Comparing process LCA and IO-LCA: bioethanol production in Spain

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Abstract: Biofuels production has risen in Europe and particularly in Spain in the last years due to a favorable legal framework. Environmental impacts have been considered by several studies, however, a sustainable study, which includes social and economic aspects should be conducted. This study shows the new Spanish Input-Output –Life Cycle Assessment (IO-LCA) tool and its implementation to a case study. Results were compared to those obtained by process Life Cycle Assessment (LCA) to the same case study. Energy demand, greenhouse gases and other pollutants emissions were estimated by both methodologies. Besides, economic output, new employment and multiplier effect were estimated by the tool. IO-LCA seems to be a clear, fast and comprehensive tool, which can be used under the Spanish particularities. The new tool offers relevant information, such as economic output and new employment, which should be considered from a sustainable point of view.

1 Introduction

In the last decade, the awareness about the climate change has increased in Europe. The concern over the environment and the need of clean energy have resulted in the promotion and implementation of several policies in Europe. One of these policies is the EU biofuels directive [1], which promotes the use of biofuels to help Europe meet its commitments on reducing greenhouse gas emissions. The production of biofuels in Europe will, additionally, reduce the dependence on imported oil.

As a consequence of this favorable legal framework, biofuels production in Spain has risen in the last years. The promotion of its production and use should be accompanied by studies that analyze the associated environmental benefits and potential negative effects due to the diversity of the raw materials used and the region particularities. Additionally, environmental benefits and impacts are not the only consequences of the promotion of biofuels, but it is necessary to consider their potential socio-economic impacts.

2 Materials and methods

2.1 Input Output -Life Cycle Assessment

The IO-LCA methodology is based on an Input-Output (I-O) analysis developed by Leontief [2,3] where the interdependencies between production sectors are described, so that the intermediate input requirements to fulfil a certain final demand can be estimated [4].
The structure of the I-O table is such that the different sectors within the economy are set in a symmetrical way.
The columns represent the production cost components and account for the resources that have been consumed from other sectors to obtain a certain production in each sector, while the rows describe how the production of each sector has been allocated to the different uses of each sector.
Gross production of one sector is defined as:

$$X_1 = (x_{11} + x_{12} + ... + x_{1n})y_{1...n} \quad (1)$$

$$X_{i,j} = \sum^{n=\infty} x_{ij} y_{1...n}; \qquad i, j = 1,2,..., n \quad (2)$$

Based on the structure of the above I-O table, the technical coefficients are obtained, which measure the input requirements per unit of a certain output (xj) [4]

$$a_{ij} = x_{ij} / X_j \quad (3)$$

where:
xij is the amount of products from sector i used by the sector j to produce its output Xj.
aij measures the input requirement from sector i to sector j per unit of sector j output.
Xj is the sector j gross production.

According to the I-O scheme, the total required output produced by a sector in order to satisfy the intermediate and the final demand can be expressed by a matrix and is defined as:

$$X = (I - A)^{-1} Y \qquad (4)$$

where:
I is the identity matrix
A is the technical coefficients matrix
(I –A) is the so called Leontief matrix
(I –A)-1 is Leontief inverse matrix, which describes direct and indirect requirements per one unit of final demand.
Y is the required final demand.

From the basic I-O expression described above, environmental and social impacts can also be estimated by adding a new matrix Ri to the equation, which describes the environmental burdens and social implications per monetary unit output of each sector considered in the national economy. The new equation is defined by:

$$L_i = R_i (I - A)^{-1} Y \qquad (5)$$

where:
Li is the environmental/social burdens associated to the required final demand Y
Ri is the environmental and social burdens matrix.
(I –A)-1 is the Leontief inverse matrix, which represents direct and indirect requirements per unit of final demand.

2.2 Spanish Input Output -Life Cycle Assessment

Following the same theoretical background structure as the University Carnegie Mellon [5], a new tool was developed considering the environmental, social and economic particularities of Spain.
The Spanish IO-LCA is based on the Input-Output Matrix, published by the Spanish National Statistic Institute (INE) within the national accounts system framework [6]. The most recent published matrix refers to year 2005 and encompasses 73 activity sectors.
The following vectors have been included in the tool: (i) Total economic output, which comprises direct and indirect impact throughout the economy, (ii) energy demand, (iii) CO2 emissions, (iv) CH4 emissions, (v) N2O emissions, (vi) SOx emissions, (vii) NOx emissions and (viii) new employment requirement.

In order to develop the vectors, social and environmental annual data was collected from public databases, produced by the Statistical Office of the European Communities (EUROSTAT) and the INE [7]. A significant data treatment was performed to express these data at the sector level defined by the Spanish national accounts. Whenever it was possible, data referred to year 2005 was used.
Related to social aspects, INE provides annual employment data by each sector considered in the national accounts system. Full-time equivalent employment data was chosen to build the vector.

2.3 Case study: bioethanol production

The plant under study is located in Spain. It produces 78900 tones of bioethanol and consumes 302976 tones of barley annually. The life time of the plant was assumed to be 20 years [8]. As co-product in the process, the plant obtains 120000 tones of Dry Digestive Grains (DDGs) per year, which are sold as a protein source for animal feed. The electricity used in the processes is generated by a natural gas turbine installed in the plant. Additional electricity is produces by the plant, 170288 GWh annually that is sold to the national electricity network.
The description of the bioethanol plant and its operation and maintenance requirements have been provided by Spanish industries involved in biofuels production and are refered to year 2006. However, some detailed data related to the components of the plant have been taken from the literature [9].
1 MJ of bioethanol produced in the plant was chosen as the functional unit, so that all results are referred to it.
The following stages have not been included in the assessment: bioethanol use, dismantling and final treatment of the materials.

2.3.1 Input Output-Life Cycle Assessment: Data and assumptions

Inputs of data to the tool were defined by final demands associated to bioethanol production in Spain.
Whenever possible, production costs were used to define these demands, but also basic prices were considered when there was not other option.
It is remarkable that all components included in this study were assumed to be final demands, although they are strictly intermediate demands, since the final good is the bioethanol produced by the plant

Basic price of barley was used as input data to define final demand of the agricultural stage. Data were taken from public agricultural surveys [10]. Straw obtained in the agricultural stage was not considered as co-product, since allocation by price was automatically done by defining the final demand. Other approach to this stage could have been done, taking into account fertilizers, use of machinery, etc and defining their demands as input to the stage. In this case, barley would have been a product and not a demand, whereas straw would have been considered as a co-product.

Acquisition and manufacturing of components, construction activities as well as operation and maintenance were included in the Spanish IO-LCA assessment through the definition of the final demands of goods and services.

Final demands for construction stage were defined through several data sources related to the construction sector [11, 12, 13, 10].

Energy consumption and emissions related to the direct use of natural gas burned in the production plant were added to the results obtained by the IO-LCA.

In order to consider the co-products, electricity and DDGs, system expansion was conducted. The DDGs reference system was defined as the production of wheat for animal feed, whereas the electricity reference system was the electricity produced by the national mix for the time reference.

All the monetary inputs data were discounted using the Consumer Prices Index Variation (CPI) provided by INE.

2.3.2 Process Life Cycle Assessment: Data and assumptions

The process LCA was conducted following the international standard series ISO 14040-44:2006 [14, 15].

Data used to assess the agricultural phase was provided by the Laboratory of Agro Energy and Botanic and Vegetal Production Department of the Higher Technical School of Agricultural Engineers of the Polytechnic University of Madrid, taken into account the agricultural Spanish conditions. Limitations and assumptions, described for agricultural systems by Ecoinvent, were followed to carry out the inventory [16]. More details on the agricultural inventory are described by de la Rúa [17].

Besides the barley grain, straw is obtained in the cereal crop and sold as animal feed. Following the international standard series ISO 14040-44:2006, system expansion was carried out. As reference system for the straw, hay alfalfa was considered.

To perform the inventory of bioethanol production process, same data provided by the industries mentioned above was used

DDGs and electricity were considered as co-products. System expansion was carried out, considering wheat crop as substitute of DDGs and national electricity mix from year 2005 for the electricity of the plant.
Results regarding greenhouse gases emissions, cumulative energy demand as well as an inventory of NOx, SOx, CO and NMVOC emissions were estimated in this study and compared with IO-LCA results. However, other emissions could have been estimated by the LCA.

3 Results

Table 1and Table 2 shows the results obtained by both process LCA and IO-LCA. More detailed information of each methodology results can be found in de la Rua, 2009 [17].
Taken into consideration that IO-LCA does not define system boundaries as LCA does, IO-LCA results were expected to be higher.

Tab.1: Energy demand and emission by method

/MJ bioethanol	Method	Total	Agricultural stage	Construction activities	O&M
Energy demand MJ	LCA	0,64	2,59E-01		3,83E-01
	IO-LCA	0,96	1,92E-01	2,69E-02	7,42E-01
Nox g	LCA	0,25	1,64E-01		8,44E-02
	IO-LCA	0,26	1,23E-01	3,88E-03	1,30E-01
SOx g	LCA	-0,18	-3,09E-03		-1,81E-01
	IO-LCA	0,08	3,04E-02	4,81E-03	4,80E-02
CO g	LCA	0,05	3,07E-02		2,36E-02
	IO-LCA	0,11	7,32E-02	8,41E-03	3,25E-02
NMVOC g	LCA	0,04	5,68E-02		-1,62E-02
	IO-LCA	0,13	1,61E-01	4,65E-03	-3,82E-02

The energy demand amounted to 0,96 MJ/ MJ bioethanol according to IO-LCA, 50% higher than LCA results. Operation and maintenance stage was identified as the main energy demanding phase by both IO-LCA and LCA, representing 77% and 60% of the total, respectively. Nevertheless, LCA estimated higher energy demand for the agricultural stage than IO-LCA.
Total NOx emissions resulted similar in both analysis, around 0,25 g/ MJ emitted. Small differences were only found in the agricultural stage, higher estimated by process LCA.

Results for SOx differ significantly. IO-LCA accounted for the emission of 0,08 g of SOx per MJ of bioethanol, whereas LCA estimated the saving of 0,18 g. The production of electricity in the bioethanol plant compensates the SOx emitted in the rest of the process and makes possible these savings.

CO emissions were higher estimated by IO-LCA than by LCA along all stages considered in the study.

In the agricultural stage, agriculture machinery, fertilizers manufacturing and use were the main CO sources according to LCA.. IO-LCA also identified "Agriculture, livestock and hunting", related to agriculture machinery and fertilizers use, as the main contributor to CO emissions. Nevertheless, emission due to "Chemistry Industry", associated to fertilizers manufacturing were around thirty five times lower than those estimated by LCA.

Along the operation and maintenance stage, both LCA and IO-LCA identified natural gas extraction and distribution as the main source of CO emissions.

In terms of NMVOC, IO-LCA estimated higher emissions than LCA in all stages. However, emissions related to fertilizers in the agricultural stage were higher estimated by LCA

Both LCA and IO-LCA identified road and pipeline transportation as well as natural gas extraction and distribution as the main NMVOC sources along the operation and maintenance stage.

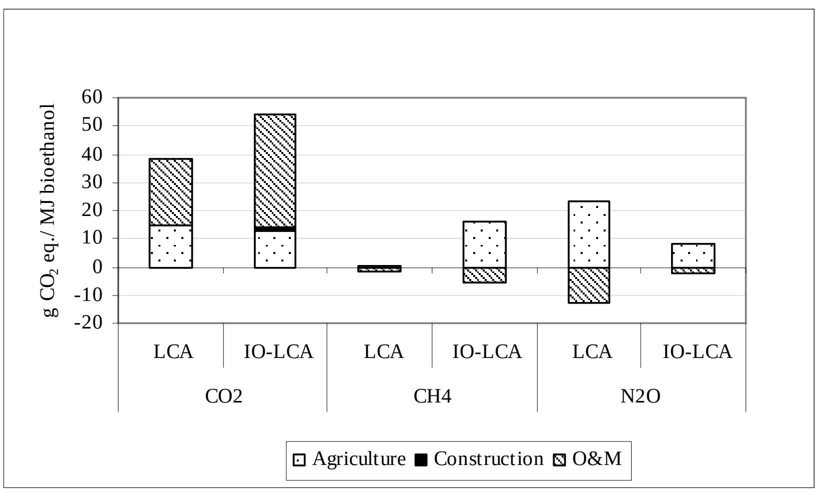

Fig.1: Greenhouse gas emissions by method

The emission of greenhouse gases along the whole system amounted to 48 g and 71 g of CO2 equivalent following LCA and IO-LCA respectively.

As can be noticed in Figure 1, emissions of CO2 and mainly of N2O were lower estimated by the IO-LCA. The use of fertilizers and agricultural machinery were the main contributors to greenhouse gases emissions, followed by fertilizers manufacturing according to LCA (see detailed results [17]). While IO-LCA correctly identified fertilizers use and agricultural machinery, associated to the activity sector "Agriculture, livestock and hunting", it estimated lower emissions related to "Chemistry Industry".

Besides the energy demand and emissions estimated by both analysis, IO-LCA offers the added value of estimating economic and social effects. Table 3 shows these results.

Tab.3: Economic output and employment required by stages

g CO2 eq./ MJ bioetanol	Total	Agricultural stage	Construction activities	O&M
Economic Output €2005	5,87E-02	4,75E-02	5,47E-03	5,67E-03
Direct Economic Output €2005	3,59E-02	3,09E-02	3,36E-03	1,59E-03
Employment requirement along the life time	24470	27358	1471	-4359

The production cost of 1MJ of barley bioethanol in Spain was estimated in 0,0345 €2005 and generated an economic output of 0,059 €2005. More than 80% of this activity would be due to the agricultural stage, followed by the operation and maintenance stage, 10%.

Knowing the production cost and economic output due to 1MJ of bioethanol produced in Spain, the multiplier effect was calculated and resulted in 1,70.

Along the life time of the plant more than 24000 new employments would be created. Around 27000 new employments would be demanded due to the agricultural stage but it must be highlighted that the IO-LCA estimated also the loss of more than 4300 employments associated to the operation and maintenance stage, due to the co-production of electricity and DDGs.

4 Discussion

In general terms, the Spanish IO-LCA resulted in higher estimation of the potential environmental impacts. These results were initially expected, since theoretically the IO-LCA considers all processes along the supply chain, whereas the LCA needs the definition of boundaries, leaving outside processes that might be relevant.

Results concerning energy demand, NOx and N2O emissions related to the agricultural stage were lower estimated by the IO-LCA. The different approaches to model this stage by both tools and the aggregation level of the activity sectors in the Spanish national accounts could explain these discrepancies.

LCA considered the agricultural stage as a productive system, including all processes from seed production to straw packing. However, the IO-LCA approached to this stage from the demand perspective of a good already produced.

Additionally, the activity sector "Agriculture, livestock and hunting" produces barley grain but other additional goods with different environmental profiles and the Spanish IO-LCA cannot distinguish among them.

As it has been shown in the results, emissions due to fertilizers manufacturing were lower estimated by the IO-LCA. "Chemistry Industry" is other example of estimation problems due to the aggregation level in the Spanish IO-LCA. N2O emissions due to manufacturing 1$ of soap and other detergent are around 100 times lower than those generated from 1$ of nitrogenous fertilizer manufacturing [5]. This limitation has been long discussed by other authors, who argue that results are based on average product data, and depend on how typical the studied product is in relation to the sector where is contained [18].

In order to obtain more accurate estimations, it would be necessary to break down some relevant activity sectors into more detailed sectors. This way, results would represent fewer goods and services but with higher precision. Several authors have disaggregated sectors from an IO table to improve the analysis. Joshi broke down a sector into different products to obtain more accurate results [19]. The combination of LCI data into the IO analysis has also been used by other authors to increase the final results of detailed systems [20,21].

The Spanish IO-LCA offers the added value of making possible the estimation of economic and social aspect, relevant from a sustainable point of view.

In terms of economic aspects, through the multiplier effect it is possible to understand the effect of the studied system within the Spanish economic context. The multiplier effect resulted in 1,70, which means that by increasing the demand of bioethanol in 1€, the final demand of national goods and services would also increase in 1,70€. The driver of this growth is the agricultural stage and specifically the sector "Agriculture, livestock and hunting".

Additionally, agricultural stage also generates the highest amount of new employments along the life time of the plant. On the contrary, the relevance of this sector can have several consequences when it products are substituted by different goods and services obtained by other activity sectors. The economic and social benefits might change as well as the environmental impacts. This case can be noticed along the operation and maintenance stage, where the production of DDG and electricity as co-products resulted in the loss of employments.

5 Conclusions

The new life cycle thinking tool for Spain was developed taking into account the national economic, environmental and social context. It allows the estimation of energy demand, greenhouse gases emissions as well as other pollutants associated to goods and services produced in Spain. The development of this tool has been carried out from public databases. The IO-LCA was used to estimate the impacts related to the production of bioethanol from barley in Spain. In order to validate the tool, the same case study was assessed by process LCA. The comparison between both IO-LCA and LCA results has proven that the new tool estimates adequately most of the environmental burdens. As expected, IO-LCA results were higher estimated than those obtained by LCA, since the first avoids the definition of the system limits, with some exceptions. The discrepancies can be explained by the aggregation level of the sectors considered in the IO-LCA. However, this limitation can be solved by breaking down the activity sectors into a higher number of sectors and even including data from LCI to atypical goods and services.

The new Spanish IO-LCA includes the analysis of other relevant aspects, such as total economic output and new employment creation, which allows a more comprehensive analysis from a sustainable point of view.

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