199.8	227.9	193.3	226.0	169.9	226.0	226.0	193.3	223.7	382.5	-
Waste doses	kg/d	4500	4500	4500	4500	4500	4500	4500	4500	4500	4500	4500	4500	3000	57000
TS doses	kg/d	490.5	576	769.5	699.525	855	273.15	769.5	607.5	769.5	769.5	513	1116	933	9141.7
VS doses	kg/d	392.4	490.8	753.3	634.3	801.1	250.2	753.3	546.1	753.3	753.3	477.0	950.8	802.4	8358.5
COD total	kg/d	572.9	745.9	1024.5	898.9	1025.5	870.0	1017.0	764.6	1017.0	1017.0	870.0	1006.6	1147.4	11977.4
BMP*	l CH_4/kg VS	294	289	317	438	390	300	297	388	250	250	200	400	388	-
CH_4 prod	Nm^3/d	123.82	152.22	256.30	298.17	335.33	80.56	240.13	227.43	202.13	202.13	102.39	408.20	334.13	2962.9
References**		(1)	(1)	(1)	(2)	(1)	(3) (4)	(1)	(1)	(1)	(1) (3)	(3) (4)	(5)	(1)	

*BMP: Biochemical Methane Potential, is the potential CH_4 production (Nm3) by the Volatile Solids (kg). This value is used to calculate **CH_4 prod.**

**References: (1) Buffiere et al., 2006;
(2) Arhoun et al., 2013;
(3) Chao et al., 2017;
(4) Catelo et al., 2014;
(5) Henk et al., 1988.

Considering the plant will have 4 digester with a total capacity of 32284 m^3 (AySA, 2018), the estimated plant OLR calculated was 1.7 kg VS/m^3 d, being this a regular value of WWTP (Cecchi et al., 1986; Mata Alvarez et al., 1990; Bouallagui et al., 2004; Fonoll et al., 2014). The OLR estimated after co-substrate addition was 1.9 kg VS/m^3.d and didn't reach the maximum value mentioned before, so the requirement of OLR was achieved. Relative to space availability, the biowaste flowrate represented only a 5% of total sludge flowrate (an extra 5% of water is added with co-substrate), so this requirement was fulfilled too (the digester is 20% overdimensioned).

5.2 Biogas and methane production

The calculation of biogas and methane production were made first for sewage sludge alone, using Metcalf and Eddy methodology (Tchobanoglous et al., 2014). It was also calculated using the heuristic method, with sludge volatile solids (VS) that the company estimates the plant will have (Table 4). It was decided to make an average of both biogas production to ensure a consistent value, avoiding underestimate or overestimate it.

The biogas production can be seen in Table 4. The addition of the co-substrate in plant digester generated an enhancement of 28% of biogas and methane production (Table 4). As It were mentioned before, It was calculated adding the **co-substrate COD(b)** to the **$COD(b)_{loading}$** of sewage sludge. To ensure the added biogas from co-substrate were correct, it was compared with the co-substrate methane production of the Table 3 (Total CH_4 prod). The total methane production was similar in both cases, so it was considered the result of Metcalf and Eddy method was consistent to estimate the biogas enhancement of co-substrate.

The total input of sludge from the Sudoeste plant was 1392 m^3/d, that represent 53720 kg VS/d (Table 5), while the input of co-substrate added to the digester was 71.25 m^3/d, that represent 8358 kg VS/d. It is interesting to remark, the great amount of Volatile Solids (VS) of the co-substrate if we see the little flowrate compared with sludge flowrate. The co-substrate flowrate (m^3/d) added to the digester represent only a 5% of sewage sludge.

Table 4: Methane and biogas production from sludge and sludge + co-substrate.

Biogas production - Metcalf and Eddy method		
COD loading	kg/d	35359
Methane production	m^3/d	9986
Biogas production	m^3/d	16643
Biogas production - Heuristic method		
Total VS	kg/d	53720
VS consumed (typical value 50%)	kg/d	26860
Biogas specific production (WEF)	m^3/kg VS	0.90
Biogas production	m^3/d	24174
Sludge Biogas (average)		
Biogas production	m^3/d	20409
Biogas sludge + co-substrate		
Total biogas production	m^3/d	26046

Table 5: Comparative sludge and biowaste flowrates

Sewage sludge		
Sludge flowrate	m^3/d	1392
TS	kg/m^3	53.6
%VS	%	72
VS flowrate	kg/d	53720
Biowaste		
Biowaste generated	kg/d	57000
Biowaste flowrate	m^3/d	71.25
VS flowrate	kg/d	8358

5.3 Energy and heat production

The construction of sewage sludge treatment in Sudoeste Plant includes a boiler and heat exchangers to warm up the digester using the biogas produced. In this TFM was proposed replace the boiler and install a **biogas engine** to produce electrical energy and use the engine combustion gases in heat exchangers to warm up the digester. The heat exchangers was the same AySA plans to construct.

The engine selected to install in the plant is the Jenbacher J320 from General Electric. This is a CHP engine that means: Combined Heat and Power. It has an electrical efficiency of 39%, a thermal efficiency of 48.5% and loses of 12.4%. In Figure 2 is presented the engine schematic functioning. The heat recovers came from combustion gases and engine refrigeration water, and both were put in contact with water heat exchangers. In Annex I is presented the engine fact sheet.

In Table 6 is presented the calculation of energy production. The power energy calculated for the biogas engine was 6935 kW, so considering the engine selected has 2716 kW of power energy, it was necessary to install 3 (three) of them (there will be extra capacity).

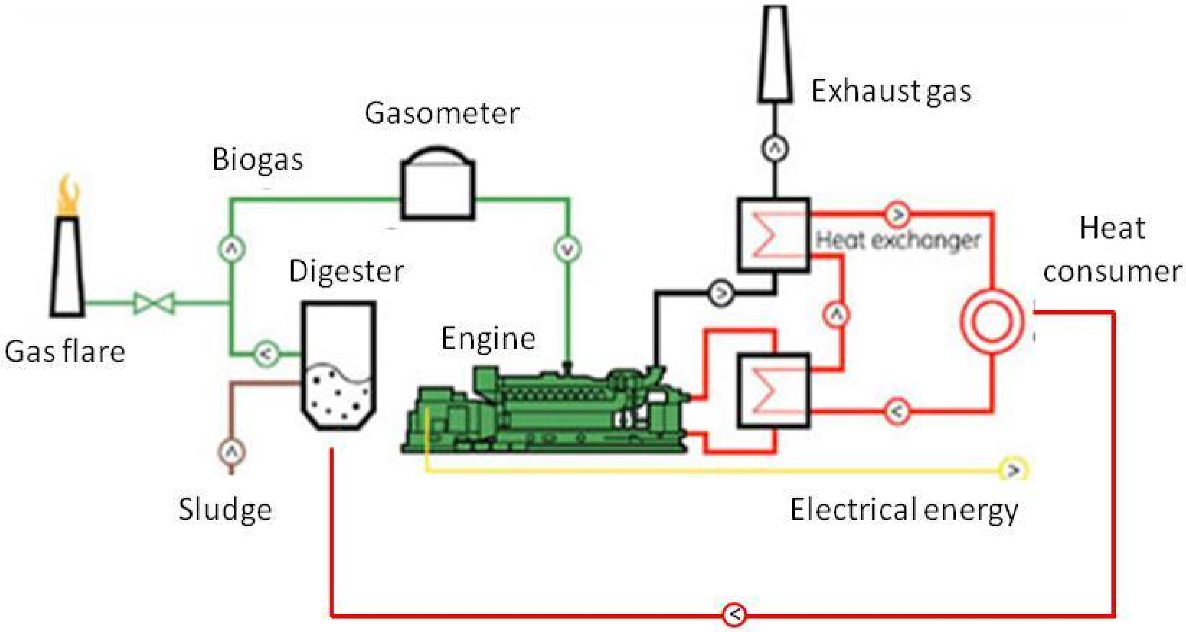

Figure 2: Configuration of energy production system using a engine CHP.

Table 6: Energy, electricity and heat calculations for engine.

Energy calculation		
PCI biogas	5500	kcal/m^3
Biogas	26046	m^3/d
Energy produced	143255063	kcal/d
	60758769	kWh/year
Power energy required	6935	kW
Engine electricity and heat		
Energy power (x3)	2716	kW
Electrical efficiency	39	%
Thermal efficiency	48.6	%
Loses	12.4	%
Electricity production	23695920	kWh/year
Heat production	29528762	kWh/year
Loses	7534087	kWh/year

The use of an engine instead of a boiler, was positive because we generate electrical energy and not only heat. But the boiler produce more heat than the engine because it has a 85% of thermal efficiency compared with the 48.6% of engine. However, the lower heat production in engine didn't compromise the digester heat needs (Table 7 and 8), that was calculated using the following formula:

$$Q_r \left[\frac{J}{d}\right] = q_0 \left[\frac{m^3}{d}\right] . p \left[\frac{kg}{m^3}\right] . \Delta T[K] . Cp \left[\frac{J}{kg.K}\right] \quad (5)$$

Q_r: sludge heat needs
q_0: sludge flowrate
p: sludge specific weight
ΔT: Temperature variation from initial and final sludge temperature
C_p: sludge specific heat

The Qr is the total heat requirement to increase the sludge temperature from 14^{o}C to 35^{o}C (ΔT=21^{o}C).The first temperature is the lower sludge temperature expected during winter season, and the last one is the temperature needed inside anaerobic digester. To know the exactly heat required is important to estimate the loses from thermal transmission by the digester walls, this value was obtained from AySA

(2018), and finally add it to the heat needs to obtain **Q_T (Total digester heat)**. In Table 7 is presented the Q_T calculation. The **q_o** includes the co-substrate and the water that is necessary to add with co-substrate (1:1 volume ratio) to facilitate the mixing (see 4.3 section). It represented a 10% extra flowrate.

Table 7: Calculations of sludge heat needs using formula (5)

	Digester heat needs	
q_0	1531	m^3/d
p	1000	kg/m^3
ΔT	21	K
C_p	4.186	J/g.K
Q_r	**1340442**	**Kcal/h**
Digester loses	1024716	Kcal/h
Total digester heat (Q_T)	**2365158**	**Kcal/h**

Once the **Q_T** was obtained, the next step was to estimate the losses of the heat exchangers employed to transfer the thermal energy from combustion gases to sewage sludge. In Table 8 was calculated the **total system heat requirement** (**Q_{ST}**) including the heat exchanger looses by thermal transmission (10%) and looses by pipe fouling (10%). The percentage of looses were given by AySA (2018). Finally, the **Q_{ST}** calculated (taking into account all the looses) was less than the heat produced by the biogas engine, so there is no need of extra energy supply to maintain the digester temperature in 35^oC.

It was considered in plant facilities exist a reserve boiler as an alternative heat production in case of engine break down. The boiler would produce the necessary heat to maintain digester temperature. This boiler was the one AySA planned to construct.

Table 8: Calculation of total system heat requirement.

Total system heat requirement		
Total digester heat (Q_T)	2365158	kcal/h
+ Heat exchangers looses (10%)	2601673	kcal/h
+ Pipe fouling looses (10%)	2861841	kcal/h
Total system heat (Q_{ST})	2861841	kcal/h

The engine electric energy production estimated (Table 6) was enough to supply the WWTP demand, considering the sludge treatment energy consumption (that today is in construction). This result is in concordance with other authors (Lindtner, 2008; Kolisch, 2010; Kappeler et al., 2012) that mentioned WWTP > 100.000 inhabitants can get self energy supply.

To estimate the energy needs of Sudoeste Plant, was used the energy consumption of other plant belonging to AySA, called Norte Plant. The reason of this was the plant mentioned has sludge treatment, so it has the same facilities configuration Sudoeste will have once the construction finished. Nevertheless, Norte Plant is a smaller plant (1.4 m^3/s treatment flowrate) comparing with Sudoeste Plant (2.87 m^3/s treatment flowrate), therefore an extrapolation were done to estimate energy consumption. Finally, the Sudoeste Plant energy consumption estimation was **1,883,804 kWh/month**, that is lower than the electrical energy produced (Table 6).

In Argentina, the energy produced by Sudoeste plant can be consumed by the company without any charge of it, and this is an important difference with Spain that obliges water companies to sell the energy and then buy it with taxes including.

5.4 Biowaste mixing and shredding (Pulper)

The biowaste needed a treatment before addition it inside the digester. This was an important step because the biowaste is a heterogeneous mixture with different components size that is necessary to treat to obtain an homogeneous stream. It was proposed to use the Chopper pump from Vaughan company (Figure 3), that is employed in a real case in a WWTP in Canada (Park et al., 2011) and act as a pulper. The pulper is an installation that combines the functions of a mixer and a shredder. The Chopper pump has an impeller with blades that cut and mix the biowaste as it passes through it. To facilitate the use of this system was important to add water with the biowaste in 1:1 volume proportion. In Table 9 is presented the principals operative parameters of this pulper system. The system considered has a mixing tank where the biowaste is continuously recirculated for a set time, and once the stream is homogeneous the valve of recirculation is closed and then the flowrate is pumped into the digester (Batch system). This procedure will be done 10 (ten) times per day. In Figure 4 can be seen the pulper system configuration. In Annex II is presented the fact sheet of Chopper pump.

Table 9: Pulper system parameters

Pulper system		
Total biowaste and water	142.5	m^3/d
Co-substrate flowrate	2.97	m^3/h
water flowrate	2.97	m^3/h
Bomb presure	20	mca
Mixing tank	20	m^3

Figure 3: Picture of Vaughan Chopper pump.

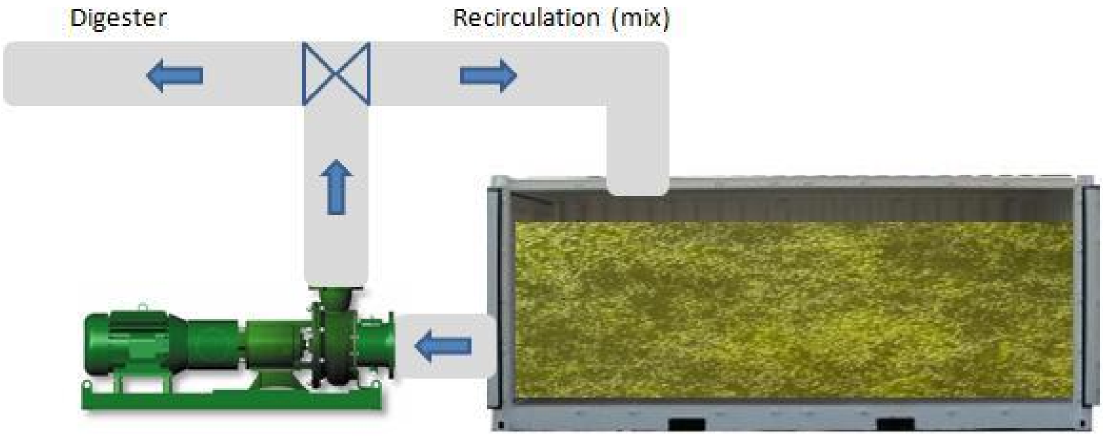

Figure 4: Pulper system configuration.

5.5 Biogas treatment

The use of co-generation engines for a long time depends of biogas quality. In a WWTP the biogas has a good quality compared with Ecopark or dumpfill biogas, where the biogas is generated from a mix of waste: organic matter, plastics, metals, solvents, etc (Baspinar et al., 2011). Biogas quality from wastewater are more homogeneous but has some component that could affect engine parts as: water gas and H_2S (Tchobanoglous et al., 2003). Both are present in biogas in small proportion, between 0 and 3% of biogas (Tchobanoglous et al., 2003; Noyola et al., 2006).

This project proposed a water gas separator to remove the water gas. This is a dispositive with physical obstacles that eliminate water vapor from biogas in its path inside the equipment as can be seen in Figure 5.

The separation of hydrogen sulfide (H_2S) were done using a bioscrubber (Figure 6). The removal of H_2S using this technology involves two stages: firstly absorption of H_2S in liquid, and secondly biological oxidation of H_2S (in the liquid). Scrubbers are designed to favor mass transfer from air to liquid phase (using bedfilters), once that is achieved, nutrients and NaOH is added to give better conditions to the microorganism responsible of H_2S oxidation. Hidrogen sulphide reduce pH in liquid, so is needed to add NaOH to control the pH of the media (Syed et al., 2006).

This treatment was selected because is cost reduced compared with other biogas treatments, and also this technology has shown good results in full scale plants (Hansen & Rindel, 2000; Potivichayanon et al., 2006; Syed et al., 2006; Arespacochaga et al., 2015).

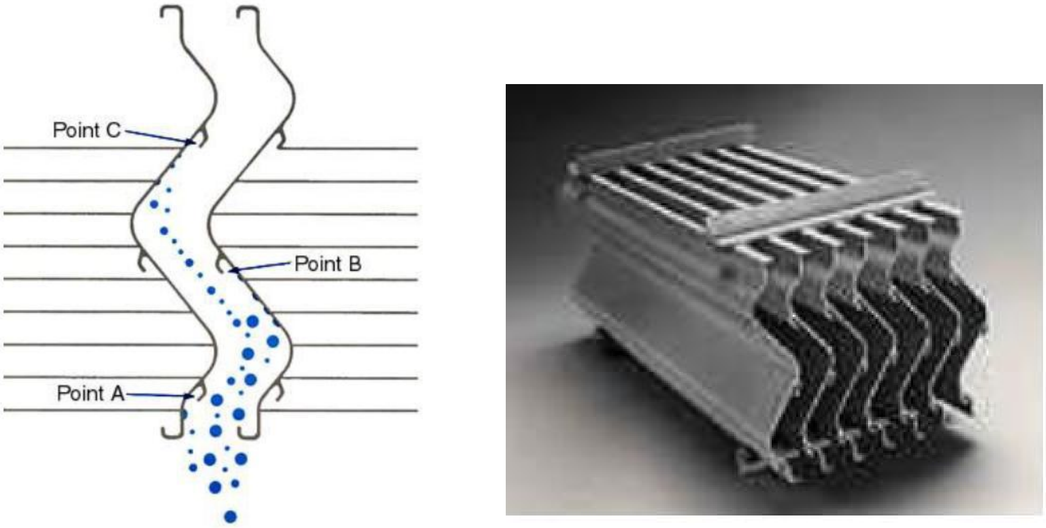

Figure 5: Water gas separator dispositive and functioning.

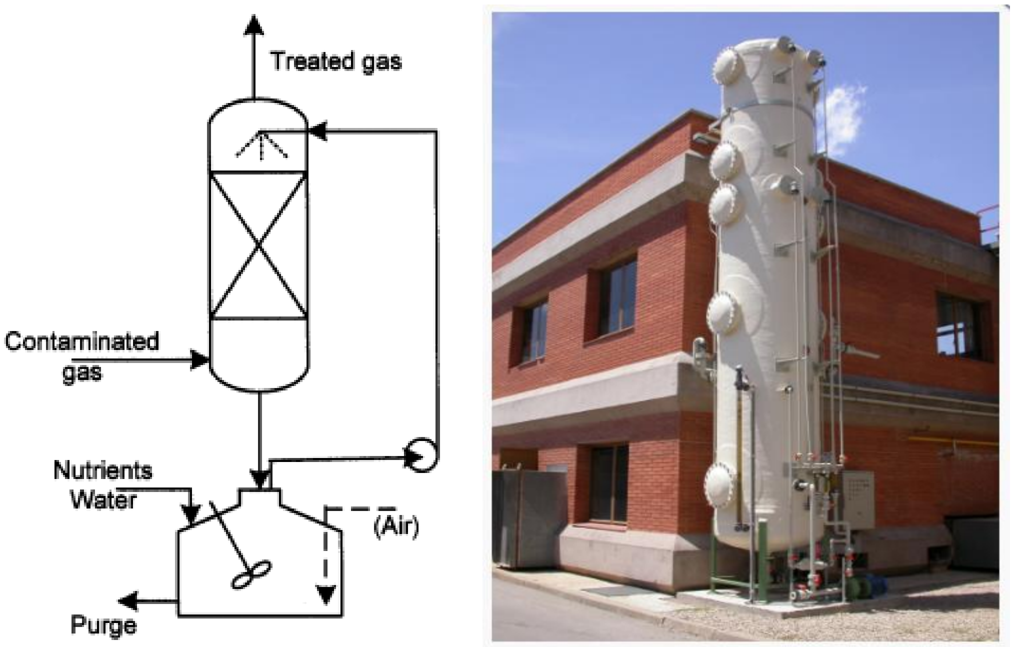

Figure 6: Bioscrubber configuration and real installation in a WWTP.

In conclusion, the facilities of co-digestion included the pulper (to convert the biowaste in a homogeneous stream), and the co-generation facilities that included biogas treatment (bioscrubber and water gas separator), engine and heat exchangers. The overall system configuration can be seen in Figure 7. In Annex III is presented the possible location of the equipment proposed.

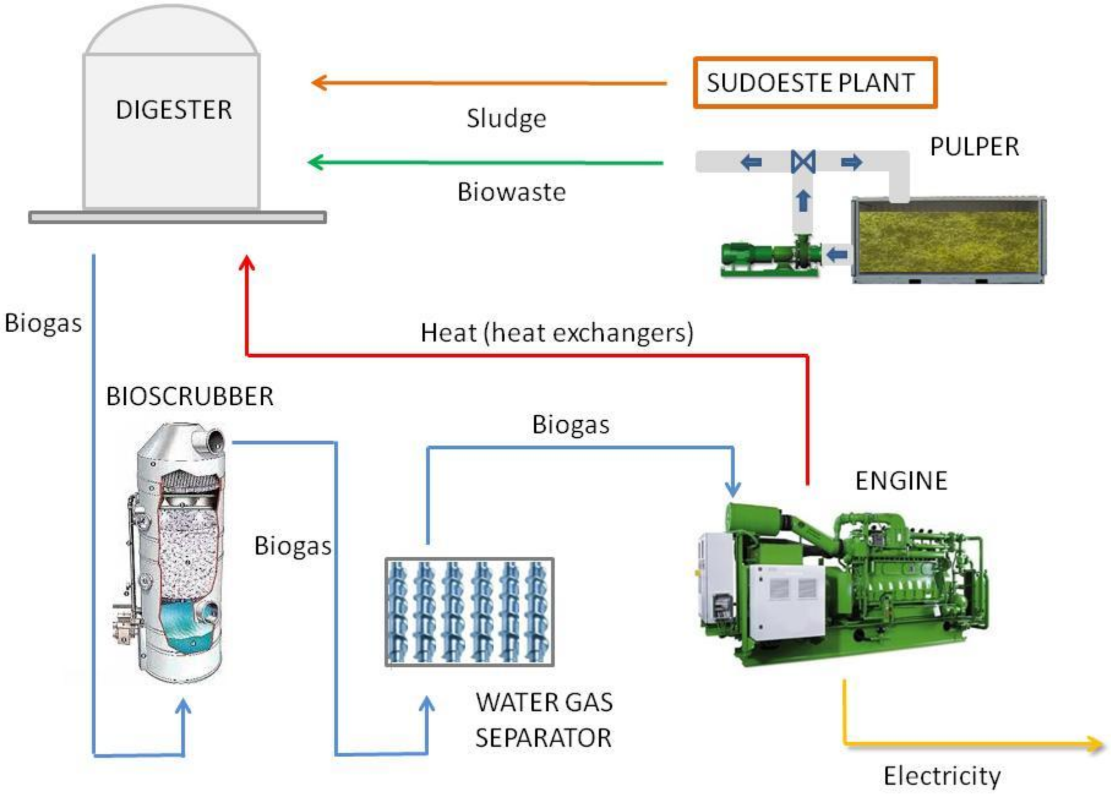

Figure 7: Co-digestion and co-generation system proposed for Sudoeste Plant.

5.6 Project economical cost

The economical analysis were made using a research work of Arespacochaga et al. (2015) where the authors investigate the current application of co-generation technologies taking operational and economical data from six industrial-scale plants. The installation costs were included in equipment capital cost showed below (Table 10). In Annex IV is presented the complete table from

Arespacochaga et al. (2015) from where was taken all the assumptions for economical analysis.

First, It was calculated the cost of co-generation engine that are the most expensive investment of overall project. In Table 10 were shown the cost of Jenbacher J320 engine, its maintenance and the transportation cost to Argentina. It is important to mention, that importation taxes are not considered in this project because the National Law 26,190 in Argentina gives to the companies the possibility to import technology without customs taxes and with local taxes reduction as well. This law encourage the use and production of clean energy to replace the consumption of fossil fuels.

Table 10: Economical data of co-generation engine

Jenbacher engine cost			
Engine cost	1000	€/kW	Arespacochaga et al. (2015)
Jenbacher power	2716	kW	-
Jenbacher cost (x1)	2716000	€	-
Jenbacher cost (x3)	8148000	€	-
Total cost (+10% transportation)	**9370200**	**€**	**-**
Maintenance cost	0.013	€/kWh	Arespacochaga et al. (2015)
Total maintenance cost	**308047**	**€/year**	**-**

The other technology necessary for co-generation system is biogas treatment. The option selected for this project was a bioscrubber. One of the principal reason to choose it was the lower operational cost in comparison with others treatment technologies (chemical scrubbers, activated carbon, etc). Bioscrubber treatment needs to add caustic soda (NaOH) and nutrients, and it quantity will depend of H_2S mass flowrate in biogas stream. In Table 11 is presented the H_2S mass flowrate calculated (It was assumed 1% of hydrogen sulfide in biogas), and in Table 12 the biogas treatment cost.

Table 11: H_2S mass flowrate calculation

H_2S mass flowrate		
Biogas flowrate	26046	Nm^3/d
H_2S flowrate (1%)	260.46	Nm^3/d
H_2S mol	10840.9	mol/d
H_2S mol weight	32	g/mol
H_2S mass flowrate	346.9	kg/d

Table 12: Biogas treatment facilities, maintenance and supplies cost. Table reference: Arespacochaga et al. (2015).

Biogas treatment		
Bioscrubber cost	1600	€/Nm^3/h
Bioscrubber total cost	1736425	€
Maintenance cost	34729	€/year
NaOH consumption	2	kg NaOH/kg H_2S
NaOH Total	693.8	kg/d
Nutrient consumption	0.15	L nutrient/kg H_2S
Nutrient Total	52	L/d
Bioscrubber electrical consumption	7.43	kWh/kg H_2S
Total electrical consumption	940800	kWh/year
NaOH cost (1 €/kg)	693.8	€/d
Nutrients cost (2 €/L)	104.1	€/d
Total NaOH and nutrients	262391	€/year

The technology proposed for co-digestion implementation was the pulper system, based on a real case in a WWTP of Canada (Park et al., 2011). That plant use a Vaughan Chopper pump in a pulper system where the biowaste is passed through pump blades, blending and transforming the biowaste in an homogeneus stream suitable to get inside plant digester. In Table 13 is presented the pump cost and its energy consumption rate.

Table 13: Economical data of pulper system

Pulper system			
Pump + mixing tank	425000	€	Vaughan Co.
Maintenance cost	42500	€/year	-
Energy consumption	35040	kWh/year	-

This project considered that the actual biowaste management cost paid by Central Market, that includes transportation and landfill disposal, will be given now to AySA as the new responsible for their waste treatment. This is beneficial for both, because AySA receive a compensation for the waste treatment and Central Market find a destination for their wastes (actual landfill will close in 5 years and the alternatives are expensive). Hence, in Table 14 was calculated the actual cost of biowaste management of Central Market, that was part of the benefit of the co-digestion and co-generation project in Sudoeste Plant.

Table 14: Biowaste management cost calculation

Biowaste management cost		
Waste management cost	27.7	€/t
Biowaste generated	57	t/d
Total waste management cost	445779	€/year
Project income	**445779**	**€/year**

5.7 Economic feasibility analysis

At this point, the work has demonstrated the project is technically viable cause the increase in biogas production, as a consequence of co-substrate addition, generate enough energy (heat and electricity) to supply Sudoeste Plant demands. Nevertheless, economic analysis was the last step to define if the project is feasible to carry out or not. In the next paragraph it is mentioned the assumptions considered for this analysis.

- The electrical energy production of Sudoeste Plant was considered as an income of the project, because is a cost the plant won't pay with the project. The excess electricity was injected to the electrical grid.
- The electricity price used for cost savings is 0,074 €/kWh, that is the real energy cost for Sudoeste Plant (AySA, 2018).
- The electricity consumption by the overall co-generation and co-digestion system (engine + bioscrubber + pulper) was considered as a cost.
- The man-power associated to the project was 2 person and 3 work shift (8 hours each work shift). The total amount of man-power cost was 124138 €/month, considering the salary of AySA in 2018.

The economical analysis to evaluate the project were done calculating the Net Present Value (NPV). The NPV is a measurement of profit, calculated by subtracting the present values of cash outflows (costs and capital investment) from the present values of cash inflows (incomes) over a period of time. A positive NPV indicates that the projected earnings generated by this project exceeds the anticipated costs. Generally, a project with a positive NPV will be profitable, and a project with a negative NPV will result in a net loss. In Table 15 is presented the parameters used to calculate the NPV. The formula to calculate NPV is the following:

$$NPV = \sum_{t=1}^{T} \frac{C_1}{(1+r)^t} + C_o$$

C_1: net cash inflow during the period *t*
C_o: total initial investment cost
r: discount rate
T: number of time periods

The capital investment, total incomes and costs can be seen in Table 15. The life of the project (T) is 15 years (equipment life), and the discount rate (r) is 8% because is the rate used by AySA to evaluate their projects (AySA, 2018).

Table 15: Capital investment, operative cost and incomes used to calculate the project NPV.

Capital Investment	11,531,625	€
Incomes electricity	1,753,498	€/year
Incomes biowaste treatment	445,779	€/year
Total incomes	2,199,277	€/year
Maintenance equipment	378,764	€/year
Equipment supplies	291,230	€/year
Man-power cost	124,138	€/year
Electricity consumption (project)	52,285	€/year
Total costs	846,417	€/year
T (number of period)	15	year
r (discount rate)	8	%
NPV	**48,154**	**€**

The NPV gave positive values (48,154 €) therefore this project is economically affordable and the company will obtain the 8% of benefits (discount rate) in 15 years of project life.

Before it was said this project was technically viable, so given the positive economical results, this project is recommended to its implementation in Sudoeste Plant.

5.8 Results scope

The convenience of co-digestion and co-generation implementation has been shown in this TFM. However, it is important to go further with the analysis and validate the assumptions taken during the development of this work. The TFM has demonstrated, the project is **technical and economical feasible,** even using conservative values, but the next step is to validate this empirically. One option would be perform a lab-scale experiment to evaluate the biogas production using a real sample of sludge and biowaste. If it were necessary, a pilot scale experiment could be done to obtain more representative results. There are two principal reasons for the necessity of experimental results. First, the co-digestion is a very complex process and could exist inhibitive and synergistic effects that hasn't been considered. Second, a project of this magnitude needs the more accurate results possible for plant engineering design. For instance, based on the analysis of this TFM, the co-digestion biogas production was enough to generate the electrical energy to supply Sudoeste Plant, but probably the values could be higher indeed (this work used conservative data), and that would change the engine capacity, heat production, heater exchangers, etc. Therefore, the TFM analysis realized was very important to demonstrate co-digestion is an excellent option for Sudoeste Plant, nevertheless will be necessary further analysis (experimental data) to achieve the final implementation of the project.

6 CONCLUSION

- The TFM demonstrated the feasibility of co-digestion between biowaste (Central Market) and sludge (Sudoeste Plant), considering the electricity and heat produced is enough to supply plant demands.
- Sudoeste Plant can absorb all the biowaste generated by Central Market. There is available space in plant digesters to add all the biowaste.
- The addition of co-substrate represent only 5% of total sludge flowrate and generate a 28% enhancement of biogas and methane production.
- The biogas produced need a pre-treatment to protect engine parts. A bioscrubber and water gas separator were selected to eliminate hydrogen sulfide (H_2S) and water vapor, respectively.
- The co-generation system produced electrical energy using a biogas engine and heat via combustions gases (heat exchangers). The electrical energy is consumed by the plant. The heat produced is used to warm up the digester.
- This project will be positive to the company and the environment as well. It will produce clean energy, reduce biowaste transportation (reducing fuel gas consumption) and avoid biowaste sending to landfill.
- The TFM proves the benefits of the project, but is needed further analysis to provide all the information required to final implementation.

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ANNEXES

ANNEX I

Engine fact sheet

ANNEX II

Chopper pump fact sheet

ANNEX III

Facilities and equipment location

ANNEX IV

Table of technical and economical assumptions