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Exergetic analysis in cane sugar production in combination with Life Cycle Assessment

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ABSTRACT

The evaluation of the environmental sustainability of a technological option requires the consideration of the complete product life cycle. By using the methodology of a classical environmental Life Cycle Assessment (LCA), it is possible to analyze the environmental problems of the sugar industry through all stages of the full process including different options for the by-products valorization. Exergy and exergetic life cycle analysis are much more resource and product, and hence also efficiency, oriented. The Cumulative Exergy Consumption (CExC) has the advantage that different kinds of resources are quantified on one single scale, which is a unique feature in resource accounting. In this work, Exergetic Life Cycle Assessment was combined with a traditional LCA of cane sugar production process developed previously by Contreras et al. (Contreras et al., 2009), for assessing four different alternatives for by-products valorization of the cane sugar process. The CExC reports the exergy consumption of each stage of the process and the total consumption for each alternative which is important in resource consumption quantification, including renewability and hence process sustainability. Results show the advantage of combining both methods for the environmental assessment of cane sugar production. The application of this combination validates the results related with the category of resources and the contribution of the agricultural stage to the overall impact of the process. The environmental benefits of producing alcohol, biogas, animal food and fertilizers from the sugar production by-products were corroborated. The alternative IV has the lowest contribution to environmental impact in resource category and the minor value of the non-renewability index (6.59E-08).

1. Introduction

The sugarcane industry has some inherent advantages. Sugar is a widely used and natural food ingredient. The sugar production process is self-sufficient in energy, providing all the energy for sugar manufacture from bagasse, the renewable fiber content of cane (BSI, 2008).

Sugar is not the only product of cane or beet, and in fact only represents 17 percent of the biomass of the sugarcane plant. In addition to the use of cane bagasse as boiler fuel, there are many other sugar processing by-products that can be used for a range of purposes (WWF, 2009). Nevertheless, the cultivation and processing of sugarcane produce environmental impacts (CABI-Bioscience and WWF, 2010).

According to Gong and Wall (2001), ecological and environmental indicators are increasingly seen today as necessary tools for sustainable development. By depleting resources and destruction of our environment this is becoming more important year by year. Today, methods like Life Cycle Assessment (LCA) have become popular since they indicate the sources of the environmental problems in the production processes.

Four components can be distinguished in LCA (ISO 14040: 2006 and ISO 14044: 2006). In the goal definition and scoping the subject of study is determined in relation to the application intended and the functional unit of the product has to be determined. In the inventory analysis the complete life-cycle of the product is analyzed leading to the inventory table. The impact assessment is a step-wise process considering classification; characterization and weighting. The final step is the interpretation. The analysis includes impacts associated with the three “Areas for protection”: resources, human health, and ecological health (Finnveden and Östlund, 1997).

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Most of the classical LCA tools that are available have a major emphasis on emissions. In this sense, exergy analysis is different in nature: it is much more resource and product, and hence also efficiency oriented. Efforts to assess environmental impact not only through resources intake but also through emission generation have been developed by Dewulf et al. (2008).

Exergy analysis is based upon the second law of thermodynamics, which states that all macroscopic processes are irreversible. According to Kotas (1995), Szargut et al. (1988), Rosen and Dincer (2001) exergy is defined as the maximum amount of work which can be produced by a system or a flow of matter or energy as it comes to equilibrium with a reference environment rather the exergy is consumed or destroyed, due to the irreversibility for any real process. Thus exergy is a measure for quality of energy. Apart from technical system analysis, it proves that exergy as a tool in environmental impact analysis may be the most mature field of application, particularly with respect to resource and efficiency accounting, one of the major challenges in the development of sustainable technology. Exergy analysis provides a powerful tool for assessing the quality and quantity of a resource, as it represents the upper limit of the portion of the resource that can be converted into work, given the prevailing environmental conditions. In many cases, exergy analysis methods take on a life-cycle perspective, quantifying the cumulated exergy consumption of a product or process from “cradle to grave”. In this regard, it is similar to Life Cycle Assessment (LCA). In fact, exergy analysis can be part of an LCA, representing a method for the life-cycle impact assessment (LCIA) of resource consumption (Dewulf et al., 2007).

Different exergy-based resource accounting methods have been proposed by Connelly and Koshland (2001), Dewulf and Van Langenhove (2002), and Soeno et al. (2003) using the exergy analysis to quantify to what extent implementation of industrial ecology principles can achieve better natural resource management.

The Cumulative Exergy Consumption (CExC) demand is a measure for environmental impact. It reflects well to what extent products and services depend on natural resources. It is able to weigh different energy and mass flows in a scientifically sound way and that it enables us to bring mass and energy onto one single scale. In fact, different kinds of resources, renewable resources (biomass, solar, wind, hydropower), fossil fuels, nuclear fuels, metal ores, minerals, water resources, and atmospheric resources are quantified on one single scale, which is a unique feature in resource accounting (Dewulf et al., 2008).

As with other life cycle approaches, boundary definition and allocation of inputs to the respective outputs are important issues in Cumulative Exergy Consumption calculation. CExC has been calculated for many common industrial processes (Dewulf et al., 2008; Morris, 1991; Szargut and Morris, 1987; Szargut et al., 1988).

By coupling recent exergy data for natural resources as available in De Meester et al. (2006) and Dewulf et al. (2007) with updated life cycle inventory databases, it becomes possible to calculate the exergy consumption pattern of over 2500 products and services. A method to calculate the exergy content and exergy losses of metals during recovery and recycling of a concept car was developed by Amini et al. (2007).

Exergy offers several additions to LCA, e.g., as a uniform indicator of total environmental impact of resources intake or when performing an improvement assessment for identifying real losses. To some extend this makes other indicators in the LCA superfluous (Gong and Wall, 2001).

The definition of goal and scope of the LCA and ELCA are completely identical. The inventory analysis of the ELCA is wider than LCA. The impact assessment is limited to calculation of the exergy of the flows and the determination of the exergy destruction in the different processes. There is no classification in ELCA. For the calculation of exergy the conditions and composition of the environment have to be specified. For processes where no location is specified it is recommended to use the standard state established by Szargut et al. (1988). The cumulation of all exergy destruction in the life cycle gives the life cycle irreversibility of the product (Cornelissen, 1997; Szargut et al., 1988). In a similar method, Gong and Wall (1997) make a clear distinction between renewable and non-renewable resources in order to evaluate the sustainability of a process or activity. This method has its roots in the earlier work on exergy analysis by Wall (1986), and may be regarded as an application of exergy to LCA and is referred to as Life Cycle Exergy Analysis (LCEA), which will be further described below. Thus, by using LCEA and distinguishing between renewable and non-renewable resources we have a method to provide the natural basis for assessing efficiency of resources use.

Bösch et al. (2007) say that the current work shows that the exergy concept can be operationalized in product Life Cycle Assessments. As a consequence of the different weighting approach, cumulative exergy demand (CExD) may differ considerably from the resource category in indicators Eco-indicator 99 and CML 2001. CExD is compared to the resource subcategories of EI’99 (Goedkoop and Spriensma, 1999) and the CML’01 Method (Guinèe et al., 2001). The comparison is performed to identify differences in the relative weighting of resources. The number of assessed resources varies considerably between CExD, EI’99 and CML’01. CExD provides exergy factors for 112 resources, while EI’99 and CML’01 assess 34 and 81 resources, respectively. EI’99 and CML’01 exclude water consumption and all renewable resources, since they do not consider them to be exhaustible. EI’99 and CML’01 do not base the characterization factors on energetic properties, but rather on the scarcity and diminishing quality of global deposits. It can also be seen that the resources with the highest factors in CExD are not considered by the EI’99 method.

Contreras et al. (2009) developed an LCA of four different alternatives for using by-products and wastes of the cane sugar process however, the evaluation of resources consumption and their classification in renewable and non-renewables was not taking in to account. The objectives of this work are to develop the exergetic analysis for quantifying the resources consumption as CExC and the comparison of these results with their assessment by means of a traditional LCA developed previously (Contreras et al., 2009).

2. Materials and methods

2.1. Cases of study

The system under study consists of a Cuban cane sugar mill with a capacity of 216 t/d of cane sugar with conventional production conditions. This capacity was considered as functional unit.

Recently, a comparative analysis of four different alternatives for the use of by-products and wastes of sugar production was developed by means of a traditional LCA (ISO 14040: 2006; ISO 14044: 2006; Contreras et al., 2009). The considerations for the agricultural stages are the same in all four alternatives, except for fertilizer consumption, which changes according to by-product usage. Alternative I represents the conventional sugar production. It is characterized by the use of synthetic fertilizers, pesticides, fresh water irrigation, traditional planting and harvesting. The bagasse is used for the combustion in order to produce steam and electricity. Other wastes constitute emissions to the environment. The other three alternatives were designed from the first alternative with different options for the by-product valorization in each case. Alternative II considers the use of wastewater, filter cake and ashes