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Life cycle energy analysis for bioethanol: allocation methods and implications for energy efficiency and renewability

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Abstract

Increased use of biofuels for transport is emerging as an important policy strategy to substitute petroleum-based fuels. However, the extent to which biofuel can displace fossil fuels and net emissions of CO_2 depends on the efficiency with which it can be produced. To demonstrate that biofuel has a positive energy balance – *i.e.* more energy is contained in than is used in the production – a life cycle approach must be employed, allowing quantification of the renewability of biofuel delivered to consumers. A novel indicator is proposed – the *energy renewability efficiency* – aiming at characterizing the renewability of (bio)energy sources. ERE measures the fraction of final fuel energy obtained from renewable sources. The LCEA for bioethanol in France has been investigated. Assessing the (fossil and non-fossil) energy used throughout the life cycle and calculating the renewability of two alternative bioethanol product systems are important goals. Physical and economic data was collected and a systemic description of the bioethanol chains has been implemented. Inventory results – calculated using four different allocation approaches and ignoring co-product credits – are analyzed in order to understand the effect of allocation in the overall energy efficiency and renewability of bioethanol. Sensitivity analysis shows that the choice of the allocation procedure has a major influence on the results. In fact, ERE values for ethanol can vary more than 50%, depending on the allocation used. Finally, we conclude that, in general, ethanol produced from sugar beet or wheat in France is clearly favorable in primary energy terms. In particular, a maximum ERE value of 55% was obtained for wheat based ethanol (mass allocation), meaning than 55% of the biofuel energy content is indeed renewable energy.

Keywords: Bioethanol, Energy Management, Energy Policy, Energy Renewability Efficiency, Life Cycle Assessment.

Nomenclature

LCEA	Life Cycle Energy Analysis
ERE	Energy Renewability Efficiency [%]
LCA	Life Cycle Assessment
ISO	International Organization for Standardization
LCI	Life Cycle Inventory
E_{prim}	Total accumulated inputs in primary energy terms [MJ/kg]
FEC	Fuel Energy Content [MJ/kg]
GER	Gross Energy Requirement [MJ/kg]
LCEE	Life Cycle Energy Efficiency [MJ/MJ]
FER	Fossil Energy Ratio [MJ/MJ]
E_{req}	Energy requirement of biofuel [MJ/MJ]
NEV	Net Energy Value [MJ]

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1. Introduction

Ever since the first oil crisis in 1973, biomass has been considered – and in some cases promoted – as an alternative source of energy to fossil fuels. Because of the transport sector's almost exclusive dependence on oil, particular attention has been given to the potential use of biomass as the basis for production of an alternative (and renewable) motor vehicle fuel – the *biofuel* [1]. Biofuels are originated from plant oils, sugar beets, cereals, organic waste and the processing of biomass. Sugar beets, cereals (wheat, corn, barley, …) and other crops can be fermented to produce alcohol (bioethanol) to be used in gasoline engines. Plant oils (colza, soybean, sunflower, palm, etc.) can be converted into a diesel substitute.

Due to the increasing mobility of people and things, the transport sector accounts for more than 30% of final energy consumption in the European Community and is expanding – a trend which is bound to increase, along with carbon dioxide emissions (EC, 2001a). The Commission White Paper [2] expects CO_2 emissions from transport to rise by 50% between 1990 and 2010, the main responsibility resting with road transport, which accounts for 84% of transport-related CO_2 emissions. From an ecological point of view, the White Paper therefore calls for dependence on oil (currently 98%) in the transport sector to be reduced by using alternative fuels such as biofuels [3].The European Commission has declared its intention to promote biofuels in different proposals and directives establishing a minimum biofuel content in transportation fuels on the basis of an agreed schedule [1,3] and allowing reduced taxation rates for biofuels [4]. In particular, the Green Paper [7] sets the objective of 20% substitution of conventional fuels by alternative fuels in the road transport sector by the year 2020.

Increased use of biofuels for transport is, therefore, emerging as an important policy strategy to substitute petroleum-based fuels. However, the extent to which biofuel can displace fossil fuels and net emissions of CO_2 depends on the efficiency with which it can be produced. In fact, all processing technologies, including biofuel options, involve (directly and/or indirectly) the use of fossil fuels in their production and/or operation, resulting in associated greenhouse gas emissions. Therefore, in practice, the actual benefits of biofuels displacing their fossil fuel equivalents depend, crucially, on biofuels energy and carbon balances, which indicate the relative magnitude of fossil fuels input (and related emissions) relative to subsequent fossil fuel savings (and avoided emissions) resulting from their use as alternatives to conventional fossil fuels. To demonstrate that biofuel has a positive energy balance – *i.e.* more energy is contained in than is used in the production – a life cycle approach must be employed, allowing quantification of the renewability of biofuel delivered to consumers.

Life Cycle Assessment (LCA) is a methodology to assess the environmental performance of a product, process or activity from "cradle-to-grave" by identifying, quantifying and evaluating all resources consumed, and all emissions and waste released into the environment. Today's LCA is based on "net energy analysis" studies, which were first published in the 1970's [6,7]. The LCA is based on systems analysis, treating the product process chain as a sequence of sub-systems that exchange inputs and outputs. A methodological allocation problem arises in an LCA involving only one of several products from the same process: how are the resource consumption and emissions associated with this process portioned and distributed over these co-products? This has been one of the most controversial issues in the development of the LCA methodology, as it may significantly influence or even determine the results of the assessment [8]. Biofuel technologies have diverse main products and co(by)-products. Thus, suitable allocation procedures need to be established and applied to partition the primary energy inputs between the different biofuel co-products [9]. However, this effect has been often underestimated in biofuel LCA's and energy analysis studies. In addition, it is important to recognize that there is no single allocation procedure which is appropriate for all biofuel processes [10]. According to the ISO 14041 [11], whenever several alternative allocation procedures seem applicable, a sensitivity analysis should be conducted.

The main world regions responsible for the production of liquid biofuels are Brazil, the USA and Europe. Biofuel production and utilization varies enormously throughout the European Union, but a remarkable increase of 93% in production was recorded between 1997 and 1999 [1]. However, only six Member States make any real contribution to the total European biofuel production. German has the leading position and France is second, with a production of almost 550 thousand tonnes in 2002, which represents 1.3% of the total national liquid fuel consumption [12]. Regarding the bioethanol sector, France has the leading position in the European Union with a production of 90500 tonnes, which is expected to increase by 75% as new agreements are allocated to the industry [12]. Ethanol can be used i) as a single fuel; ii) blended with gasoline or iii) blended with gasoline, after conversion in its derivative ETBE (Ethyl Tertiary Butyl Ether), obtained through the reaction of ethanol with isobutene [13]. Bioethanol production in France is based on two alternative chains (sugar beet or wheat), which can generally be described by the following four main stages [14,15]: *i)* the agricultural sector; *ii)* the biomass transformation industry; *iii)* the petroleum industry, responsible for the refining and mixing processes necessary to obtain the final combustible and *iv)* the fuel energy transportation market, in which bioethanol is delivered, replacing its fossil fuel equivalent.

The main goal of this paper is to present an LCEA performed to bioethanol chains in France, describing the energy use throughout the alternative bioethanol life cycles and allowing the calculation of overall energy efficiencies. This aims at characterizing the renewability of the bioethanol systems, which are able to compete with (and displace) petroleum-based fuels in the market place. Different allocation methods are explored in order to understand their effect on the calculation of overall energy efficiency and renewability of bioethanol. The product systems investigated include two alternative bioethanol chains (sugar beet and wheat).

This paper is organized in 5 sections, including this introduction. Section 2 gives an overall view of the methodology, presents a novel indicator – the *energy renewability efficiency* – and discusses the implications of multifunctionality. Section 3 demonstrates the implementation of the modeling approach and analyzes the inventory results, obtained using different allocation approaches. Section 4 presents the main results and discusses the implications of allocation for the renewability of bioethanol produced from sugar beet and wheat. Section 5 concludes with the presentation of our research findings.

2. Methodology: Life cycle energy analysis

2.1 Life Cycle Inventory and energy renewability efficiency

Life Cycle Energy Analysis (LCEA) is based on the standardized LCA methodology [16], limited, however, to assess the energy aspects and, in this study, with a particular focus on energy efficiencies indicators aiming at characterizing the renewability of bioethanol product systems. An LCA study offers a clear and comprehensive picture of the flows of energy and materials through a system and gives a holistic and objective basis for comparisons. The results of an LCA quantify the potential environmental impacts of a product system over the life cycle, help to identify opportunities for improvement and indicate more sustainable options where a comparison is made. Its background can be traced back at least as far as the development of energy analysis in the 1970's, *e.g.* refs. [6,7]. The LCA methodology consists of four major steps. The first component of an LCA is the definition of the *goal and scope* of the analysis. This includes the definition of a reference unit, to which all the inputs and outputs are related. This is called the *functional unit,* which provides a clear, full and definitive description of the product or service being investigated, enabling subsequent results to be interpreted correctly and compared with other results in a meaningful manner. In this study, in particular, the functional unit should enable the comparison of the energy used throughout the alternative bioethanol product systems.

The second component of an LCA is the inventory analysis, also Life Cycle Inventory (LCI), which is based, primarily, on systems analysis treating the process chain as a sequence of sub-systems that exchange inputs and outputs. Hence, in LCI the product system (or product systems if there is more than one alternative) is defined, which includes setting the system boundaries (between economy and environment, and with other product systems), designing the flow diagrams with unit processes, collecting the data for each of these processes, performing allocation steps for multifunctional processes and completing the final calculations [17]. Its main result is an inventory table, in which the material and energy flows associated with the functional unit are compiled and quantified [16].

The "*end point"* defined for this life cycle study is the final (bio)fuel product, quantified by the energy content (MJ/kg). The various bioethanol LCI results are, subsequently, compared in the basis of 1 MJ of biofuel energy content. In LCA, the selection of the final product as an "end point" is often designated by the "cradle-to-gate" approach, instead of the more metaphoric "cradle-to-grave". The "gate" can be seen here as the fuel pumping station where (bio)fuel is delivered to vehicles. The choice of the "cradle-to-gate" approach is appropriate because it enables LCI results and biofuels' energy efficiencies to be analyzed in a variety of different ways, namely concerning allocation, enabling optimization or comparison with fossil fuels displaced. In fact, delivered energy as an end point avoids the complexities of adding further assumptions, in particular concerning vehicle performance factors, as it would be if, for example, "kilometers traveled" were adopted as the reference (end point). In some studies, kilogram (or liter) of biofuel have often been used as reference, *e.g.* refs. [18–21]. However, this is definitely not an adequate basis for comparison of the function provided by different (bio)fuels.

The functional unit chosen for this investigation is 1MJ of fuel energy content, measured in terms of the lower heating value (heat of combustion excluding the latent heat in combustion products). This is consistent with the goal and scope of the study, which is to calculate the life cycle energy efficiency of bioethanol chains in France and compare these values with their fossil fuel equivalents, aiming at assessing the renewability of alternative bioethanol product systems or, inversely, fossil fuel resource depletion.

Fossil fuel resource depletion must be quantified in terms of *primary energy* (**E_{prim}**), which is defined as the cumulative energy content of all resources extracted from the environment [22,23]. As such, it is an indicator of energy resource availability and implicitly takes into account the *energy quality*, being greater than the energy provided by fuels and electricity used by consumers, known as delivered energy. The total amount of primary energy consists of the cumulative sum of *i)* the direct energy due to the use of fuels and electricity, *ii)* the indirect energy associated with the production of materials, equipment, etc., and *iii)* the energy contained in any feedstocks, such as chemicals and materials derived from fossil fuels. According to ref. [10], an additional consideration is that the energy requirement of a fuel can also include the fuel delivered energy, *i.e.* the *fuel energy content* (**FEC**, MJ/kg), in which case the result is referred to as the *gross energy requirement* (**GER**, MJ/kg). In (bio)energy analysis studies, an essential comparison needs to be made between the primary energy input to biofuel life cycle, *i.e.* the energy requirement of biofuel (E_{prim}) and the primary energy input throughout the life cycle of non-renewable fuels, the gross energy requirement (GER).

The life cycle inventory results provide an opportunity to quantify the total energy demands and, therefore, the overall energy efficiency. Quantifying the overall energy efficiency of a biofuel is helpful to determine how much (fossil) energy must be expended to convert the energy available in the raw materials (biological cultures) to 1 MJ of available energy in the transportation fuel. The more fossil energy is required to make the biofuel, the less we can say that this biofuel is "renewable". Thus, the renewable nature of a fuel can vary across the spectrum of "completely renewable" (*i.e.*, no fossil energy input) to nonrenewable (*i.e.*, fossil energy inputs as much or more than the energy output of the fuel) [22].

Among the LCA and energy analysis literature there is lack of consensus concerning the definition (and designation) of energy efficiency indicators to be used in a life-cycle perspective and, in particular, to characterize the energy requirements of renewable energy systems. In fact, various indicators have been used, often with the same meaning but different definition, or inversely, *e.g.* energy efficiency [23]; overall energy efficiency [7,24]; overall energy balance [25]; gross energy requirement and net energy requirement [26].

In particular, Sheehan *et al.* [22] have used the LCEE *(life cycle energy efficiency)*, defined as the ratio between the biofuel FEC (fuel energy content) and the biofuel GER (gross energy requirement). **LCEE** = FEC/(E_{prim}+FEC). The LCEE can be seen as a measure of the fraction of the GER (primary energy required throughout the biofuel life cycle plus the biofuel energy content), which actually ends up in the fuel product. The same authors have also adopted the *fossil energy ratio* (FER), defined as **FER** = FEC/E_{prim}. According to this definition, if the fossil energy ratio is less than 1 the fuel is nonrenewable, as more energy is required to make the fuel than the energy available in the final fuel product. Biofuel with FER greater than 1 can be considered as (partially) renewable. In theory, a total renewable fuel would have no requirements of fossil energy and, thus, its fossil energy ratio would be infinite. In ref. [23] the FER is also used, but under the designation of "energy efficiency". Other authors, have used the *"energy requirement"* (**E_{req}**), defined as the "primary energy input per delivered energy output" [9,10,27,28]. This indicator is also used in refs. [19,25], but under the designation of "net energy*"* and "overall energy balance", respectively. It should be noted that E_{req} is the inverse of the FER. The "*net energy value"* (NEV)*,* defined as the biofuel FEC minus the fossil energy required to produce the biofuel (E_{prim}) is proposed in refs. [18,20]. In this case, negative *net energy values* indicate that (bio)fuel is non-renewable, while positive values indicate the fuel is renewable to a certain extent. In this study the energy requirement E_{req} is used to identify the relative contributions to the total primary energy input from different stages of the production chains and to evaluate the implications of the allocation method chosen for the energy efficiency of bioethanol.

In addition, a novel indicator is proposed – the *energy renewability efficiency*, aiming at characterizing the renewability of an energy source. The *energy renewability efficiency (ERE)* measures the fraction of final fuel energy obtained from renewable sources. It can be defined as **ERE** = (FEC–E_{prim})/FEC and to our knowledge was not previously proposed in the literature. A biofuel may be considered renewable if ERE assumes values between 0 and 100%. In case there were no inputs of non-renewable energy, the biofuel would be completely renewable, with an ERE of 100%. If the ERE is lower than zero, then the biofuel should be characterized as non-renewable since the non-renewable energy required to grow and convert biomass into biofuel would be greater than the energy present in the biofuel final product. In this case, the biofuel is, in fact, not a fossil energy substitute and increasing its production does little to displace oil imports and increase the security of energy supply. By definition, non-renewable energy sources have negative values of ERE. For example, the conventional fuel to be displaced by bioethanol – gasoline–, shows a ERE value of –14.5%, meaning that the total primary energy required to produce gasoline is 14.5% greater than its final energy content.

2.2 Multifunctionality and allocation

Most industrial and agricultural processes are multifunctional. In particular, many of the feedstocks for biofuels are either co-produced with other products or are from by-products from other production processes. Biofuel production system generates large quantities of co(by)-products and, thus, LCA practitioners are faced with the problem that the product system under study provides more functions than that which is investigated in the functional unit of interest. This leads to the following central question: how should the resource consumption and emissions distributed over the various co(by)-products. An appropriate procedure is thus required to partition the relevant inputs and outputs to the functional unit under study.

Options for dealing with co-production include to: *i)* sub-divide the process into two or more sub-processes; *ii)* expand the product system to take into account potential effects of providing a new use for the co-products, on systems currently using the co-products – known as system boundary expansion – and *iii)* allocate inputs and outputs between product streams based on causal relationships [11]. The international standards on LCA, states that allocation[1] should be avoided where possible by sub-division or system boundary expansion. Where this is not possible allocation should be undertaken using causal relationships, based on economic or physical properties of the co-products. However, Ekvall and Finnveden [29] have analyzed a large number of LCA studies where subdivision or system expansion was applied and found no case study where an allocation problem is completely eliminated through sub-division. In general terms, system expansion requires that there is an alternative way of generating the exported functions and that data can be obtained for this alternative production [29]. Many co-products are competing with other co-products, so expanding the system boundary would only result in an increasingly complex system [9,30]. In particular, many of the co-products of biofuel technologies have no separate main means of production. Hence, a simple substitute cannot be identified and, consequently, it is necessary to use an allocation procedure.

According to the ISO 14041 [11], allocation should reflect the physical relationships between the environmental burdens and the functions, *i.e.* how the burdens are changed by quantitative changes in the functions delivered by the product system. Thus, allocation can be based on physical properties of the products, such as mass, volume, energy, because data on the properties are generally available and easily interpreted. Where such physical causal relationships cannot be used as the basis for allocation, the allocation should reflect other relationships between the environmental burdens and the functions. In some cases, this allocation may coincide with allocation based on physical, causal relationships. The choice and justification of allocation procedures is a major issue for life cycle assessment [16], especially since they can have a significant influence on subsequent results [9,10,19,20,31,32].

In many biofuel studies mass of co-products has been chosen as a basis for allocation [23,33,34]. Other studies, have used the energy content, e.g. [35,36]. However, the main reason

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[1] The meaning of allocation in LCA is often used misleading. According to the ISO 14041, sub-division and system boundary expansion are not formally part of the allocation procedure.

for using mass seems to arise because both main and co-products can be weighed, and the use of energy content would only be relevant if both main and co-products were actually burned as fuels. Allocation can also be based on the exergy content [37,38]. Another method is based on the replacement value of co-products, *i.e.* energy credits are assumed to be equal to the energy required to produce a substitute for the co-products [20,36]. Allocation based on the relative economic value (market price) of main and co-products has been used by [9,31,39]. However, there are concerns about the effect of price variation on the calculation of allocation parameters. In most studies no discussion is provided regarding the selection of the allocation procedure and, in general, no complete justification can be found concerning the reason to choose one and not a different one allocation procedure. In fact, it is important to recognize that there is no single allocation procedure which is appropriate for all biofuel processes [10]. Therefore, whenever several alternative allocation procedures seem applicable, a sensitivity analysis should be conducted [11]. Next section analyzes the cycle energy use throughout the life cycle in order to assess the effect of the allocation approach chosen. The inventory results were calculated using four different allocation approaches, based on: *i)* output weight; *ii)* energy content, *iii)* economic value and *iv)* replacement value of co-products, which are compared with results obtained ignoring co-product credits.

3. Life cycle modeling and inventory results

3.1 Goal, scope and main assumptions

This section presents the modeling of the LCI for bioethanol in France. Sector production data along with life cycle data from commercial databases have been combined to build the LCI model. Relevant assumptions are outlined and a systemic description of the bioethanol production schemes is implemented, including agricultural, transportation and industrial transformation stages. The results are summarized in terms of indicators of fossil fuel depletion, particularly analyzing bioethanol energy requirement E_{req} values.

Energy analysis of biofuel systems shows frequently varying results due to different assumptions on critical variables that have a decisive impact on the energy balance, *e.g.* biomass yields and conversion technologies, fertilizer application rates, co-product evaluation, number of energy inputs included in the calculations [20,21]. Below, the main assumptions are outlined. The "cradle-to-gate" approach is adopted since the combustion of bioethanol does not modify the energy balances, provided that no additional energy source is necessary for the combustion. To convert energy inputs into primary energy terms, the following efficiencies were considered: 91% for natural gas; 83% for oil; 94% for coal and 33% for electricity [34]. Primary energy inputs associated with fertilizers and energy content of diesel fuel used in farm and transportation activities are based on data from [34]. Agricultural production data has been collected for sugar beet [34] and wheat [40]. The energy associated with transportation activities is estimated by using the following assumptions: fertilizers –200 km by rail and 100 km by road; biomass –100 km by road, from farms to biofuel production plants; ethanol –200 km by rail, from distilleries to the refinery [33,34]. Road and rail transportation energy inputs were obtained using the French model [33]. The energy embodied in the materials used to construct biofuel plants, transportation equipment and farm machinery ("capital energy") was not considered. Capital energy becomes negligible when distributed over the throughput achieved in the lifetime of those equipments [20,24] and data on industrial processes is seldom more accurate than 5% [24]. Economic allocation was performed using average market prices of products and co-products [41]. Energy content and replacement credits of co-products were estimated using data from [25].

3.2 Bioethanol life cycle

Fig. 1 and Fig. 2 illustrate two alternative way of producing bioethanol, namely from sugar beet and wheat, respectively. The flow charts simplify the actual chain of processes for the sake of clarity and the arrows show the direction of the logistics flow. The agricultural production of sugar beet and wheat cultivation includes several steps, namely: soil preparation, plowing, weeding, fertilization, sowing and harvesting.

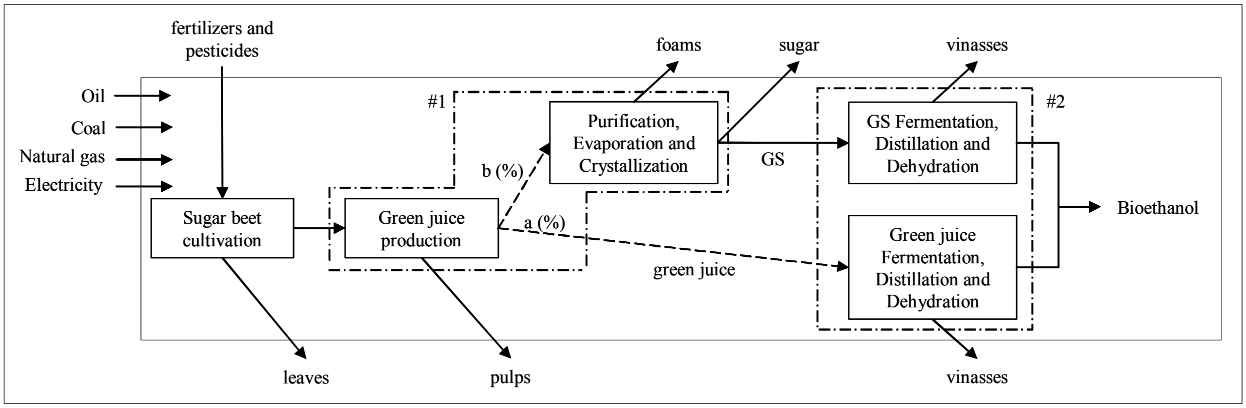

Fig. 1. Flow chart illustrating the bioethanol production chain from sugar beet.

The production of ethanol from sugar beet (Fig. 1) comprises two steps: *i)* green juice and green syrup (GS) are produced at the sugarhouse, by subjecting biomass to a sequence of processes, namely washing and diffusion to obtain green juice and afterward purification, evaporation and crystallization to obtain GS from green juice, with sugar as a co-product; *ii)* ethanol is produced both from green juice and GS at the distillery through the following processes: fermentation using yeast, followed by distillation to increase ethanol concentration and, finally, dehydration to obtain anhydrous ethanol. The purification step also produces foams that are used as organic fertilizer. Vinasses, another co-product from ethanol distillation of green syrup, are concentrated and spreaded on agricultural land. Details concerning the technological description and the mass and energy balances of these steps can be found in great detail in ref. [34]. The technological processes involved to obtain ethanol from sugar beet are not self-dedicated to the production of ethanol. Instead, the whole chain is shared by the alcohol and sugar industries. According to current industrial and commercial practices in France, 50% of the bioethanol produced comes from green juice and the other half comes from GS [34]. With this share, 3.96 kg of sugar are obtained for each kg of bioethanol produced (Table 1). The commercial feasibility of producing ethanol from sugar beet involves a comparison of alternative revenue streams from sugar beet with ethanol or sugar product forms, *i.e.* the trade-off between relative sugar and alcohol returns is a key factor driving the allocation of sugar beet between sugar and bioethanol [42]. In contrast to *joint production*, in which the relative output volume of the co-products is fixed [38], the share of sugar and bioethanol extracted from sugar beet is independently variable (*combined production*, illustrated in Fig. 1 by dashed lines), which offers the sugar beet transformation industry the opportunity to broaden its revenue base and to assure continued financial viability by pursuing the ethanol and/or sugar options. For combined production, allocation can be avoided simply by modeling directly the consequences of a change in the output of the co-product of interest (that which is used in the product system under study) [8]. This approach is used in the LCI of bioethanol produced from green juice (route *a* in Fig. 1).

The production route of ethanol from wheat (Fig. 2) includes a sequence of mechanical and chemical processes, which can be divided in three main stages: *i)* grinding of grains and malting, where artificial enzymes are introduced to break down the starch into sugar; this sugar is washed out of the wheat with water and the leftover residue (Distilled Dried Grain with Solubles, DDGS) is extracted as a co-product that can be sold for animal feed; *ii)* fermentation of the sugar juice using yeast to produce ethanol at 10/15% concentration and subsequent distillation of this solution to produce ethanol at higher concentrations and *iii)* dehydration, producing, as a result, anhydrous ethanol.

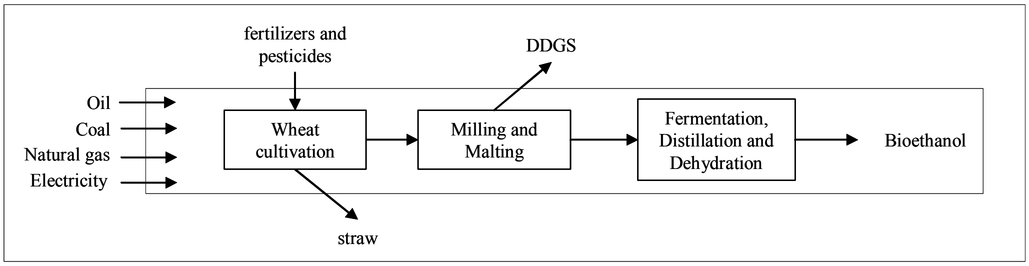

Fig. 2. Flow chart illustrating the bioethanol production chain from wheat.

Allocation was avoided by extension of system limits to include the additional functions related to the following co-products: leaves from sugar beet cultivation; foams from purification of green juice in the sugarhouse and vinasses from distillation of ethanol, after fermentation of green juice and green syrup in the distillery. Sub-division was used by splitting bioethanol production chain (from sugar beet) into case #A (route *a*, Fig. 1), where only ethanol is produced, and case #B (route *b*, Fig. 1), where sugar is the major product; however, allocation has to be performed for case #B, where ethanol is produced (joint) with sugar.

Table 1.
Agricultural and industrial data for the production of 1 tonne of ethanol.

		Ethanol (sugar beet)			**Ethanol (wheat)**
		#A	50%A/50%B	#B	
Agricultural production	Land [ha]	–0.172	–0.521	–0.870	–0.469
	N fertilizer [kg]	–21.1	–63.8	–106.5	–99.2
	P_2O_5 fert. [kg]	–12.0	–36.5	–60.9	–15.9
	K_2O fert. [kg]	–30.1	–91.2	–152.3	–15.7
	Diesel [l]	–27.7	–83.9	–140.1	–53.9
	Leaves [t]	0.75	2.27	3.79	—
	Straw [t]	—	—	—	3.05
	Biomass [t]	**11.58**	**35.06**	**58.55**	**3.58**
1st industrial conversion stage	Natural Gas [MJ]	–6127.8	–17933.6	–29378.2	–18702.7
	Oil [MJ]	–4860.2	–13377.5	–21604.4	—
	Coal [MJ]	–4009.6	–9429.7	–14609.7	—
	Electricity [kWh]	—	–653.3	–1306.7	–1602.8
	Sugar [t]	—	3.96	7.92	—
	Pulps [t]	0.60	1.83	3.06	—
	DDGS [t]	—	—	—	1.35
	Ethanol [t]	**1**	**1**	**1**	**1**

A: Ethanol production from sugar beet; # B: Sugar production, with sub-production of ethanol; t = tonne; l = liter.

Eight individual processes have been identified where allocation was applied: *i)* sugar beet cultivation, green juice production and purification, evaporation and crystallization of green juice and *ii)* wheat cultivation, milling and malting. The use of resources (energy and materials) and the output of co-products for the production of 1 tonne of ethanol are listed in Table 1. The production process is separated into two stages, the production of the agricultural energy feedstock and the conversion of the feedstock into bioethanol. Three distinct situations are shown for ethanol production based on sugar beet: *i)* case #A; *ii)* case #B and *iii)* case "50%A/50%B", representing the current commercial practice in France. Input and output coefficients are given negative and positive signs, respectively.

3.3 Allocation and implications for inventory results

Table 2 reports the mass allocated "cradle-to-gate" fossil energy use (functional unit of 1MJ of bioethanol energy content) and identifies the relevant contributions from the different stages. Bioethanol production is by far the most energy intensive stage. Fossil energy input during biomass production mainly results from the energy content of fertilizers and from the use of agricultural machinery. Case #B of sugar beet based ethanol exhibits the worst results due to the higher energy requirements associated with processing of green syrup as compared to green juice processing. In each case, the transportation stages hardly contribute to the energy balances.

Table 2.
Ethanol "cradle-to-gate" primary energy requirements (E_{req}) using mass allocation.

Stage	**Ethanol (sugar beet)**			**Ethanol (wheat)**
	#A	50%A/50%B	#B	
		E_{req} (MJ/MJ)		
Biomass production	0.05664	0.04043	0.03830	0.05347
Biomass transport	0.00864	0.00617	0.00584	0.00147
Bioethanol production	0.56070	0.73279	0.92923	0.38915
Bioethanol transport	0.00348	0.00348	0.00348	0.00348
TOTAL	**0.630**	**0.783**	**0.977**	**0.448**

Table 3.
Allocation approach: Implications for bioethanol primary energy requirements (E_{req}).

Allocation Procedure	**Ethanol (sugar beet)**						**Ethanol (wheat)**	
	#A		50%A/50%B		#B			
				E_{req} (MJ/MJ)				
Without co-product credits	0.702	(100%)	1.860	(100%)	3.041	(100%)	1.210	(100%)
Mass	0.630	(89.7%)	0.783	(42.1%)	0.977	(32.1%)	0.448	(37.0%)
Energy	0.661	(94.2%)	0.883	(47.5%)	1.124	(37.0%)	0.656	(54.2%)
Market Value	0.679	(96.7%)	0.818	(44.0%)	1.016	(33.4%)	0.566	(44.8%)
Replacement	0.673	(95.9%)	0.893	(48.0%)	1.134	(37.3%)	1.036	(85.6%)

Implications for bioethanol life-cycle primary energy requirements are presented in Table 3 for each of the four allocation procedures used. For comparative purposes, results obtained ignoring co-product credits are also presented. A minimum energy requirement of 0.448 MJ/MJ was obtained for wheat based ethanol, using mass allocation. The percentage of energy use assigned to bioethanol is shown inside brackets – 37% of the total energy requirements are assigned to bioethanol if mass allocation is used. For case #A of sugar beet based ethanol at least

90% of the energy used to produce the biofuel is assigned to bioethanol, since the contribution of pulps (the other co-product) is not relevant. The same does not apply for case #B, where sugar is the major output and, thus, allocation results in about a 30 to 40% energy assigned to bioethanol. Cases #A and #B, as well as case "50%#A/50%#B", are not as sensitive to allocation as ethanol from wheat, in which variations in E_{req} due to allocation are significant. Table 3 also shows that energy replacement values result in less energy credits than the other methods, *i.e.* it is the least favorable allocation approach for biofuels from an energy use standpoint.

4. Results and discussion

Fig. 3 illustrates the energy renewability efficiency of bioethanol, compared with gasoline. ERE results for each alternative bioethanol chain are presented, for the five procedures adopted. As stated before (Table 3), ethanol from wheat is much more sensitive to the allocation procedure chosen than sugar beet based ethanol, with ERE values ranging from -3% to 55%. The best energy renewability efficiency is obtained for ethanol produced from wheat. In particular, a maximum ERE value of 55% is achieved using mass allocation, meaning that more than 50% of the ethanol energy content is indeed renewable energy. However, wheat based ethanol also shows a negative ERE value (replacement method), due to low energy credits from co-products substitution. Ethanol from sugar beet (case #A) is clearly renewable, even before adding co-product energy credits, with ERE values of around 30% regardless of the allocation approach chosen. Higher shares of sugar imply lower energy renewability efficiencies (cf. case "50%#A/50%#B" and case #B in Fig. 3), due to the high energy inputs associated with processing of sugar. ERE values for case "50%#A/50%#B" and case #B without co-product credits are not meaningful –and thus are omitted from Fig. 3–, since these cases are also dedicated to sugar production.

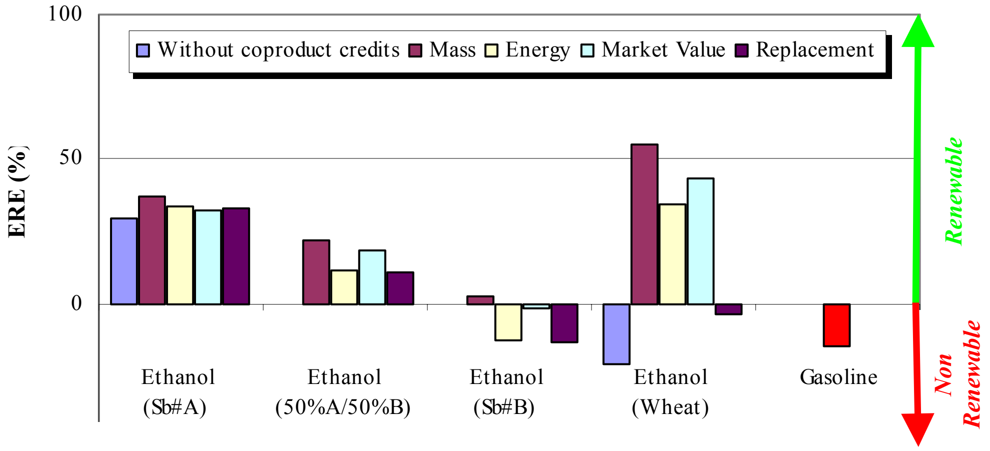

Fig. 3. Energy Renewability Efficiency (ERE) values: bioethanol and gasoline (Sb#A or Sb#B – Sugar beet, case #A or case #B).

All chains exhibit higher ERE values than gasoline –except for ethanol from wheat without co-product credits–, which clearly indicates that considerable reductions in fossil fuel depletion would be achieved by replacing gasoline with ethanol form sugar beet and, even greater savings, if wheat based ethanol was adopted for substitution.

5. Conclusions

This paper has demonstrated how a life cycle energy approach can be used to assess the energy efficiency and renewability of biofuels. A novel indicator aiming at characterizing the renewability of (bio)energy sources is proposed – the *energy renewability efficiency* (ERE) –, which measures the fraction of final fuel energy obtained from renewable sources. ERE values were calculated for two alternative ways of producing ethanol (from sugar beet or wheat) and compared to gasoline. Implications for the fossil fuel depletion associated with the various stages of the production of bioethanol have been addressed by estimating primary energy inputs and calculating the accumulated energy requirement. LCI results together with E_{req} and ERE values are presented using four different allocation approaches (and ignoring co-product credits) in order to understand the effect of allocation in the overall energy efficiency and renewability of bioethanol production. Results demonstrate that the LCEA of biofuel systems is highly sensitive to the allocation method used. In fact, ERE values for ethanol from wheat can vary more than 50% ranging between -3% (replacement method) and 55% (mass allocation), with 34% for energy allocation and 43% for allocation based on market values. However, the energy renewability efficiency of ethanol from sugar beet (case #A) varies only between 32% and 37%, being less sensitive to allocation because in this case co-production is not much relevant. ERE values calculated ignoring co-product credits are, in some cases, very low, emphasizing the importance of using an appropriate allocation procedure.

This study demonstrates that both ethanol produced from sugar beet and wheat in France are clearly favorable in primary energy terms in comparison with gasoline. It can be concluded that the use of bioethanol as a liquid transportation fuel reduces fossil fuels depletion and increases the security of energy supply. This conclusion is in line with Directive 2003/30/EC recommendations to increase the share of biofuels in the transportation sector [3]. Nonetheless, it should be emphasized that optimum use of co-products, such as protein-rich residues for animal feed (e.g. pulps and DDGS) and wheat straw as an energy source is needed to improve the energy efficiency of bioethanol production. In some cases, however, overestimating the benefits of these co-products is speculative, since the practicality and economic viability of their massive use is still subjected to uncertainty. Although the inventory analysis presented in this paper is focused only on bioethanol, the methodology presented and, in particular, the assessment of the implications of the allocation approach used might be applied to other biofuels. In addition, the inventory analysis performed in this research can be used as a starting point for a complete LCI, since it lays out a formal methodology for conducting an LCA for biofuels, where a detailed list of environmental impacts should be adopted with the aim of addressing the sustainability of bioethanol chains, which is beyond the scope of this paper.

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