Chapter 6
The Effect of Biofuel Production on Greenhouse Gas Emission Reductions

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6.1 Introduction

Fossil fuel consumption is a major cause of climate change. Biofuels can reduce the consumption of fossil fuels and thus reduce carbon dioxide emissions, because biofuels are carbon neutral. More specifically, the carbon dioxide that is emitted when a biofuel is burned merely returns to the atmospheric carbon dioxide that was taken into plants from the atmosphere by photosynthesis. Therefore, biofuels seem to be a very effective means for reducing these emissions, at least at first sight.

However, the reality is not so simple but controversial (Edwards et al. 2007; Fargione et al. 2008; Hill et al. 2006; Menichetti and Otto 2009; Searchinger et al. 2008). The production of a biofuel consists of growing an energy crop and using biomass obtained from the crop as a raw material for making liquid fuel. The production of bioethanol includes processes of fermenting sugarcane, corn, or other sugar-based feedstock and distilling the contents in a similar manner to distilling liquor, and the production of biodiesel includes a chemical reaction (transesterification) using vegetable oil as a raw material. Additionally, feedstock is collected in the farmland to the fuel production plants, and then biofuels are distributed to filling stations, where they are sold to consumers. These processes inevitably consume energy.

Moreover, it has been pointed out that greenhouse gases (GHGs) are also generated by the cultivation of energy crops. One of the GHGs, nitrous oxide, is generated when fertilizers are used to raise the yields of energy crops. Furthermore, when forest land is converted to use for energy crop plantations, the carbon dioxide absorption of the forests is lost, in addition to which organic matter in the soil breaks down and generates carbon dioxide. All these issues mean that the production of

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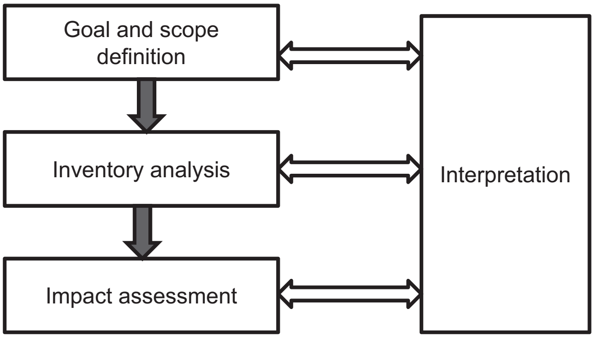
Fig. 6.1 Basic scheme of life cycle assessment



biofuels leads to GHG emissions, to a greater or lesser extent. In other words, there is a trade-off between the carbon dioxide reductions when biofuels are used instead of fossil fuels and the GHGs that are generated in the production of biofuels.

A quantitative evaluation with life cycle assessment (LCA) is necessary for a judgment of this trade-off. The environmental loading of a biofuel can be evaluated from the beginning to the end use in LCA. The net effect may be evaluated by calculating increases and reductions in GHGs throughout the life cycle.

LCA is a tool originally devised for the chemistry industry. Their salient features are combining and quantitatively evaluating environmental loads associated with the manufacture of a product, from the acquisition of raw materials to disposal. LCA is useful in design for environment and employed for sustainable consumption and consumption of products with low environmental loading. The environmental loading associated with creating and disposing of these products may not be immediately apparent. This hidden environmental loading is estimated by LCA and is referred to as embodied environmental loading. Terms such as embodied energy and embodied CO_2 are used when evaluating the environmental aspects of products. The prime example of application of LCA for the public is carbon footprint, a figure focusing on carbon dioxide.

The basic phases of LCA are shown in Fig. 6.1. The environmental loads include energy consumption and emissions of a wide range of substances such as GHGs, air pollutants, water pollutants, or heavy metals. First, the goals and scope of an analysis are specified. In this phase, the scope is suitably determined with consideration to the purpose for using LCA, and the environmental loads to be analyzed are specified. Next, an all-encompassing inventory of emissions relating to the selected environmental loads is created. In the impact assessment phase, these environmental loads undergo a comprehensive evaluation. The environmental loading is ascertained, and processes are improved by interpretation phases.

Previous researches on LCA of biofuels have been controversial and produced diverse reports. In some reports, biofuels were found to be beneficial for the environment, and in other reports, they were found to be ineffective or even damaging. Reasons for the contradictions among these results include the questions of which environmental loads were considered and which biofuels were considered. Another issue is that environmental loading differs between different geographic regions.

Although there are different carbon intensity of the fuels that are used in ordinary manufacturing industries, GHG emissions are broadly proportional to energy consumption. However, this does not apply to biofuels. Byproducts and residues of biomass cultivation processes and production processes are carbon-neutral biomass. When these byproducts and residues are used as energy sources, this counts as energy consumption but does not count as GHG emissions. Therefore, life cycle energy consumption and life cycle GHG emissions must be evaluated differently. LCA could indicate that biofuel does not save energy but does lead to a reduction in GHGs.

6.2 Biofuel LCA

6.2.1 LCA Framework

When biofuels are used as a fuel for vehicles, LCA is applied in a way that enables comparison with a LCA for conventional fuels, such as gasoline or diesel fuels. When these fossil fuels are used, crude oil is extracted from an oil well, transported, refined, sold, and loaded into a vehicle fuel tank. These steps are referred to as the well-to-tank (WTT) stage. The fossil fuel is then burned while the vehicle is running, which is referred to as the tank-to-wheel (TTW) stage. An analysis of the two together is referred to as a well-to-wheel (WTW) analysis. It is convenient to use this division for biofuels also for comparison with fossil fuels.

GHG emissions from fossil fuels are small in the WTT stage and large in the TTW stage. In contrast, with a biofuel that is a carbon-neutral fuel, the environmental loading is small for the TTW stage and large for the WTT stage, complicating the analysis.

Although biofuels are not obtained by digging oil wells like petroleum, the WTT stage consists of raw material acquisition, processing, storage, and distribution (Fig. 6.2).

The raw material acquisition stage includes growing an energy crop. Analysis of the energy loading of this cultivation step is an analysis of the energy loading for agricultural activity, which differs from the industrial production for which LCA is usually used. For industrial production, the raw materials and energy that are input, and the pollutants generated by the artificial manufacturing are ascertained. These are originally understood at the design stage for the artificial manufacturing process, so data and reports are easy to obtain. In contrast, agriculture depends on nature, and effects on the environment that result from artificial utilization of land must be evaluated. Unlike an industrial process that is performed under controlled conditions, the environmental loading of agriculture has to be evaluated under conditions that are greatly influenced by climate and the like. The fate of fertilizers that are used and changes in the soil that are caused by agricultural activities should also be included.

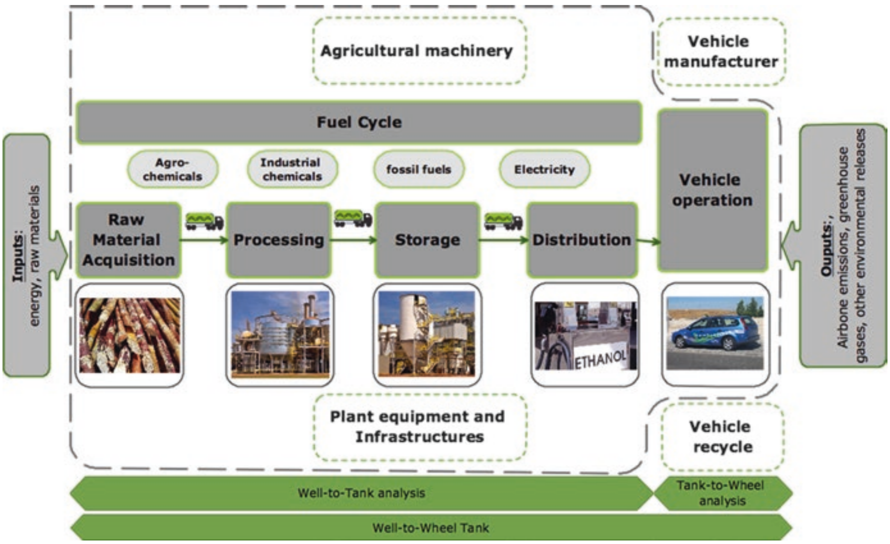


Fig. 6.2 Well-to-tank and tank-to-wheel analysis of biofuel

In GHG emissions, there is the possibility of large amounts of nitrous oxide being generated during cultivation of feedstocks. This originates from nitrogen fertilizers and is produced by processes of nitrification and denitrification. The amounts generated do not depend solely on the amounts of nitrogen fertilizer used but also on soil characteristics and climate conditions, so there can be a very wide range of values for emission factors. It should be noted that when land with a soil such as peat that stores large amounts of organic carbon is developed and cultivated, the carbon accumulated in the soil is released into the atmosphere as carbon dioxide. The carbon dioxide is generated from a natural source, but it should be accounted as anthropogenic production.

The production of biofuels is an industrial process, so it does not differ greatly from the usual LCA. However, there are several points to consider. Because factories that carry out these production processes are often located in agricultural areas, available energy sources in those locations are limited. Unlike industrial raw materials, energy crops include many unusable parts such as straw and husks, and how these byproducts are used is an important question.

In the TTW stage, combustion conditions differ from the case of using standard gasoline or diesel. Therefore, differences in vehicle combustion efficiency and differences in atmospheric pollutant emission are important and will vary depending on the performance of the vehicles using the fuels.

When each phase of LCA is applied to biofuels, the key issues are shown in Fig. 6.3. In the goal and scope definition phase, target energy crop, agricultural waste production, and process must be determined. The comparison of different kinds of environmental loading is the main issues in the impact assessment phase.

In LCA functional unit (FU) is determined first, and environmental loading is calculated with reference to these functional units. For example, in an LCA for

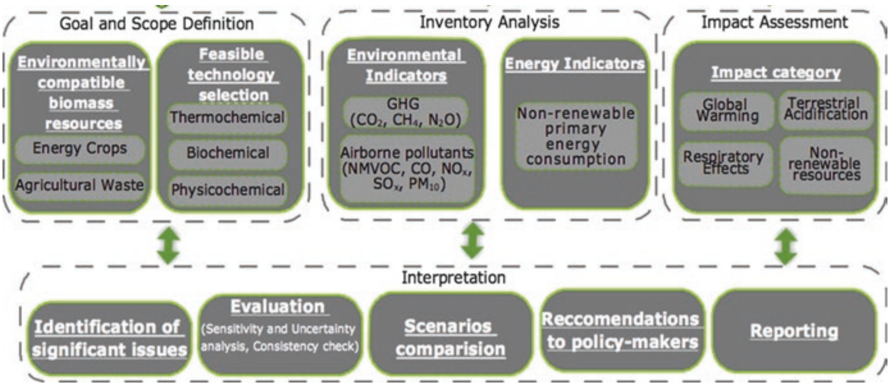


Fig. 6.3 Key issues in each step of LCA of biofuel

refrigerators, one refrigerator of certain volume is the functional unit, and for a raw material such as cement, the functional unit is 1 ton of cement. Comparing results that are organized by the same functional unit is a fundamental feature of LCA. Different functional units may be used depending on the reasons for carrying out LCA.

For biofuels, there are a number of possible different functional units that can be considered. Cherubini and Strømman (2011) identified four different FUs that are commonly used to describe bioenergy systems: (i) feedstock based, which refers to the unit of input biomass and does not depend on conversion processes and products; (ii) product based, which allows an evaluation from a downstream angles; (iii) agricultural land related that refers to the farmland used to cultivate feedstock; and (iv) per year unit that assesses results in a yearly basis. A simple example of a functional unit is 1 l of the biofuel. However, if gasoline and bioethanol are compared, the different fuels have different heat values, so a simple comparison by units of volume is inappropriate. One method often used to express results is units of energy of biofuel (e.g., kJ), which is reasonable for evaluating biofuel production processes. However, if the final TTW stage is included, the performance actually obtained is running a vehicle. Therefore, the results of the LCA may be expressed in vehicle kilometers traveled (VKT). This method considers biofuels from the downstream end of the material flow. It is also possible to look at the upstream end and express the environmental loading by production volumes of biofuel per hectare of agricultural land.

6.2.2 Evaluation of Effects of Byproduct Recovery and Use

One of the characteristics of biofuels is that large amounts of byproducts and residues, such as straw and husks, are produced in the processes of cultivation and production. It is important for the LCA to evaluate whether these byproducts and residues are used effectively. The possibility of quantitatively evaluating effective use is one of the advantages of LCA. However, analytical methods for this are complicated. There are two different strategies to evaluate apportion environmental loads between the final products and its byproducts. Either practitioners can proportionally divide the burdens between output flows based on their physical (mass or energy) content or economic value (called as allocation) or alternatively system boundaries can be expanded to include additional credits related to the byproducts displacement (called as system expansion).

Bagasse, a typical byproduct of sugarcane, is most commonly used for thermal energy and electricity generation. Thus, environmental loads can be divided between bagasse and ethanol based upon its energy content. This is a straightforward method that guarantees stable outcomes, as physical properties are constant. However, the allocation of physical properties may encounter criticisms, since environmental loads are not necessarily proportional to products' mass/energy content. Thus, practitioners can consider the expansion of the system boundary. When bagasse is used as an energy source, it has the effect of replacing a fossil fuel. In the LCA, this effect is evaluated as the avoided environmental loading from the fossil fuel. This is a typical case of system expansion.

If petroleum is replaced by a byproduct, the effect may be calculated as a reduction in the environmental loading caused by petroleum production. When electricity is generated by a byproduct, the effect reduces the environmental load associated with generating electricity. The substance replaced by a byproduct depends on the geographic region, and because a number of different kinds of fuel are used in a power grid, it is important to determine which fuels are replaced by the byproduct. For example, if electricity is generated by a byproduct in a region where the grid electricity is generated with coal, this leads to a large reduction in CO_2, whereas if electricity is produced from a byproduct in a region that uses hydroelectric power generation or nuclear power generation in the grid, the CO_2 reduction effect is very low.

As an example, we consider composting solid waste and substituting it for a chemical fertilizer (Fig. 6.4). In this case, the system boundary must be expanded to include fertilizer production. If the waste were not recycled through composting, the waste would be landfilled, causing an environmental load such as methane emission, while energy would be used in the industrial production of chemical fertilizer. Various environmental loads are caused by these processes. On the other hand, if compost is produced from the waste, an environmental load is caused by this production, but the abovementioned environmental loads of landfilling the waste and producing the chemical fertilizer are avoided. These calculations must be performed so that the effectiveness of the compost matches the effectiveness of the chemical fertilizer that is replaced. As the fertilizing effects of 1 ton of compost and 1 ton of chemical fertilizer are not the same, adjustment is necessary in the calculation.

With biofuels, energy substitution by residues and replacement of chemical fertilizers are typical uses of byproducts. Large amount of residues are produced from the conventional process for producing a biofuel from an energy crop. This residue can replace large amount of fossil fuel. On the other hand, if the production yield is raised by an innovative process, less amount of residue can be used to replace fossil

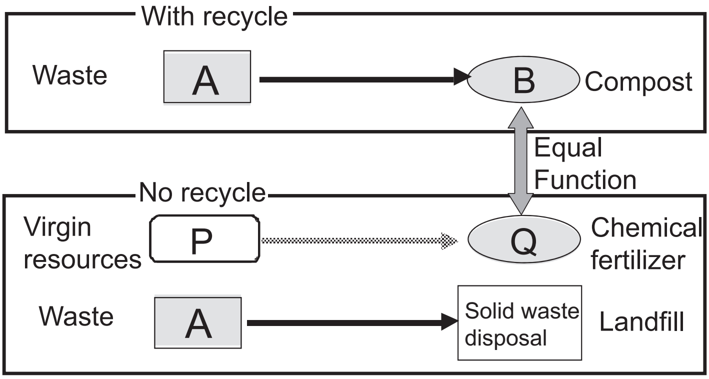


Fig. 6.4 LCA of waste utilization

fuel. As a result, the environmental loading per unit of energy for the biofuel produced may be smaller in the conventional process than in the innovative process. In other words, the innovative process can produce more biofuel, but environmental load per unit fuel increases.

Not readily biodegradable materials such as wooden stems are decomposed by pretreatment and then converted in the so-called second-generation biofuel production. As a result, residues used for process energy in the first-generation biofuel process are reduced in the second-generation process. Apparently environmental loading per amount of biofuels is larger, though yield of biofuels from the energy crop is high in the second-generation process. This is the controversial issue of the functional unit.

6.2.3 *The Necessity of Localized LCA*

Discussions of how local characteristics are included in LCAs and whether they should be included involve profound questions. Universal evaluations irrespective of location are often pursued in manufacturing LCA. Moreover, because the components and materials used in ordinary industrial processes are distributed all over the world, it is not practical to identify the production locations and include local characteristics of the production locations in LCAs. Therefore, it is appropriate to use global average values.

With biofuels, however, long-distance transportation of energy crops is not practical, and all stages up to production are carried out in the region of cultivation. Therefore, the environmental loading associated with biofuel production is affected by the characteristics of each region. First of all, the selection and growth yield of an energy crop greatly depends on the climate of a region. Sugarcane, cassava, oil palm, and similar crops grow in tropical regions, while other energy crops are suitable for temperate regions. Yields of the crops per unit of land area also differ between regions.

GHG emissions from the soil, such as emissions of nitrous oxide from the applied nitrogen fertilizers and the release of carbon dioxide from peat are affected by the soil of an agricultural area. Furthermore, utilization of agricultural residues as energy source or fertilizer depends on the technologies employed in the region.

The replaced energy sources by the residue vary by region. GHG reduction through this replacement is larger in coal-dependent area than oil-dependent area. This difference in energy sources is most remarkable in the replacement of electric power generation. In mainland China, where coal-fired power stations are dominant, the carbon emission factor is about 1.1 kg CO_2/kWh (Department of Climate Change, National Development and Reform Commission, China 2008). In the Tokyo region of Japan, the carbon emission factor in 2010 was about 0.4 kg CO_2/kWh (Ministry of Environment 2010), only one-third as much. This means that replacement of power generation would have a large CO_2 reduction effect in China and a small effect in the Tokyo region. The amounts would be even smaller in a region that uses hydroelectric power, such as Brazil (0.2 kg CO_2/kWh) (Portugal 2011).

The TTW stage is not affected by the production region but by local characteristics of regions in which a biofuel is consumed. Large amounts of biofuel are distributed internationally. Average lifespan and performance of vehicles and atmospheric pollution standards differ greatly between countries. Mixing ratios for biofuels and conventional fuels also vary between countries. For instance, in Brazil, ordinary gasoline (commonly referred to as *gasohol*) is blended with 18–25% (v/v) of anhydrous ethanol (MAPA 2011b), whereas in Japan the legal limit of ethanol blends is 3% (v/v) (Fukuda et al. 2006).

These points show that, when evaluating the GHG reduction effect of biofuels, LCA must be carried out considering the local characteristics of the producing regions and consuming regions.

6.3 Sugarcane Ethanol Production in Brazil

As stated earlier, LCA is a useful tool to evaluate the climate change mitigation potential of biofuels. Yet, it is also a source of controversy as LCA results are significantly dependent on local conditions of production and utilization, and options made by practitioners when selecting system boundaries, allocation procedures, and the functional unit of the system, among others. Thus, the truthful GHG and fossil fuel resource savings from biofuel life cycle and uncertainty factors behind LCA results are yet to be surely understood. To clarify these matters, a LCA has been conducted to evaluate the GHG emission and nonrenewable energy (NRE) consumption of sugarcane ethanol production in the South-Center region of Brazil and its application in the Brazilian national passenger vehicles. The analysis is focused on current practices, taking as reference the base year 2008 (the latest year for which

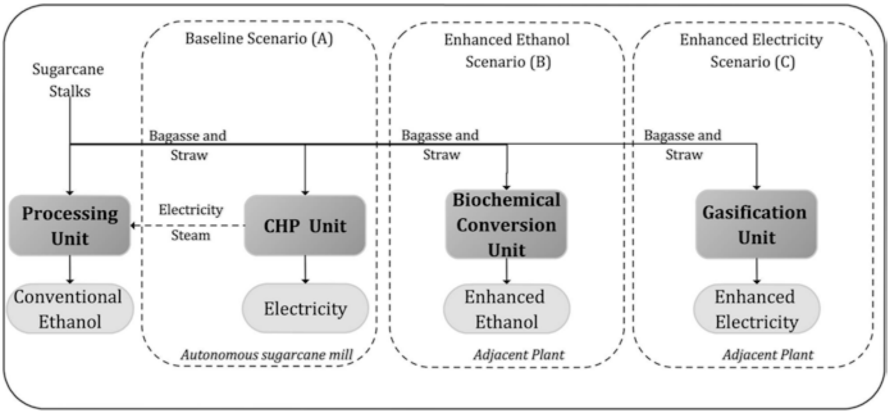


Fig. 6.5 Schematic diagram of baseline and alternative scenarios

data inventory was available), as well as on the forecast of potential technological and efficiency improvements up to a 2030 horizon. Results are presented through different angles, in terms of function unit selection and allocation procedures, in order to understand how background assumptions and methodological choices constrain the overall LCA results.

6.3.1 Description of the Case Study and its Scenarios

Brazil is an important World player in the ethanol market, being the second largest producer after the USA. Nearly 9.67 million hectares were dedicated to sugarcane farming, producing around 25.7 million m^3 of ethanol (MAPA 2011a). While the production of sugarcane ethanol is a well-known and optimized process, significant gains can be achieved by enhancing the efficiency recovery of its byproducts, bagasse, and straw. In this view, a baseline scenario and two alternative scenario forecasts were considered. The baseline scenario (A) attempts to describe the current state of the art of sugarcane farming practices and ethanol refining units, as well as likely future improvements, without considering any processing technological shift. Alternative routes, on the other hand, forecast the recovery of bagasse and straw via advanced biochemical or thermochemical processes, designed as cellulosic ethanol scenario (B) and enhanced electricity scenario (C), respectively. The scheme of the baseline and alternative scenarios is presented in Fig. 6.5.

Accordingly, the baseline scenario encompasses the *status quo* of the sugarcane farming and ethanol processing activities. Sugarcane farming occurs in a 6-year cycle, including five harvest periods with gradual yield decline and one planting season. During the farming stage, fossil fuel energy consumption is mainly associated with agrochemical application and diesel used in machinery during agricultural operations. Harvest activities are primarily manual and labor intensive, followed by an open-air fire on the field, which brings advantages in terms of diesel consumption. Nevertheless, driven by other environmental (urban air pollution due to PM, NO_x, and SO_x pollutants) and social concerns, manual harvest technique planned to be phased out by 2014–2017 (Goldemberg et al. 2008). In the simulation period (2030), besides the phaseout of the open-air burning, changes of sugarcane farming practices are related to the boost of sugarcane productivity, the increase of application of agrochemicals, and the rising consumption of diesel (due to a higher rate of harvest mechanization). Additionally, with the introduction of mechanical harvest, straw (initially burned in the field) could be recovered to supply the ethanol refining process.

The ethanol processing stage was modeled assuming a conventional autonomous ethanol refining unit, where only ethanol is produced, through conventional mechanical and biochemical processes. First, harvested sugarcane passes through a cleaning unit to remove impurities, followed by an extraction system, where sugarcane is chopped, and shredded, and juice with high content of sugar is separated and cleaned. Bagasse and filter cake are also generated as coproducts. Following juice extraction, the mixture is fermented by yeasts (commonly the *Saccharomyces cerevisiae*). Finally, the resulting wine is purified through fractional and azeotropic distillation processes. Besides the final product anhydrous ethanol, vinasse is also generated. As this coproduct has a high nutrient content (N, P, K), it is commonly recovered and used for ferti-irrigation. One tone of vinasse recovers 0.36 kg of N-fertilizer (Donzelli 2007).

The ethanol processing consumes energy for activating pumps, fans, and milling equipment, as well as thermal energy for the juice concentration and distillation processes. The process is assumed to be energy self-sufficient, i.e., the consumed energy is entirely powered by bagasse and straw (from mechanically harvested fields), in combined heat and power (CHP) units. Currently, CHP systems are generating steam at low pressure (~22 bar), which results in limited electricity generation. However, old boilers are being replaced by efficient high-pressure steam boilers (~65 to 90 bar, 480 °C) that increase the amount of surplus electricity (Macedo et al. 2008; Seabra et al. 2010). Thus, in the baseline scenario, forecasts up to a 2030 horizon were modeled taking into consideration the shift to high-pressure steam boilers and penetration of more efficient processes in ethanol production.

Alternatively, the cellulosic ethanol route (scenario B) considers the integration of an adjacent plant next to the principal ethanol distillery unit that produced cellulosic ethanol (the so-called second-generation ethanol) sourced by disposed bagasse and sugarcane straw. Prior to the fermentation and purification stages, the pretreatment processes are applied. Acid or enzymatic hydrolysis is done in order to separate degradable cellulose and hemicellulose compounds from the nondegradable lignin compounds. Accordingly, bagasse and straw biomass are pretreated via diluted sulfuric acid, followed by enzymatic hydrolysis with co-fermentation. The product is recovered, and purification follows common processes of the sugarcane-derived ethanol. Thus, an extra 46.3 l per ton of sugarcane is expected to be generated from the cellulose coproducts.

Table 6.1 Product flows of baseline and alternative sugarcane ethanol production scenarios (2030 horizon)

	Outputs	
	Ethanol	Electricity
Scenarios	$m^3.ha^{-1}$	$MWh.ha^{-1}$
Baseline (A)	9.6	14.0
Cellulosic ethanol (B)	14.3	5.2
Enhanced electricity (C)	9.6	18.7

On the other hand, the enhanced electricity route (scenario C) assumes that the disposed bagasse and sugarcane straw are recovered in a gasification unit. Biomass is firstly dried, conditioned, and then transformed into syngas. Later, syngas generates electricity in a gas turbine combined cycle (GTCC). The thermal and electrical efficiency of GTCC units is higher than conventional CHP units; thereby electricity production of enhanced electricity scenario is optimized. This option gives clear priority to electricity production, whereas enhanced ethanol route gives advantage to ethanol production.

Table 6.1 summarizes the main characteristics of these scenarios. Despite the common input flows, different processes are applied to each of the alternative scenarios. Thereby, output flows are considerably divergent. Predictable, in cellulosic ethanol route, ethanol production is maximized (14.3 m^3 per ha, namely, 54% higher than in the baseline scenario), whereas in electricity route, surplus electricity generation is prioritized (18.6 MWh per ha, which is 29–33% more than in the baseline scenario).

With regard to the utilization stage, three different light passenger vehicles were modeled, according to the Brazilian fleet. In Brazil, three different vehicles can be found: (i) E25 Otto-cycle vehicles running with E25 blended fuel (25% of anhydrous ethanol and 75% of conventional gasoline), referred to as gasohol; (ii) flexible-fuel vehicles (FFV), a new technology of vehicles that detects in real time the ratio of oxygen and fuel in the engine and accepts any kind of ethanol/gasoline blend (In this study, a share of 60% of hydrous ethanol and 40% of gasohol is assumed.); and (iii) dedicated ethanol vehicles that are exclusive only on hydrated ethanol (E100) that were discontinued in 2007.

6.3.2 LCA Framework

In this study an LCA framework was applied, which encompasses the goal and scope definition, the inventory analysis, life cycle interpretation assessment, and interpretation of result consistency. Figure 6.6 illustrates the steps followed in the LCA conducted.

The following paragraphs describe in detail the most relevant parameters and assumptions taken into consideration when evaluating the sugarcane ethanol production and utilizing scenarios.

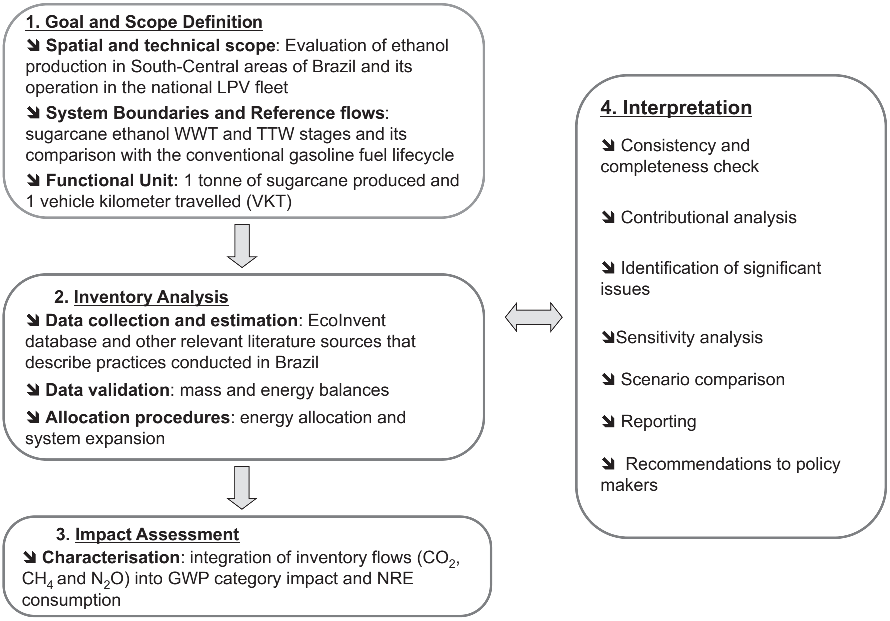


Fig. 6.6 Theoretical framework applied in this study

6.3.2.1 Definition of System Boundaries and Reference System

The evaluation included both the WTT stage that encompasses the sugarcane farming, ethanol refining processes, and intermediary transportation stages (collection of sugarcane and distribution of ethanol) and the TTW stage, which reflects the utilization of ethanol blended fuel in the E25, FFV, and E100 vehicles. The designed sugarcane ethanol scenarios have been compared with the equivalence reference system. Once ethanol is potentially substituting conventional gasoline, the reference system chosen is the production of gasoline and its use in conventional Otto-cycle light passenger vehicles. Figure 6.7 presents the system boundaries of sugarcane ethanol scenarios and the reference systems.

6.3.2.2 Functional Unit

Two different FUs were selected for this study: (i) a product-based unit, i.e., 1 vehicle kilometer traveled (VKT), which considers the efficiency of the ethanol blended fuel combustion in the E25, FFV, and E100 vehicles, and (ii) a feedstock-related unit, 1 ton of sugarcane harvested, which reflects solely the production of sugarcane and is independent from the ethanol processing and operation stages.

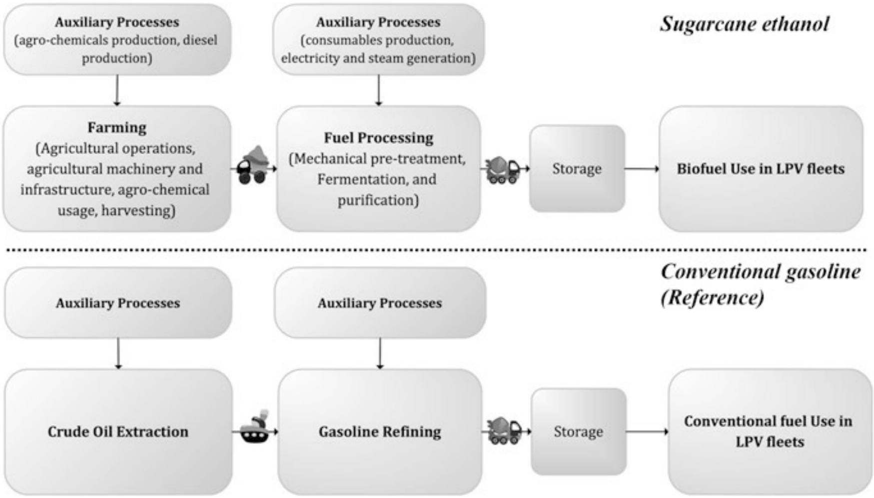


Fig. 6.7 System boundaries of sugarcane ethanol life cycle and reference system (conventional gasoline life cycle)

6.3.2.3 Allocation Procedures

Two different approaches have been followed to divide the environmental loads and energy consumption between ethanol and its byproducts. Thus, energy-based allocation and system expansion approaches were selected. In the energy-based allocation, environmental burdens were allocated based on the energy content of each of the products and byproducts. Accordingly, in the farming phase, loads have been portioned between sugarcane stalks and straw, over 98% of the loads being associated to the former. In the fuel production stage, loads were divided between ethanol, bagasse, and filter cake. Being ethanol the final product of the system, allocation factor accounts for nearly 78% in the baseline scenario (2030). As for the enhanced ethanol scenario, the allocation factor is larger, as it assumes maximization of ethanol production. On the contrary, in the enhanced electricity pathway, the allocation factor is lower because higher amount of electricity is produced than in the baseline scenario.

Alternatively, the system expansion approach assumes that the surplus electricity produced from the bagasse and sugarcane straw recovery displace Brazilian electricity grid. Thereby, 1 kWh of surplus electricity substitutes kWh of grid electricity.

6.3.3 Life Cycle Inventory Analysis

The life cycle inventory analysis provides the necessary input and output flows to model the environmental burdens associated to the sugarcane ethanol production and utilization in vehicle. As for the production stage, data include agrochemical production and usage in the farmland, diesel consumed during farming activities, agricultural machinery, consumables and energy consumption in the ethanol distillery plant, as well as the distance traveled in the intermediary transportation stages when collecting the sugarcane feedstock in the farmland and distributing ethanol to filling stations. In the utilization stage, data accounts for the fleet typology and mobility behavior that reflect the fuel consumption and emission patterns of the national vehicle fleet in Brazil.

The data was collected based on local and regional specificities of Brazilian reality. Data related to farming and processing stages, as well as fuel utilization in vehicle, was collected during the field survey conducted in March 2009 and related literature. Data referring to auxiliary processes, namely, agrochemical and other consumable production, was obtained in the ecoinvent database (Stutter 2006).

6.3.4 *Life Cycle Impact Assessment*

In the life cycle impact assessment (LCIA), the GHG emission and nonrenewable energy (NRE) consumption impact categories have been evaluated. The GHG is calculated as carbon dioxide equivalents (CO_{2e}), being carbon dioxide along with methane and nitrous oxide the greatest anthropogenic contributors. Global warming potential for 100-year time horizon in IPCC (2006) was used in Eq. 6.1:

$$\text{GHG} = \sum f_i . m_i \tag{6.1}$$

where:

GHG	Emissions of CO_{2e} [mass unit]
f_i	Characterization factor (global warming potential), 1 for CO_2, 25 for CH_4, and 298 for N_2O (IPCC 2006)
m_i	Emissions of CO_2, CH_4, and N_2O [mass unit]

NRE consumption accounts for the amount of fossil fuels withdrawn during the life cycle of a product. It is given as the ratio of primary fossil fuel energy required throughout the alternative fuel life cycle, as shown in Eq. 6.2:

$$\text{NRE} = \frac{E_{\text{xp}}}{E_f} \tag{6.2}$$

where:

NRE	Nonrenewable energy consumption ratio (MJ.MJ^{-1})
E_{xp}	Input primary fossil fuel energy required during the life cycle of the product
E_f	Final energy output

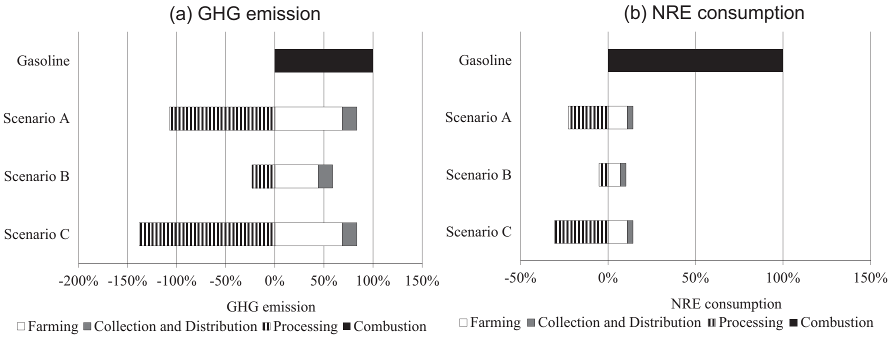
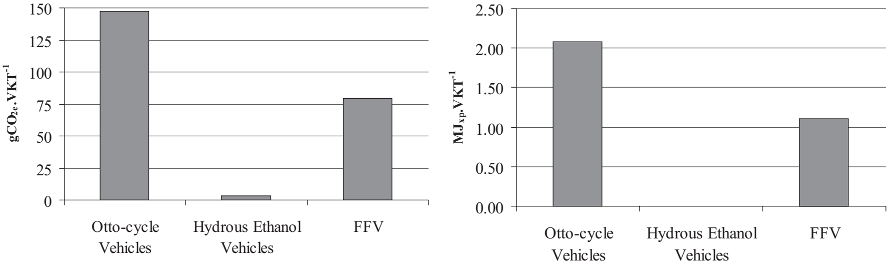


Fig. 6.8 Comparison of sugarcane ethanol production scenarios with gasoline fossil fuel production (2030)

According to the definition (Malça and Freire 2006), if the NRE consumption ratio is less than 1, it means that the fuel is renewable. On the other hand, if the ratio is larger than 1, more fossil energy is required to make the fuel than the energy available in the final fuel product. Thus, the fuel is classified as nonrenewable.

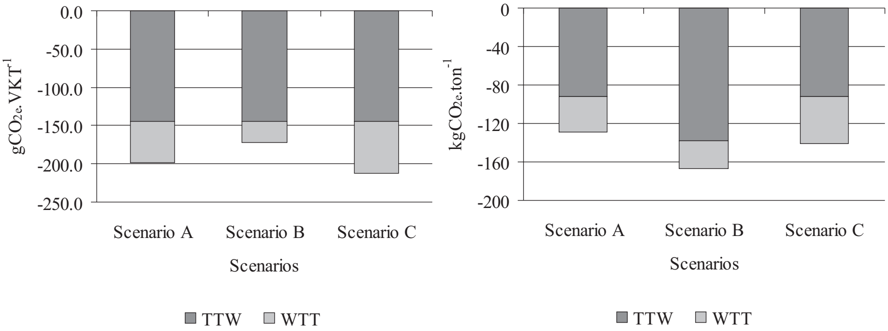
The life cycle inventories of the WTT part reflect the GHG emission and NRE consumption during the production stage. The results suggest that the baseline ethanol production pathway saves GHG emissions and NRE expenditure even without considering the carbon neutrality of biofuels, as shown in Fig. 6.8 in which gasoline combustion is shown as 100% for the comparison. The alternative route that prioritizes the generation of electricity from the bagasse and straw (scenario C) leads to greatest savings in terms of GHG and NRE consumption, owning to the displacement of the grid electricity by the surplus electricity generated. Once the surplus electricity generated from bagasse and straw releases nearly null GHG emissions and NRE expenditure, it presents lower impacts than Brazilian grid electricity. By this mean, net credits are obtained because the impacts during processing stage are regarded as negative. The net GHG and NRE consumption impacts of enhanced electricity production route are 155% and 116% less than gasoline, respectively. As against this, the production of enhanced ethanol (scenario B) pathway yields lower direct emissions than scenario C, owning to its higher yield of ethanol per hectare, but generates less electricity than the electricity route because the bagasse and straw waste are less.

The major steps that contribute to environmental loads are farming activities including fertilizers and agrochemical use and diesel consumption by tractors and other agricultural machineries. The fuel processing step is a modest contributor or even results in GHG and NRE consumption credits, since the energy in the ethanol refinery is supplied by bagasse and straw, which are renewable and carbon-neutral resources. The feedstock collection and fuel distribution steps also play a minor role in the overall environmental performance of the ethanol routes.



(a) GHG emission **(b) NRE consumption**

Fig. 6.9 Comparison of E25 and E100 vehicle operation in Brazil (2030)



(a) FU: VVKT (Vehicle kilometer travelled) **(b) FU: ton of sugarcane**

Fig. 6.10 Influence of FU in the GHG of WTW sugarcane ethanol scenarios

The TTW analysis of the operation of ethanol in conventional Otto-cycle (E25), ethanol-dedicated (E100), and flexible-fuel vehicles (FFV) shows a clear advantage of ethanol fuel in terms of GHG emission and NRE consumption, as displayed in Fig. 6.9. In fact, GHG emissions and NRE consumption from the combustion of ethanol are admitted to be null, given that ethanol is a carbon-neutral and renewable fuel. Thus, in E100 vehicles, GHG emissions only account for CH_4 and N_2O pollutants, which are nearly negligible. The environmental impacts of FFV vehicles solely reflect the 40% share of gasoline.

The WTW analysis integrates the previously displayed results of WTT and TTW analysis. Figure 6.10 presents the avoided GHG emissions and NRE consumption of ethanol production pathways and its use in E100 vehicles. The FUs are VKT and weight of sugarcane in Fig. 6.10a, b, respectively. All results show negative values which mean that GHG emission is reduced in all cases.

The analysis based on different FU apparently shows different results. On the one hand, the enhanced electricity scenario (scenario C) that maximizes the production of electricity via the bagasse gasification results in larger savings of NRE expenditure and GHG emissions per VKT (Fig. 6.10a), due to displacement of grid electricity. On the other hand, the enhanced ethanol scenario (scenario B) that shows the lower generation of surplus electricity results in the lowest savings. However, through a feedstock-oriented FU (Fig. 6.10b), results reveal different perspectives. The enhanced ethanol scenario (scenario B) that prioritizes the production of ethanol via biochemical synthesis of bagasse seems to be the most advantageous when applying a feedstock-based FU, as it shows higher yield of ethanol production per ton of sugarcane. Despite the lower savings by the use of small amount of waste biomass, the enhanced ethanol scenario shows larger savings during the operation stage, as it has higher yields of ethanol production per ton of sugarcane, than scenarios A and C. Therefore, savings per ton of sugarcane are more significant than in the other evaluated routes.

6.4 Final Remarks

The potential of biofuels to mitigate climate change and reduce dependency on fossil fuels is involved in an intense controversy, as its real benefits are significantly constrained by local geographic factors, technology of production, background assumptions, and methodological parameters of LCA. Major sources of uncertainty are data inventory, selection of allocation procedures, system boundaries, and functional unit. An LCA was conducted to discuss the source of uncertainty in LCA and to evaluate the GHG emission and NRE consumption category impacts of sugarcane ethanol production and utilization in Brazil within a 2030 horizon.

The results suggest that ethanol carriers effectively yield GHG and NRE savings, both in the production and operation stages. In the production stage, a key advantage is the recovery of sugarcane byproducts, straw, and bagasse, either to maximize the production of ethanol or to prioritize the generation of electricity. The former has lower direct emissions, but the latter results in GHG and energy credits as generated surplus electricity displaces grid electricity in Brazil. In the operation stage, the use of ethanol either in conventional, ethanol-dedicated, or flexible-fuel vehicles results in negligible GHG emission and NRE consumption, as ethanol is admitted to be a carbon-neutral renewable fuel.

The integrated WTW analysis discloses the overall benefits of ethanol carriers. Applying both a product-based and feedstock-related FU, ethanol shows gains in terms of GHG emission and NRE consumption, but results have dual interpretation according to which FU is selected. When applying a VKT as FU and system expansion approach, the enhanced electricity route reveals higher credits. On the contrary, a ton of sugarcane FU indicates that the enhanced ethanol pathway brings more advantages. This implies that the better process choice depends on the purpose and evaluation criteria.

This study has shown a wide variation of GHG emission and NRE consumption results, depending upon the selection of the functional unit, allocation procedures, and biofuel technology production pathways. Thus, it calls the attention to the need of improving LCA framework in order to evaluate the sources of uncertainty in complex systems, such as biofuel life cycles.

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