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Assessment of biodiesel energy sustainability using the exergy return on investment concept

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ABSTRACT

Biofuels are part of the current energy mix and their contribution will increase in the years to come. However, policymakers and NGO have concerns regarding their sustainability. An adequate sustainability indicator is the energy return on investment (EROI), which evaluates the ratio of fossil energy consumption during their production. This paper applies the Exergy Cost Theory to different biodiesel production pathways, from crop cultivation to the production plant, in order to check if this principle is achieved using exergy instead of energy. For this purpose, it introduces a new sustainability indicator, called ExROI, defined as the ratio between the exergy of a particular resource and the amount of exergy required to obtain it. In other words, using exergy terms it tries to answer to the question: How much biodiesel would be needed to produce 1 kg of biodiesel? The paper demonstrates that the usual biodiesel production pathways are sustainable in this sense, although measures must be taken to decrease the rate of non-renewable energy consumption in the process, in order to make them economically competitive too.

1. Introduction

Biofuels are considered a renewable energy source, necessary to diversify the energy mix if nations want to decrease their emissions and reduce their dependence from instable countries. However, although renewable, as for every industrial system, biofuel manufacturing consumes natural resources. The production cycle is not reversible which means that resources are consumed and lost forever.

The great advantage of biofuels production is that a great part of the resources consumed is renewable: solar radiation used to grow the plant from which the biofuel is obtained.

Still, part of the resources consumed, the non-renewable resources, are not regenerated and this contributes to accelerate the natural increase of the earth's entropy, fostered by the economic progress [1].

In order to make sure that biofuels achieve the aims for which they are being promoted, it is necessary that they have a positive resource balance, which means that they do not imply the consumption of more non-renewable resources than the resource they are by themselves. One instrument to measure this property is the EROI, Energy Return on Energy Investment. The EROI concept, also known as EROEI or ERoEI, was defined by Cleveland et al. [2] in 1984 as the ratio of the amount of usable energy acquired from a particular energy resource to the amount of energy expended to obtain that energy resource.

The calculation of EROI does not usually include the consumption of natural sources, only the human-applied ones. The EROI concept brings an indication of the sustainability of a product only from an energy perspective (energy sustainability) and cannot be used to indicate the sustainability of a product as a whole because it does not take into account other factors such as the potential deforestation, land use changes, pollutant emissions, etc.

When applying this concept, the selection of the system boundaries is of upmost importance and always needs to be considered when obtaining conclusions of the analysis of results. For one specific product, different EROI values can be obtained if the control volume considered varies. Therefore without sufficient information two EROI results may not be comparable.

This concept has already been applied to several biofuel production processes, giving differing results depending on the control volume, raw material, production chains and energy allocation method. Thus, Russi [3] obtained that, according to different bibliographic sources, the EROI for biodiesel [4] could vary between 0.2 for soybean based

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biodiesel without allocation of energy consumption to the by-products and 4.5 for sunflower based biodiesel if meal is used as fuel [5].

However, the concept of EROI does not take into account the quality of energy, which, according to Cleveland could bring misleading conclusions in an energy balance. For this reason, he started using exergy in EROI calculations. Cleveland and Herendeen [6] applied it in solar parabolic collectors. They demonstrated that not taking into account the quality of energy (i.e. exergy or capacity to produce work) could derive in considering as qualitative the same heat at 50 and at 350 °C despite the different capacity to produce work. In a latter study focused on oil and gas extraction in the US [7], Cleveland concluded that quality corrections have important effects on the results of energy analysis, thus proposing to calculate the so-called "quality-corrected EROI". The reason is that because unlike energy balances, exergy does not only take into account the quantity of flows entering and exiting the system but also the losses of useful energy caused by the degradation of the flows along the process (irreversibility) and the capacity to produce work of the outputs. This degradation of the biodiesel cycle is "captured" by the exergy concept but not by a typical energy balance.

The exergy of a product, which is defined as the minimum amount of work required for its production, is the concept normally used in thermoeconomic analysis and represents the measure of the usefulness of the energy contained in the production flows [8]. It allows the integration of matter and energy flows in the analysis of production systems using the same concept and units for both.

The entropy generated or irreversibility represents the useful energy (exergy) destroyed in the physical processes. The more resources are consumed, the more entropy is created and the more irreversible the process is which translates in a lower sustainability.

Based on Cleveland's work, this paper defines the concept of ExROI, the Exergy Return on Exergy Investment (ExROI) on the basis of the Exergy Cost Theory and applies it to the production of biodiesel or, in other words, it calculates the ratio of non-renewable exergy consumed in the system (exergy cost) to the exergy that the biodiesel has.

This study only focuses on biodiesel, because it is the most important biofuel in Europe, achieving an 80% of the share and, therefore, special attention must be paid to it in the EU [9]. Biodiesel is produced mainly from energy crops. The most important one in the EU is rapeseed, although sunflower and palm are increasingly being considered, amongst others.

2. Exergy use for sustainability purposes

The concept of exergy has been used by many authors in different ways to assess the sustainability of production chains and life cycles, and some of them have specifically applied it to biofuels. Here a short list of papers is presented. None of the articles calculated the exergy costs of the life cycle production using the Exergy Cost Theory as applied in this paper. In addition, most of the analyses only consider the non-renewable energy consumption meanwhile this paper analyses the consumption of non-renewable resources, being these energy or material flows. In any case, independently of the specificities of the different analysis all the authors coincide to point out that the use of exergy provides a better instrument for life cycle and process analysis than the use of energy.

Cornelissen and Hirs [10] analysed the value of the so-called exergetic life cycle assessment (ELCA) and concluded that ELCA is a more appropriate instrument to quantify the environmental problem of the consumption and depletion of natural resources than the conventional life cycle assessments. In particular, they concluded that in the case of mineral resources there is no depletion at all but an increase of irreversibility caused by the need to obtain minerals from poorer and poorer ores which involves a higher loss of natural resources to obtain the same quantity of minerals. This measure of "loss" was done using the concept of exergy.

Dewulf et al. [11] analysed the production chain of soybean and rapeseed methyl esters and corn based ethanol using exergy values in order to evaluate their efficiency and renewability. They calculated the cumulative exergy consumption as the amount of resources both renewable and non-renewable that has to be extracted out of the ecosystem in order to deliver a product. Unlike this paper, they considered the irreversibility provided by the renewable inputs. As results, they obtained that the biofuels under study had a non-renewable fraction between 24.3 and 34.2.

Hovelius and Hansson [12] studied the energy and exergy efficiency of rapeseed methyl ester production. The exergy analysis was performed for the energy flows according to the "process analysis method". Unlike this paper, the chemical exergy of the materials was excluded. They concluded that the energy ratio of the production chain was 2.4 while the exergy ratio was 3.0 for the same process thus showing differences, specially caused in the processes where steam was used.

Laura Talens et al. [13] produced a so-called Exergy Flaw Analysis (ExFA) to biodiesel production from used cooking oil, in order to analyse the loss of exergy along the production process. They also performed Extended Exergy Accounting [14] to biodiesel from used cooking oil and rapeseed oil by including in the analysis the externalities (capital, labour and environmental impact) measured in homogeneous units (GJ).

Velásquez et al. [15] used exergy accounting in palm oil biodiesel production process and proposed a renewability performance indicator defined as ratio of the net exergy associated to the products to the non-renewable energy used and the deactivation exergy of the wastes. As results they concluded that palm oil biodiesel production was a friendly environmental process with a renewability of 29.1.

Berthiaume et al. [16] also used exergy to calculate the renewability of a biofuel. In this case, the renewability indicator not only took into consideration the cumulative exergy consumption from non-renewable energy sources but also the exergy needed for the restoration of the altered environment to its initial state when these resources were used. Taking these factors into account they concluded that corn based bioethanol was not sustainable.

3. ExROI and exergy cost theory

The concept of ExROI can be defined from the basis of the Exergy Cost Theory. This methodology, developed by Valero and Lozano [17] defines the exergy cost of a product C_P as the amount of exergy needed for its production.

The calculations of the exergy costs can be performed by means of the Symbolic Exergoeconomics [18], which, by the so-called Fuel–Product table, see Table 1, gives the relation between the exergy of the products and of the resources produced and consumed in the whole process. The Exergy carried from the i-th process to the j-th process is represented by E_{ij}.

The production exergy cost of each process is given by:

$$C_P = \left\langle \mathbf{P}^* \right| \mathbf{E}_0, \tag{1}$$

where $\mathbf{E}_0 \equiv (E_{01}, \ldots, E_{0n})$ is a $(n \times 1)$ vector that contains the exergy of the external resources consumed by each process and $\langle \mathbf{P}^* | \equiv (\mathbf{U} - \langle \mathbf{FP} \rangle)^{-1}$ is a $(n \times n)$ matrix whose elements are the cost distribution ratios, and represents the amount of external resources from the i-th process required to obtain a unit of the j-th product. **U**