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Direct Energy Balance of Anaerobic Digestion (AD) Toward Sustainability

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Currently, the biogas production from organic waste (OW) refuses through AD has been and continues to be one of the most widely used processes for energy production. Usually, AD is carried out in thermophilic (TC) or mesophilic conditions (MC); some authors claim that it is far better to work in TC than MC, others explain that there are no major differences, while some others affirm that the MC has highest performance. Even if each in of single case, the statement is true, it is necessary nowadays to have a valid and objective criterion in order to compare different studies and mainly to assess the energetic sustainability of AD. To this purpose, in this paper, an Energy Sustainability Index (*ESI*) parameter is candidate. The *ESI* is the ratio between the energy obtained under form of H_2 and/or CH_4, and that spent as direct energy to heat the fermenting broth at the working temperature and when present, the energy spent as heat in the broth pretreatment. In Author's opinion this fact is the first check toward sustainability of AD technology as mean to produce energy. Only in the case of *ESI* > 1, it is possible to consider others energy spent to produce the energy, in fact, for *ESI* < 1 the energy obtained is less than the spent one, i.e. the process is unsustainable. About 30 studies were initially taken into account, but only 15 of them provided the necessary information to carry out the study. Among 15, only 3 studies proved to be truly energetically sustainable, with an *ESI* > 1. The *ESI* here proposed represents the first step of a more detailed energy sustainability evaluation procedure, performed using a LCA (life cycle assessment) approach.

1. Introduction

In latest years, AD has gained more and more attention as technology, able to produce energy under H_2 as well as CH_4 form, using OW refuses as feedstock. AD has been considered the main commercially option for both treatment and recycling of biomass wastes, being of great interest from the energetic point of view, converting the organics in energy and in a residue able to be used in agriculture.

Recently, a two-stage process combined hydrogenesis and methanogenesis has been received increasing attention. Owing that H_2 production from OW is accompanied by the production of volatile organic acids which are suitable substrates for CH_4 production. The energy analysis performed by Ruggeri et al. (2010) suggested that the two-stage fermentation process had greater net energy recovery than the single H_2 fermentation process. The AD technology is commonly conducted either in TC or MC, each of one with their respective advantages. Many authors describe these advantages, giving greater or lesser importance to those aspects which considered most relevant. For example, Lee et al. (2008) affirm that MC is preferable to TC for H_2 production. Nazlina et al., (2009) noticed that H_2 production rate in TC (60 °C) slows, while Liu et al. (2008) revealed that H_2 production yield is higher at TC. Jingquan et al. (2008) on their part, assert that the advantage of TC derives from higher metabolic activities and higher substrate conversion rates of encreasing methane production rate. All these statements are true in each respective case, however, it would seem that TC provide a lot of benefits more than MC, but, from the energetic point of view, it is important to know if the energy produced is higher than that spent. For this reason, a study to assess how convenient is to work under different temperature conditions arises. In Author's opinion, thermal balance is the first step to be consider towards energy sustainability, because if the energy consumed for heating the substrate until the working temperature plus the heat spent for the pretreatment of the feed, is greater than the energy produced, this is sufficient to say that the process is in energy debt. However, if the energy produced is greater, the sustainability would be questionable, because it is necessary consider some other aspects such as the energy consumed to maintain the substrate at working temperature, the energy consumed for agitation, the energy spent to produce chemicals, the energy for the maintenance etc.

To evaluate the sustainability we propose an energy sustainability index (*ESI*), that takes into account the total energy produce as H_2 and/or CH_4, respect to the direct energy spend under heat form. This is a first

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step of a more accurate tool to score and compare several AD process in an objective way, and more important, indicating the direction of such technology change towards energy sustainability.

2. Methodology

To assess the sustainability we propose the ESI, which takes into account the total amount of energy produced as H_2 and/or CH_4, and the amount of energy spent to heat the substrate from ambient temperature to the working temperature and/or to the pretreatment temperature: it is defined as:

$$ESI = E_p/E_c \tag{1}$$

where E_p is the total energy produced, (kJ/m^3 or kJ/m^3·d) and E_c is the total energy consumed in the thermal aspect (kJ/m^3 or kJ m^3·d). If the ESI > 1 means that the process is sustainable at least for the thermal aspect. If ESI ~ 1, the process is questionable, and lastly, for ESI < 1, the process is not energetically sustainable. The total energy produce was calculated considering the moles of H_2 and/or CH_4 produced per unit of volume of the fermenting broth, multiplied by the respective Low Heat Value (LHV), as follows:

$$E_p = \sum n_i * LHV_i \tag{2}$$

where n_i is the total amount of moles produced (mol/m^3 or mol/m^3·d); LHV_i: Low Heat Value (kJ/mol). [LHV_{H2} = 239.20 kJ/mol and LHV_{CH4} = 800.29 kJ/mol];and *i*: hydrogen or methane. The moles were calculated considering the gases volume at standard conditions. On the other hand, the E_c to heat 1m^3 of fermenting broth from ambient temperature (10°C, taken as an average between winter and summer times) to working temperature was calculated in this way:

$$Ec = \dot{\rho} * cp * \Delta T \tag{3}$$

where $\dot{\rho}$ is the specific density (1000 kg/m^3) and C_p is the specific heat capacity (1kcal/kg·°C), considering the fermenting broth similar to water; this because the total solid concentration in the study considered never was higher than 15%; this mean that the study is valid for wet fermentation processes alone.

2.1 The Sustainability evaluation approach

The *ESI* is a first screening of a technology towards the energy sustainability. Figure 1 reports a so called "Analogical model". A flow-sheet of showing each energy flow, including that embedded in the material necessary to be considered in order to define the sustainability of the technology. Ruggeri et al. (2013), unlike Authors as Cleveland and Costanza (2010), preferred to use the term *"useful"* for the energy delivered to society and the term net for the energy produced by the plant minus the direct energy necessary to run the plant itself. According to the concept introduced by Röegen (1976), in order to have the energy sustainability it is necessary that the technology is vital (*viable*). Like a biological system, an energy technology must be able to produce a quantity of *useful* energy that is able to sustain itself in order to sustain "others". It necessarily needs to use only a part of the energy source for its operational necessities and reproduction, and the remaining part will be used to feed civilization in an appropriate form.

Some explanation on the used terms of Figure 1, for additional details refers to Ruggeri et al. (2013). To perform the energy balance, all the energy quantities should be evaluated in energy units per unit volume of bioreactor (MJ/L). First of all it is important to estimate the energy available from the substrate used as feed; the calculation of the "Available Energy" is based on the *LHV* of the substrate. The "Produced Energy" is the total energy that the AD technology, including actual biological and reaction engineering knowledge, is able to produce in the gas form, i.e. the energy contained in the biogas as H_2 and CH_4 retrieved from the reactor during its lifetime. The "Direct energy" is the energy spent in order to operate the process: it considers the heating heat necessary to reach the working temperature, the heating heat necessary to reach the pretreatment temperature (if present), the thermal energy loss (which depends on the outdoor ambient temperature and the duration of the fermentation), the electrical energy necessary to mix the fermenting broth during the fermentation, the electrical energy necessary to mix the biomass during the pretreatment and the electrical energy necessary for feeding and drawing the fermenting broth in reactor.

The "Net energy" is the difference between energy produced and that spent directly. The "Net energy" and "Useful Energy" differ from each other because of the contribution of the "Indirect Energy". Both Direct and Indirect Energy need to be measured in a physical energy unit; hence it is necessary to convert all the material flows into energy units. In the process, materials that were produced elsewhere are usually used. This leads to a higher consummation of energy, but without it the process cannot take place.

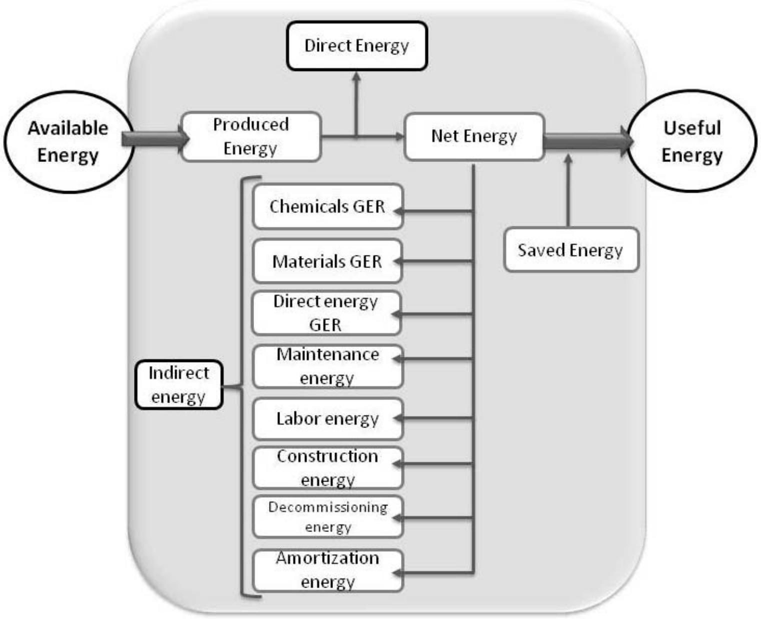

Figure 1: Analogical model of a generic process

The Saved Energy is evaluated considering the *GER* of landfill disposal OW using the Ecoinvent database (Ecoinvent, 2007). As time boundary was considered the operational time of the plant i.e. the time during which all the generated energy was computed and, at the same time, all the spent energy was computed.
After the *ESI* and the Analogical Model evaluation, the sustainability assessment is finally completed by using two parameters: Energy Return On Investment (*EROI*) and Energy Payback Time (*EPT*). In agreement with the notations explained for the Analogical Model, *EROI* is the ratio between the total amount of Net Energy produced by a technology during its working lifetime and the amount of total Indirect Energy involved in the process to produce energy. It is a ratio between two energy quantities, and is therefore dimensionless. In mathematical terms, *EROI* is:

$$EROI = \text{Net Energy} / \text{Indirect Energy} \qquad (4)$$

Numerically speaking, only an *EROI* > 1 indicates a sustainable process. *EPT* is a similar and related concept; it represents the time required for a process to produce an amount of energy equal to the amount of energy used for its construction and operation as indirect energy, so it indicates the time at which the technology is able to feed the energy service for the society.

3. Results and Discussion

3.1 About the necessary date for sustainability analysis

Initially, about 30 studies were taken into account to perform this research, however not all of them could be effectively evaluated because the information provided was incomplete or was not clear enough. For this reason it is extremely important to establish which data are essential and how they should be expressed, in order to permit the comparison of different studies in a clear and simple way. Besides a detailed explanation of the process, data such as reactor volume and mode of operation, type, concentration and *LHV* of the substrate, temperature, pH, residence time, biogas production, H_2 and/or CH_4 concentration in the biogas must be accurately supplied, as reported in Table 1.

Table 1. Parameters of interest in an anaerobic digestion process.

Parameter	Unit
Volume of reactor	L – m^3
Operation mode	Batch – Semi Continuous – Continuous
Substrate concentration	g*TSS*/L – g*TVS*/L – kg*TSS*/m3 – kg*TVS*/m^3 g*TSS*/L.d – g*TVS*/L.d – kg*TSS*/m^3.d – kg*TVS*/m^3.d
LHV of the Substrate	kJ/kg*TSS* - kJ/g*TSS* - kJ/kg*TVS* - kJ/g*TVS*
Temperature	°C
Residence time	h – d

Biogas production	L/L – m^3/m^3 – L/kg*TSS* L/L.d – m^3/m^3.d – L/kg*TSS*·d	
Hydrogen/Methane	%	L/L – m^3/m^3 L/L.d – m^3/m^3.d
Energy produced	kJ/L – kJ/m^3 – kJ/kg*TSS* - kJ/g*TSS* - kJ/kg*TVS* - kJ/g*TVS* kJ/L.d – kJ/m^3.d – kJ/kg*TSS*.d - kJ/g*TSS*.d - kJ/kg*TVS*.d - kJ/g*TVS*.d	

In the present study such parameters as residence time and the biogas production, H_2 and/or CH_4 concentration, were difficulty to found, with the consequence that about half of the studies were cancelled. In some reports, the retention time were changed many times, apparently without any criterion, and without even having done a cycle. Another anomaly found was that in a continuous process, the biogas production came not expressed per unit of time, and in some cases were expressed per unit volume of the reactor instead the fermenting volume used.

On the other hand, It is necessary to highlight the importance of the *LHV* of the substrate because this parameter allows to evaluate the efficiency of a AD process, i.e. the quantity of energy produced by AD on that embedded in the substrate. In this study was not possible to calculate the efficiency owing the lack of the values of *LHV* of the substrates.

3.2 Energetic sustainability

Table 2 summarize the results of the first step of energy sustainability analysis. In it, the main data from each study and the energetic analysis are reported. 15 studies were analysed; some produced H_2, some other only CH_4, or both; 6 were performed in batch condition and 9 in continuous mode, with different substrates and inoculum. We included in the analysis our experimental work (Mejias, 2013) too; the vast majority of studies were conducted in TC, with the exception of studies #6 and #15, with temperatures ranging from 52 to 70 °C. Among all the considered reports, only in the case #15 the substrate was thermally pretreated at 100 °C for 10 minutes. In this case the energy consumed is referred to the energy spent in the pretreatment alone, supposing that the broth was cooled not heated, to the working temperature of 35 °C. Analysing in detail the Table 2, it can be seen that only 6 of the 15 studies has a *ESI* greater than 1, which means that they are possible sustainable process. Despite this, it is true that #13 and #14 have *ESI* > 1, but it is also true that the energy produced is barely enough to cover the energy needed for heating the substrate. These studies probably would be unsustainable when the others terms of the Analogical Model will be considered. Only the studies #6, #9, #10 and #12 would be sustainable; among them, the study 9, which has an *ESI* of 2.49, is quite questionable due to the low value of *ESI*. Finally among the analysed studies, only 3 are sustainable, #6, #10 and #12, because they produce about four-five times more energy than the energy spent as heat. It is very important to highlight the magnitude of the analysis made in this study, because of the 15 studies reviewed, only 3 actually turn out to be energetically sustainable, leading us to affirm that it is extremely necessary to make an analysis of this type. On the other hand, as shown in Table 2 the H_2 production alone in TC is tremendously unsustainable. In contrast, the CH_4 production in TC is still questionable while the CH_4 production using MSW in TC is unsustainable. However, it can be seen that the two-stage studies, producing H_2 plus CH_4, are more sustainable, compared with the single stage producing only CH_4.

4. Conclusion

For the *ESI* evaluation as first step towards the energy sustainability of AD technology, 30 studies were considered. From these only 15 merited to be analysed, because the lack of necessary information, and among them only 3 had an *ESI* greater than 1, indicating that the energy produced as biogas either H_2 or CH_4 or both, it was higher than the energy spent as heat to conduct the fermentation. This could introduce a serious reflection on the thermal balance of the AD process.

Table 2. Literature review of hydrogen and methane fermentation and their sustainability analysis.

#	Reference	Substrate	Inoculum	Operation	Working Temperature (°C)	Hydrogen		Methane		E_P	E_C	*ESI*
						m^3/m^3	kJ/m^3	m^3/m^3	kJ/m^3	kJ/m^3	kJ/m^3	
1	Forster-Carneiro et al., 2007	Municipal Solid Waste (MSW)	Sludge	Batch	55	-	-	1.14	34004	34004	188100	0.18
2	Nazlina et al., 2009	Food Waste	Sludge	Batch	55	2.14	19032	-	-	19032	188100	0.10
3	Karadag et al., 2009	Glucose (9 g/L)	Culture from turkish hot spring	Batch	52	-	16385	-	-	16385	376200	0.04
4	Wang et al., 2011	Cassava Stillage	Sludge	Batch	60 - 60	0.55	4840	0.97	28531	33371	209000	0.16
5	Liu et al., 2008	House Solid Waste (HSW)	Manure	Batch	70	5.14	43714	-	-	43714	250800	0.17
6	Mejias, 2013	Organic Waste Market (OWM)	Acid Manure - Manure	Batch	35 - 35	1.17	11081	15.53	492099	503180	104500	**4.82**
				atch		V (m^3/m^3·d)	kJ/m^3·d	V (m^3/m^3·d)	kJ/m^3·d	kJ/m^3·d	kJ/m^3·d	
7	Wen-Chien and Kae-Yiin, 2007	Kitchen Waste	Mix (pig farm, kitchen waste and sludge)	CSTR	55	-	-	0.30	8959	8959	39710	0.23
8	De la Rubia et al., 2006	Sludge	-	CSTR	55	-	-	0.40	11902	11902	12540	0.95
9	Fdéz.-Güelfo et al., 2010	Organic Fraction of Municipal Solid Waste (OFMSW)	Leachate and Sludge	CSTR	55	-	-	0.63	18746	18746	7524	**2.49**
10	Cavinato et al., 2011	Biowaste	Seed Sludge	CSTR	55 - 55	0.84	7437	1.76	52220	59657	14929	**4.00**
11	Jingquan et al., 2008	Sewage Sludge	Sewage Sludge	CSTR	55	-	-	0.24	7186	7186	125400	0.06
12	Cavinato et al., 2012	Food Waste	Sludge	CSTR	55 - 55	1.11	9906	2.32	68898	78804	14929	**5.28**
13	Wang et al., 2011	Cassava Stillage	Sludge	CSTR	60 - 60	1.84	16118	9.12	267290	283408	209000	1.36
14	Chun-Feng et al., 2010	Food waste	Sludge	CSTR	55 - 55	5.62	49946	3.53	104886	154832	144692	1.07
15	Zhu et al., 2011	MSW	Sewage Sludge	CSTR	35 - 35	0.74	7046	3.80	120411	127457	300960	0.42

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