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Process Energy Sustainability Evaluation trough a LCA Approach

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In the present contribution an analysis of the sustainability of Anaerobic Digestion (AD) technology is performed by applying the Energy Return On Investment (EROI) and the Energy Payback Time (EPT) approachs. The present paper contributes to the evaluation of renevable energy source sustainability. The evaluation of each energetic term is performed following a Life Cycle Thinking (LCT) approach. A substantial distinction between the net energy production and the useful energy are highlighted. The sustainability of the AD is strongly dependent on the diameter of the reactor, for values less than 4 m it is not reached.

1. Introduction

The present energy crisis and environmental issues are forcing humankind to search new energy sources. Solutions can be found by many technologies using renewable sources. One of the difficulties is the need to measure the sustainability level of different technologies, and it is more important to have such an objective and effective tool to determine and possibly to score what is the direction of changes towards sustainability. To this aim in latest years several approaches were candidate ranging from a thermodynamic one such as the exergy analysis (De Swan Aron, et al., 2004), to a more industrially oriented one (Azapagic, 1999). Today the Life Cycle Assessment (LCA) is one of the most promising approaches towards the selection of a sustainable technology even if a long ways remain ahead to reach the goal. Hall et al. (2009) have proposed that the most appropriate way to judge the relative merits of different energy source could be pursued by calculating the ratio between the amount of energy produced and the energy needed to produce it, described as the EROI. EROI in its simplest form measures the output energy at the point of production. However, to take account of the final form in which the energy is used to support the needs of actual society and the efforts to maintain the civilization, it is important to introduce the concept of *energy service*, intending the energy necessary at the end user as *useful energy*. In order to have an indicative figure, EROI for oil is 20, this means that for 1 unit of energy spent for extracting, well-head treatments and new exploration, 20 unit of energy is returned to the society. At the level of the end user to cover the needs of society/civilization, EROI would need to be at least 10 (Hall et al., 2009). In this paper

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we suggest to score energy producing process by the evaluation of the useful energy and to measure it by EROI. Even if LCA has been gained wider acceptance as a method that enable quantification of environmental impacts (Dewulf and van Langenhove, 2006), it is also candidate for process selection, design and optimization (Jolliet et al., 2003). In the present paper the energy metrics of LCA will be used in order to quantify the indirect energy to evaluate the "amortization energy" in the determination of useful energy. The methodology will be applied to evaluate the sustainability of biohydrogen plus biomethane production by AD using a probe organic substance as glucose easily experimentally tested.

2. Methodology

EROI in the case of no-renewable resources is usually applied at the mine-mouth or wellhead, in the present case following the prescription of the ISO-14040 (1998) the "goal and scope definition" are: the evaluation of the useful energy produced by the technology referred to the energy embedded in the source, which is evaluable by the Low Heating Value LHV. The gate of the process is the boundary conditions, hence the analysis is of "from the cradle to gate" type, disregarding the energy spent to obtain the source because it can be considered as organic refuse produced in such process (e.g. alimentary chain). In the present contest the EROI is the ratio of the total amount of energy delivered to society by a technology during its working lifetime to the amount of total energy used directly and indirectly in such process to produce energy. It is a ratio between two energy quantities, so it is dimensionless. If its value is less than 1, this means that the technology is energetically in loss, higher values means more sustainable technology:

$$\mathrm{EROI} = \frac{\text{Total Useful Energy Produced}}{\text{Total Energy Spent}} = \frac{\mathrm{TUEP}}{\mathrm{TES}} \tag{1}$$

It is to remark that EROI is not to be confused with conversion which is well depicted by energy efficiency, i.e. going from one form of energy to another one. An analogous concept is the EPT: the ratio of the total energy expenditure to construct the plant and the useful energy produced per year; the value, expressed in years, indicates the time required for a process to produce an amount of energy equal to the invested one:

$$\mathrm{EPT} = \frac{\text{Total Energy Spent}}{\text{Yearly Total Useful Energy Produced}} = \frac{\mathrm{TES}}{\frac{\mathrm{TUEP}}{\mathrm{td}}} \tag{2}$$

To score the sustainability of a technology, it is taken into account not only the direct energy necessary to run the technology, but also all the energy expenditure for: construction materials, chemicals, maintenance energy costs, even if those energies have been spent in some other places in the World. As EROI should present a high value, EPT should present a low value: less time necessary to payback the invested energy for a specific technology. Figure 1 (left) shows the Total Energy Spent (TES) for plant construction (primary materials, construction materials, transportation, assembling, site preparation and facility construction), the Total Useful Energy

Produced (TUEP) (difference between the energy generated minus the self-use for operation, maintenances and amortization), and the duration of the facility (td) (its effective lifetime).

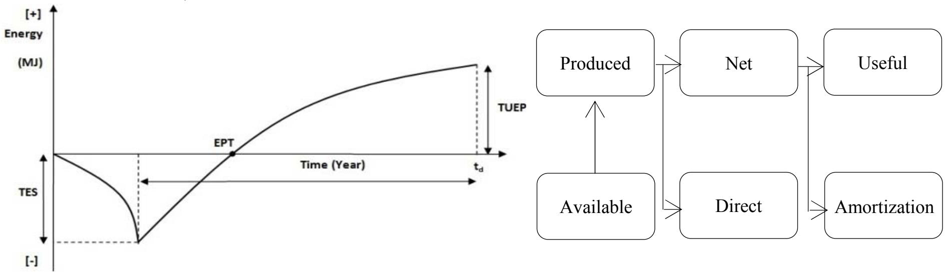

Figure 1: (Left) Global Net Energy Balance vs. Time; (Right) Energy flow-sheet of a generic process.

3. Useful Energy Evaluation

A deep theoretical formalization of the approach here is shown and each energy flow is analyzed in detail, focusing particularly on Energy Amortization which is often not considered in the literature; disregarding it is a theoretical and a practical error, because it has a great impact as quantitative term (see results). The analysis of energy flows is referred to a defined time period (e.g. 1 year or entire plant life) and to a functional unit, in the LCA words, according with the specific process under study (e.g. 1 m^3 of volume for a reactor). In Figure 1 (right) it is reported a diagram of the energy terms encountered in the energy analysis of such process.

As stated the term "useful" is for the energy delivered into the society and the term "net" is for the energy produced by the process minus the energy necessary to run the process itself. The evaluation of the useful energy assesses the change in the physical scarcity of energy resources, secondly it is a measure of the potential of such technology to do useful work in sustainable way, and finally it is possible, by it, to rank energy supply technologies. To perform a Useful Energy Analysis (UEA) of such technology it is necessary to evaluate direct and indirect energy required. Following the schematization reported in Figure 1 (right), the produced energy is the energy that the process under study is able to extract from the source in a two-step: hydrogen and methane; direct energy is the fuel and/or the electricity directly used to run the process "in gate" including the energy necessary for the facilities. The difference between produced energy and direct energy is the net energy produced in the classical term of energy analysis. Indirect energy is the energy used for: producing materials, assembling the plant, producing chemicals and all other necessary consumables, and energy spent to produce the fuels and electricity in order to have a unit of direct energy. It is important to remark that both direct as well as indirect energy need to be measured in an energetic physical unit, hence it is necessary to convert all the material flows in energy unit. To do this we used the Global Energy Requirement GER evaluated by the software SimaPro 7.2.4 (2010) and Ecoinvent database (2007). The sum of all the indirect energy is called the "energy embedded" in the technology. The useful energy is the difference between net energy and embedded energy. In mathematical terms:

$E_{net} = E_{pr} – (E_h + E_{el})$ $E_u = E_{pr} – (E_h + E_{el} + E_{it})$ (3-4)

Where: E_{net} is net energy, E_u is useful energy, E_{pr} is produced energy, E_h is energy spent for heating, E_l is electrical energy and finally E_{it} is total indirect energy. Following a LCT approach, E_{it} is energy necessary to produce construction materials E_{cm}, that due to chemicals production E_{chem}, energy necessary to produce a unit of electrical energy E^i_{el} and, finally, energy spent for labor E_{lab}; hence the total indirect energy consumption is:

$E_{it} = E_{cm} + E_{chem} + E^i_{el} + E_{lab}$ (5)

It is important to underlain that the electricity is considered twice: in equation (4) as direct and in Equation (5) as indirect. The energy spent for labor has an intrinsic difficulty to be evaluated (Brown and Herendeen, 1996) and it is often disregarded, but it could be of utmost importance in comparing different labor and capital intensive technologies. In this paper the energy embedded in labor has not been taken into account due the difficulties of both theoretical and computational point of views (Cleveland and Costanza, 2010). This means that the scoring is valid only for the comparison of similar technologies as for an example, gasification or combustion and not with energy crop production by harvesting biomass with intensive use of human labor.

4. Case study

The sustainability evaluation of the AD producing hydrogen and methane has been reported as case study of proposed LCT. We select it because we have an experimental knowledge of the technology and mostly because, in the panorama of alternative technologies candidate to produce energy from organic refuse, it is going out from the laboratory to reach the full plant application. The evaluation of the produced energy as well as the scale-up procedure to have estimation along the diameter of the bioreactor has been already reported (Ruggeri et al., 2010), here only the parameters used to evaluate the indirect energy will be shown. It is remarkable that for negative net energy values the technology is unsustainable and it makes no sense to score it.

Table 1: Contribution of indirect energy

Heat	η global efficiency for burning and heat exchange	0,6 dimensionless
Electrical Energy	Combustion of CH_4	1,12 MJ/MJ
Steel	Global Energy Requirement	27.05 MJ/kg
Polystyrene	Global Energy Requirement	135.08 MJ/kg
NaOH	Global Energy Requirement	12.55 MJ/kg (mean value)

In Table 1 GER evaluation of the used materials is reported, under the following conditions: reactor stainless steel of $3·10^{-3}$ m as structural element and polystyrene foam of $0.3·10^{-3}$ m thick as insulator; operated in batch mode with climate temperature of 5 °C and 15 °C in winter and summer time respectively; working temperatures from 16 °C till 35 °C; the plant runs for 300 d yearly, for a duration of 15 y, an additional charge of 50% of the energy embedded in construction materials has been considered for ordinary and exceptional maintenances; direct energy was supplied by in-loco methane cogeneration by producing heat and electricity; two operational situations have been considered: recovering or not the 50 % of the heat spent to heating the fermentation broth by an heat exchanger having a 60 % of efficiency; lastly, as chemicals, the addition of NaOH to control the pH of the fermenting broth has been considered in ration of 20 ml of 2N solution per liter of reactor (Ruggeri et al., 2010).

5. Results

Only some results will be shown. EROI variation vs. reactor diameter (which is the scale-up parameter for this kind of technology) is reported in Figures 2 (left): the sustainability of the technology increases with dimensions; it is possible to state that with a diameter in the range 3÷4 m, EPT is under 1 y and EROI is over 10. Lastly the best sustainable situation is reported in Figure 2 (right). It is interesting to examine in deep the meaning of the percent values: 100 % is the theoretical available energy, the percent value drops to 60 % as produced energy; this depends on actual know-how about the fundamentals of DA technology. The percent value goes down further to 44% considering the actual technology of heat exchanger and electricity production rewarded on optimization of the system, the 15 % is consumed as direct energy. In a classical energy analysis approach, 44.8 % is the percentage of energy delivered to society.
Embracing a global vision of the system, it is necessary to take into account also the energy expenditure occurred for producing materials in such part of the World. In this respect the true useful energy effectively available in the society by this technology is 9 %: this is strongly depending on materials used to construct the plant and a complete ignorance of it is not justified. Moreover the “amortization” energy for materials and consumables might depend on design hypothesis. In the present analysis we disregarded the energy content in the feedstock because glucose is not used to produce energy. This will be an interesting aspect in the case of organic refuses: the energy necessary to spend to dispose the refuses, which represent an energy cost avoided. A final consideration regards the modality to supply direct energy to run the plan: it is possible

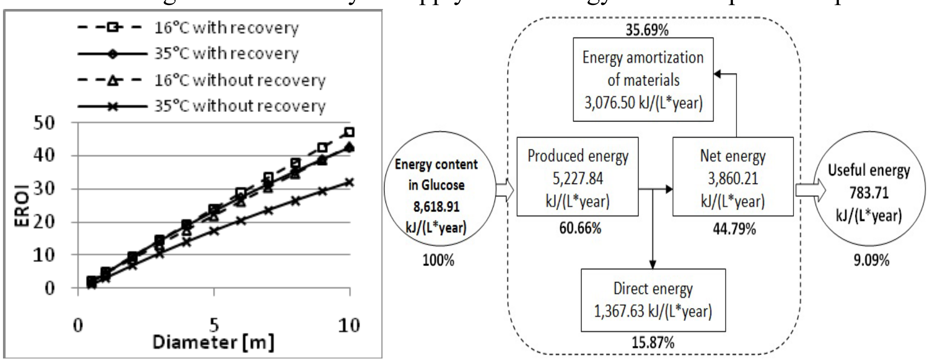

Figure 2: (Left) EROI for H_2 and CH_4 technology; (Right) Global energy balance for H_2 and CH_4 technology at T=35 °C with heat recovery, EPT=1, reactor diameter=4.

to consider furnishing this energy by using different sources, for example from a renewable one such as solar energy or wind power. In this case the degree of sustainability does not change because the use of renewable sources are removed from a different energy service in the society, in fact the useful energy remains constant. Using the exergy approach to score the sustainability of the technology, the use of renewable rather than no-renewable sources makes the difference, but this introduces only a "false-perception" of sustainability.

6. Conclusion

EROI and EPT are applied as parameters to score the sustainability of AD technology. The evaluation of indirect energy consumption following a LCA is consistent for the sustainability analysis. The sustainability of AD technology depends strongly on reactor diameter; for values lower than 4 m the technology is not able to sustain the wellbeing of the society; the effect of construction materials could be very important, in this respect a sensitivity analysis on the sustainability is welcomed.

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