Brazilian ethanol for transport - Life cycle inventories and guidelines

Jorge Manuel Fernandes Gonçalves

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Supervisors: Prof. Carla Alexandra Monteiro da Silva
Dr. João Filipe Pinto Ribau

Examination Committee

Chairperson: Prof. Mário Manuel Gonçalves da Costa
Supervisor: Dr. João Filipe Pinto Ribau
Member of the Commitee: Prof. Tiago Morais Delgado Domingos

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I want to dedicate this work to my parents, for all the support through all these years. Also to every friend or stranger that somehow has helped me in my growth. And finally to João Ribau for the all the guidance.

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This university covered a great and very important part of my life. It's so funny to remember the person I was when I entered and realizing how much I grew. There were along this journey some professors I would like to mention. First of all my mentors for this assignment: professor Carla Silva and also professor João Ribau. Also professor Edgar Fernandes, the one that sparkled my interest for the energy field; professor Paulo Peças, an inspiration as a person; and professor Paulo Ferrão, that inspired me to work in the LCA domain. This journey was much easier thanks to some friends of mine, especially Paulo Domingos, Ricardo Xavier and Ana Carrelhas. Ana Carrelhas really supported me a lot when I was in a particular difficult period of my life, so to you many thanks! Last, but not the least, my parents paid all my education and were always there for me, so one huge thank for you too!

Resumo

Os biocombustíveis contribuem para a independência do sector dos transportes da energia fóssil e dos seus impactos a nível ambiental, energético e económico. O Brasil foi um país pioneiro que conseguiu implementar um biocombustível no sector dos transportes: o bioetanol produzido a partir de cana-de-açucar. A sua frota rodoviária sofreu investimentos, e a tecnologia flex-fuel teve grande importância, porque permite usar um combustível composto por 100% gasolina, 100% etanol, ou uma mistura de ambos.

Esta tese tem o objetivo de analisar o ciclo de vida ”Well-to-Gate” do etanol no Brasil, e responder às questões: Que processos existem na produção de etanol? Quanta energia é requerida e poluentes são emitidos nessa fase?

Vários estudos de ciclo de vida foram comparados baseados nos mesmos critérios e unidade funcional, tendo em conta três níveis relativamente à fronteira do sistema: (Nível 1 considera operações directas, Nível 2 considera operações envolvidas na produção dos recursos do Nível 1 e o Nível 3 considera as operações envolvidas na construção de infraestruturas e equipamento).

Foram identificados os processos de produção que influenciam a eficiência, consumo de energia e emissões de gases de efeito estufa (GEE). Guias para futuros estudos de ciclo de vida são apresentados.
Sobre os estudos analisados, verificou-se que o consumo de energia fóssil variou entre 0.03-0.15 MJ_{fossil}/MJ_{etanol}, com grandes variações no Nível 1 - operações agrícolas. As emissões de GEE variaram entre 10-25 gCO_2eq/MJ_{etanol}, com grandes variações também no Nível 1 e também no Nível 2, produção de químicos e lubrificantes.

Palavras-chave: Bioetanol, Cana-de-açucar, Ciclo de Vida, Emissões de efeito de estufa, Energia fóssil.

Abstract

Biofuels have become increasingly important as they contribute to the independence of fossil energy in the transport sector and its consequent impacts on the environment, energy and economy. Brazil was a pioneer country that successfully managed to implement a biofuel in the transport sector: bioethanol from sugarcane. Road vehicle fleet suffered a huge investment, and the flex-fuel propulsion technology was very significant, allowing to use a fuel composed of 100% gasoline, 100% ethanol or a mixture of both.

This thesis aims to analyze the life cycle ”Well-to-Gate” of sugarcane ethanol in Brazil, and answer the following questions: Which processes exist in the production of ethanol? How much energy is required and greenhouse gas (GHG) are emitted in this phase? Several life cycle studies will be compared with the same criteria and functional unit, and taking into account three levels of life cycle for the system boundary. Operations in the chain of production of 1 MJ of ethanol (FU) that consume more fossil energy and that emit more pollutants were identifyed, as well as the key factors that influence efficiency, energy consumption and greenhouse gases emissions. Finally, guidelines for the preparation of similar studies in the life cycle are presented.

It was found that fossil energy consumption ranged from 0.03-0.15 $MJ_{fossil}/MJ_{ethanol}$, with major variations in life cycle Level 1 (sugarcane agriculture operation). Moreover, GHG emissions ranged from 10-25 $gCO_2eq/MJ_{ethanol}$, with major variations also in Level 1, in sugarcane agriculture operation, and also in Level 2, in chemicals and lubricants production.

Keywords: Bioethanol, Sugarcane, Life Cycle, GHG Emissions, Fossil Energy.

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Accronyms

EU	-	European Union
FE	-	Fossil Energy
FIT	-	Feed-in Tariff
FU	-	Functional Unit
GHG	-	Greenhouse Gases
GSR	-	Global Status Report
GREET	-	Greenhouse gases Regulated Emmisions and Energy use in Transport
GWP	-	Global Warming Potential
IEA	-	International Energy Agency
ISO	-	International Standard Organization
LCA	-	Life Cycle Assessment
PTW	-	Pump-to-Wheels
RPS	-	Renewable Portfolio Standard
TE	-	Total Energy
UNICA	-	União da Indústria de Cana-de-Açúcar
WTG	-	Well-to-Gate
WTP	-	Well-to-Pump
WTW	-	Well-to-Wheels

Glossary

$CaCO_3$ - Calcium carbonate.

Comparative Assertion - Environmental claim regarding the superiority or equivalence of one product versus a competing product that performs the same function[22].

Co-Product - any of two or more products coming from the same unit process or product system[22].

Feed-in Tariff (Feed-in Policy or Feed-in Premium) - policy that typically guarantees renewable generators specified payments per unit (e.g., USD/kWh) over a fixed period. Incentive examples: 1. payment is structured as a guaranteed minimum price; 2. whether the payment floats on top of the wholesale electricity price.[35]

Functional Unit - Quantified performance of a product system for use as a reference unit. The functional unit defines what is being studied. All subsequent analyses are then relative to that functional unit, as all inputs and outputs in the LCI and consequently the LCIA profile are related to the functional unit[22].

K_2O - Potassium oxide.

ILUC - Indirect Land-Use Change.

ISO - Is a worldwide federation, which prepares International Standards.

Life Cycle - Consecutive and interlinked stages of a product system, from raw material acquisition or generation from natural resources to final disposal[22].

Life Cycle Assessment (LCA) - Compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle[22].

Life Cycle Impact Assessment (LCIA) - Phase of life cycle assessment aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts for a product system throughout the life cycle of the product[22].

Life Cycle Interpretation - Phase of life cycle assessment in which the findings of either the inventory analysis or the impact assessment, or both, are evaluated in relation to the defined goal and scope in order to reach conclusions and recommendations[22].

Life Cycle Inventory Analysis (LCI) - Phase of life cycle assessment involving the compilation and quantification of inputs and outputs for a product throughout its life cycle[22].

Life Cycle Inventory Analysis Result (LCI Result) - Outcome of a life cycle inventory analysis that catalogues the flows crossing the system boundary and provides the starting point for life cycle impact assessment[22].

LUC - Direct Land-Use Change.

Mitigation - Corresponds to the reduction of GHG emissions obtained by the production and use of a biofuel[22].

N - Nitrogen.

P_2O_5 - Phosphorus Pentoxide.

Process - Set of interrelated or interacting activities that transforms inputs into outputs[22].

Product - Any goods or service. It can be categorized as: services (e.g. transport); software (e.g. computer program, dictionary); hardware (e.g. engine mechanical part); processed materials (e.g. lubricant)[22].

Renewable Portfolio Standard (RPS) - An obligation placed by a government on a utility company, group of companies or consumers to provide predetermined minimum targeted renewable share of installed capacity, or of electricity or heat generated or sold. A penalty may or may not exist for non-compliance.[35]

System Boundary - Set of criteria specifying which unit processes are part of a product system[22].

Chapter 1

Introduction

1.1 Context

The transportation sector has always been one of the most important sectors in mankind history. It provides mobility and better access to goods, improving significantly our life-style. Unfortunately it has also become one major contributor to air pollution, global warming and fossil fuels depletion. To avoid all these problems, solutions must be found and one of those possible solutions is the use of renewable energies, more specifically alternative fuels such as ethanol and biodiesel. Electricity is also an important alternative energy vector for the transportation sector, with the implementation of electric propulsion systems.

This work is focused into fuels used in road vehicles, in other words, fuels that power road vehicles (cars, motorcycles, buses and trucks) by means of internal combustion engines. Fuels that power non-road vehicles, such as planes, trains and boats, weren't taken into consideration. Inside the road fuels category a major focus was made to alternative fuels, specifically the Brazilian sugarcane ethanol. Why Brazil and why ethanol? Because Brazil is a successeful example of a country that really tried to implement an alternative fuel solution, and that fuel was ethanol. Ethanol, at least locally, is more environment friendly than fossil fuels and is a renewable source. Being a good example and inspiration for other countries, Brazil was the country and ethanol the fuel chosen for this work analysis.

A Well-to-Gate analysis of ethanol production and use was made, in other words: resources, energy consumption and emissions related to ethanol production (from the moment the sugarcane is planted until ethanol is in fact made) were studied. Every operation and resources were analyzed, the major causes of greenhouse gases (GHG)[1] emissions and energy consumption were detected and the parameters that most affect the entire process were identifyed. To achieve all this, different ethanol studies were read and compared.

[1]GHG are gases which contribute for the increase of the greenhouse effect

When focusing on pollution it's common to think only about the Pump-to-Wheels stage (see section 3.4). Which means that conventional fuels (crude oil based) are thought as the most harmful fuels for the environment. But in a life cycle analysis (LCA) all stages must be considered. Are alternative fuels that environmental friendly as many may think? Of course this is not an easy question to be answered, but this work allows more data to be added to the enormous and complex world of road fuels.

1.2 Transport sector

To support the importance of this study, an overall analysis of transportation's sector relevance in nowadays society was made. In Figure 1.1, statistics of the consumption of total energy by end-use sector in the US [38], Brazil [39] and European Union [26] can be seen. This data corresponds to the year 2012.

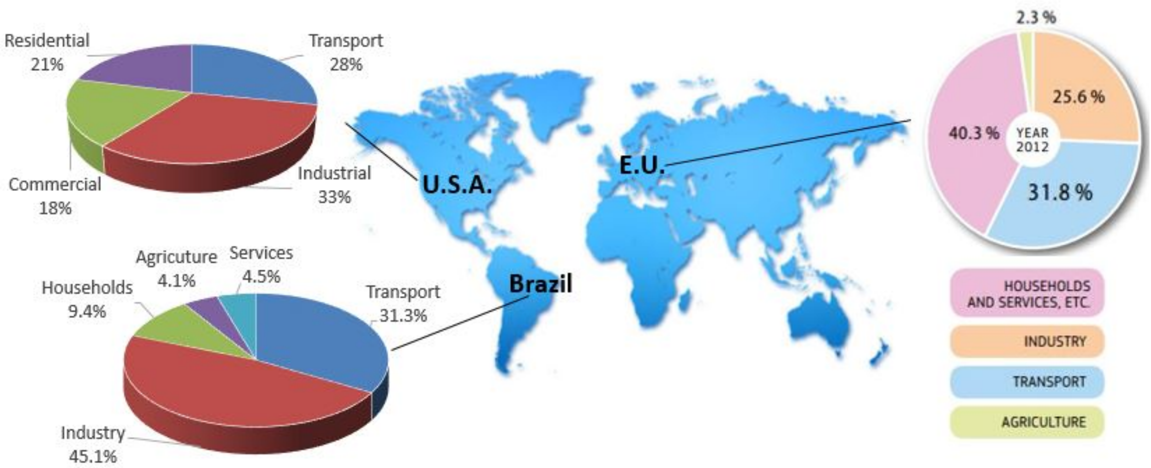


Figure 1.1: Consumption of Total Energy by End-Use Sector 2012 [38][39][26]

The transportation sector corresponds to approximately 30% in US, Brazil and Europe. With no doubt this sector has a major relevance in nowadays society. In Figure 1.2, statistics of the consumption of total energy by transportation mode in the US [18], Brazil [40] and EU [26] can be seen.

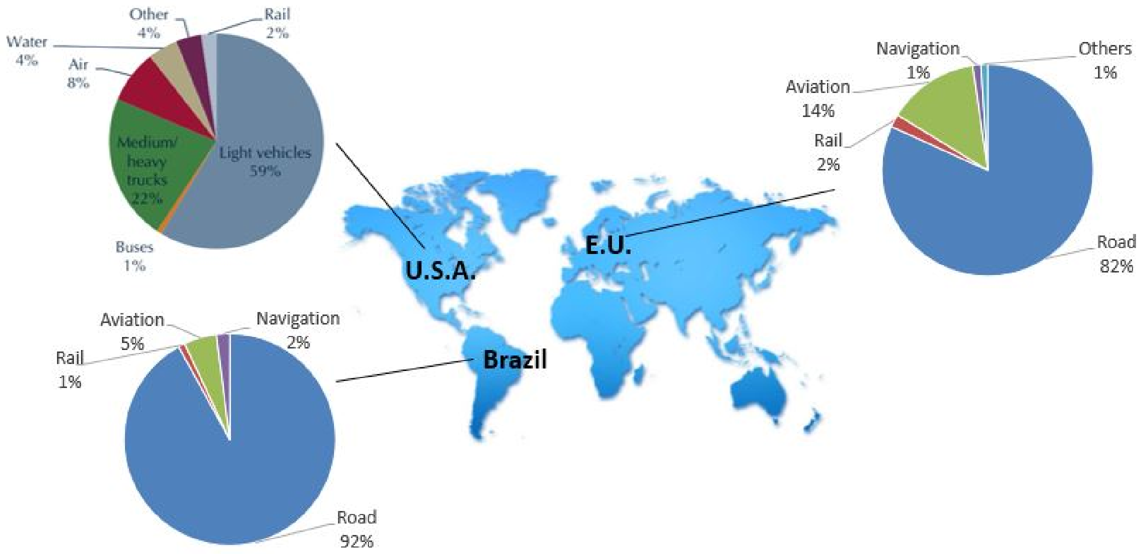


Figure 1.2: Consumption of Total Energy by Transportation Mode 2012 [18] [40] [26]

Road transports cover 80% or more of total energy use in the transportation sector, which means that by covering road transports the majority of the transportation sector is being analyzed. Another interesting indicator that helps understanding the transportation sector importance is the motorization rate. This indicator is defined as the number of passenger cars per 1000 inhabitants. Passenger cars include road motor vehicles, other than a motorcycles [19]. In Table 1.1 some motorization data can be found [19] [38]:

Table 1.1: Motorization rate

Country/Region	Motorization Rate (2002)	Motorization Rate (2012)
Africa	23	34
Brazil	116	187
China	12	82
Germany	541	530
India	10	24
Portugal	554	406
USA	816	808

The motorization rate presents an idea of a country's development, and presenting data from 2002 to 2012 gives an idea of the evolution of that development. For example, China has increased a lot its motorization rate, which means China is really investing and growing in what road vehicles are concerned. Brazil's motorization index has also grown considerably. Resuming, by looking at Table 1.1 it can be concluded that developed countries such as Germany and US have more or less maintained their motorization rate, while developing countries such as Brazil and China are increasing it. This shows that the tendency for developing countries to increase their motorization rate is a reality, what only justifies more the urgency in finding alternatives to fossil fuels. In the next chapter more is discussed about one alternative to fossil fuels: the biofuels.

1.3 Road fleet and sales

A research of some countries' road fleet and vehicles' sales was made, to better understand the biofuel's relevance in nowadays society. Knowing how many "biofuel vehicles" are in current use and also how many were sold recently, are great ways to estimate the current biofuel's relevance in the sector.
To simplify this comparison a division of: gasoline, diesel, flex-fuel[2], electric and other alternative vehicles was made. "Other alternative vehicles" include LPG and natural gas vehicles. "Electric vehicles" include every electric vehicle type (hybrid, plug-in, 100% electrical). The following values, presented in Tables 1.2 and 1.3 represent the road fleet and sales of passenger cars and heavy vehicles (trucks and buses) in the USA [6], Brazil [11] [16] and European Union [19]. Some European data was not available for the year 2012, so an approximation was made from the immediate previous year.

Table 1.2: Road fleet 2012

Vehicle Type	**ROAD FLEET 2012 (millions)**		
	USA	Brazil	European Union
Gasoline	209	12	144
Diesel	1	0	89
Flex-Fuel	11	19	No data
Electric	3	0	0
Other alternatives	1	0	10

As it can be seen gasoline vehicles dominate in the USA road fleet, representing 93.3% of the fleet. Flex-fuel vehicles represent 4.71%, while diesel and electric represent 0.4% and 1.2% respectively. In Brazil the situation is quite different, with flex-fuel vehicles counting for about 60% of the total fleet. No data was found for flex-fuel vehicles in Europe. But just like the USA, in Europe the gasoline cars also represent the majority with about 59% of the total road fleet.

[2] Flex-fuel vehicles can run 100% in gasoline, 100% ethanol or with a mixture of these two fuels [1]

Table 1.3: Road vehicles sales 2012

Vehicle Type	**ROAD VEHICLES SALES 2012 (thousands)**		
	USA	Brazil	European Union
Gasoline	11403	259	5222
Diesel	214	22	7352
Flex-Fuel	1561	2834	-
Electric	467	0	17
Other alternatives	58	-	273

The road vehicles sales presented in Table 1.3 are a good indicative of the ”new tendencies”. In the USA gasoline vehicles still present the major percentage with 83% of the total sales. Flex-fuel vehicles and electric represented 11% and 3.4% respectively, which indicates that flex-fuel and electric technology are raising in the USA fleet. In Brazil flex-fuel vehicles sales represented 91% of total sales. Which shows the huge bet Brazil is making in flex-fuel technology. Just like the fleet, in Europe also the sales are mainly represented by gasoline and diesel vehicles with shares of 41% and 57% respectively. Once again no data about flex-fuel vehicle was found.

1.4 Biofuels

A biofuel is a generic term that is typically applied to liquid fuels produced from agricultural (e.g. sugar cane, soya beans), forestry (e.g. black liquor, forestry residues) or other organic feedstocks (e.g. animal fats, algae). It can also be used as a term to include biogas and biomethane and, in future, biohydrogen from a variety of renewable sources [23]. Some examples of biofuels are [17]: ethanol, biodiesel, biogas, methanol and propanol.

1.4.1 Advantages and Disadvantages

Advantages

Compared to fossil fuels the usage of biofuels present some advantages such as:

- **Biofuels are renewable**. This is one of the major advantages of biofuels. Petroleum is made from plants that grew millions of years ago [1], while biofuels are made from crops that just need a a few months or years to grow. Fossil fuel reserves are limited.
- **Biofuels can be blended with fossil fuels** or even replace them. For example flex-fuel vehicles can run in 100% ethanol. In Brazil, flex-fuel vehicles can run on any blend of anhydrous ethanol,

from E18 to E25 to ‘neat’ E100 hydrous ethanol (see section 2.2), and these have been on sale since 2003 [23].

- **Economy boost for countries with no oil reserves**. Not every country has large reserves of crude oil. For them having to import the oil puts a huge dent in the economy [3].
- **GHG and pollutant emissions reduction**. Tailpipe emissions of CO and HC are reduced due to the improved combustion process. In other words, they may be considered locally more environmental friendly.
- **Improve vehicle’s performance**. Ethanol can be used pure or blended with gasoline. Ethanol has higher octane number than gasoline. Higher octanes in the fuel the engine can work at higher compression rations without ”knocking”, than, extracting more mechanical energy - higher efficiency. The thermal efficiency is slightly increased due to the increased combustion speed, and tailpipe emissions of CO and HC are reduced due to the improved combustion process.
- **Enhance rural economic development**. Production of biofuels from crops such as corn and wheat (for ethanol) and soy and rape (for biodiesel) can provide an additional product market for farmers and bringing economic benefits to rural communities [27].

Disadvantages

Like anything in life biofuels also present disadvantages, such as:

- **High cost of production.** Biofuels are quite expensive to produce in the current market and such a disadvantage is still preventing the use of biofuels from becoming more popular. Right now the interest and capital investment being put into biofuel production is fairly low but it can match demand. If the demand increases, then increasing the supply will be a long term operation, which will be quite expensive[3].
- **Pollution due to fertilizers use.** Biofuels are produced from crops that need fertilizers to grow better. Fertilizers can have harmful effects on surrounding environment and may cause water pollution. Fertilizers contain nitrogen and phosphorus, that can be washed away from soil to nearby lake, river or pond.[3]
- **Shortage of food.** Biofuels are extracted from plants and crops that are also used as food crops. It will take up agricultural space from other crops, which can create a number of problems. Even if it doesn’t cause shortage of food, it will definitely put pressure on the current growth of crops. One major worry being faced by people is that the growing use of biofuels may just mean a rise in food prices as well.
- **Vehicle issues.** Specific fuel consumption is increased due to LHV reduction with ethanol blends, leading also to higher CO_2 emissions when compared with gasoline. The water affinity with the ethanol may lead to corrosion and lubrication problems in the engine.

- **Well-to-Pump pollution.** Biofuel's production - WTP stage (see section 3.4) - is largely dependent on lots of water and oil. Large scale industries that produce biofuel are known to emit large amounts of emissions and cause small scale water pollution as well. More efficient means of production must be put into place[3].
- **Water use.** Large quantities of water are required to irrigate the biofuel crops and it may impose pressure on local and regional water resources, if not managed wisely[3].

1.5 Legislation

According to the *Renewables 2015 Global Status Report* [35], the majority of countries have enacted policies to regulate and promote renewable energies in the power generation, heating and cooling, and transport sectors, driven by the need to mitigate climate change, reduce dependence on imported fuels, develop more flexible and resilient energy systems and create economic opportunity.

Targets for renewable energy deployment were identified in 164 countries as of early 2015, up from 144 countries in 2014. Examples of new or revised system-wide targets from 2014 include France's target of 32% of final energy consumption from renewables by 2030, and Ukraine's target of 11% renewables in the national energy mix by 2020. In Figure 1.3, it can been seen a scheme of the world countries with targets and/or policies [35].

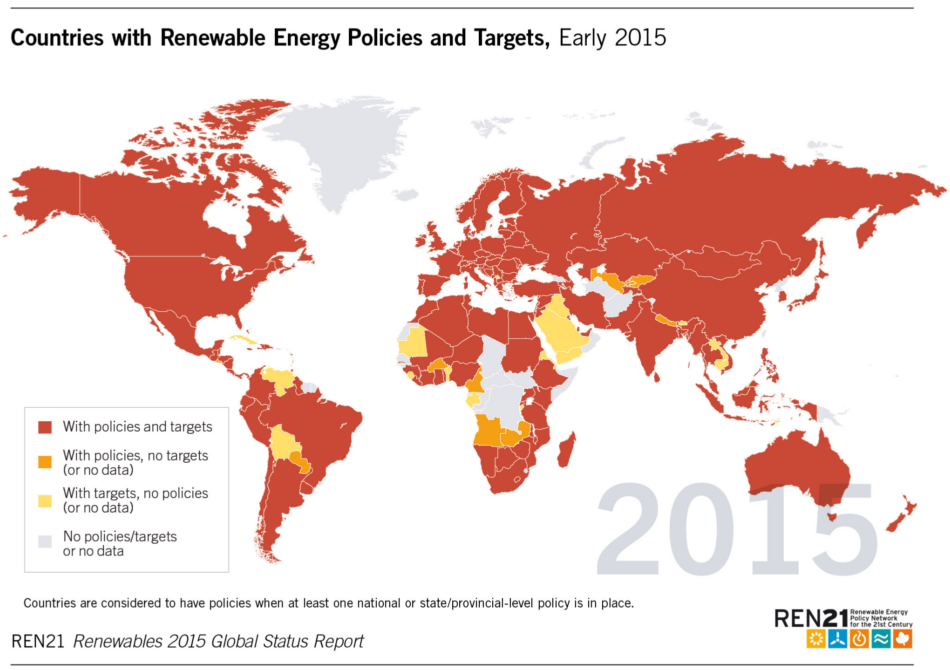


Figure 1.3: Countries with Renewables Policies and Targets [35]

Concerning more specifically to renewable energy transport policies, the majority of transport-related policies continued to focus on the biofuel sector and on road transport. Policies promoting the linkage between electric vehicles and renewable energy have received little focus to date[35]. Biofuel blend mandates — which require that specific shares or volumes of biodiesel, ethanol, and/or advanced biofuels be mixed with petroleum-based transportation fuel — are now in place in 33 countries. In Table 1.4 some of those countries and the respective mandate can be seen [35].

Table 1.4: Biofuel Blend Mandates

Country	**Mandate**
Brazil	E27.5 (27.5% ethanol, 72.5% gasoline) and B7 (7% biodiesel, 93% petroleum diesel)
China	E10 (10% ethanol, 90% gasoline) in nine provinces
USA	E10 (10% ethanol, 90% gasoline) in Hawaii; E2 (2% ethanol, 98% gasoline) and B2 (2% biodiesel, 98% diesel) in Louisiana; B5 (5% biodiesel, 95% diesel) in Massachusetts; E20 (20% ethanol, 80% gasoline) and B10 (10% biodiesel, 90% diesel) in Minnesota; E10 (10% ethanol, 90% gasoline) in Missouri and Montana; B5 (5% biodiesel, 95% diesel) in New Mexico; E10 (10% ethanol, 90% gasoline) and B5 (5% biodiesel, 95% diesel) in Oregon.

Other policies, more related to GHG emissions control, have also been stablished. Different countries have different policies. Biofuels must obey each country sustainability criteria, so that it can be used or exported to that country.

Europe has its own directive that stablishes criteria for biofuels usage and goals for GHG emissions reduction. Published on the 23rd of April 2009, the *Directive 2009/28/EC of the European Parliament*[32] promotes energy from renewable sources, which include wind, solar, aerothermal, geothermal, hydrothermal and ocean energy, hydropower, biomass, landfill gas, sewage treatment plant gas and biogases. It also establishes sustainability criteria for biofuels and bioliquids. **The sustainability criteria apply to biofuels/bioliquids produced in the EU and to imported biofuels/bioliquids**[32]. This *Directive* establishes mandatory national targets for the overall share of energy from renewable sources in gross final consumption of energy and for the share of energy from renewable sources in transport [8]. Here are some of the main criteria of this *Directive* [32]:

TARGETS

- " The greenhouse gas emission saving from the use of biofuels and bioliquids (...) shall be at least **35%**."
- "With effect **from 1 January 2017**, the greenhouse gas emission saving from the use of biofuels and bioliquids (...) shall be at least **50%**"

- "From **1 January 2018** that greenhouse gas emission saving shall be at least **60%** for biofuels and bioliquids produced in installations in which production started on or after 1 January 2017."

Biodiversity Related

- Biofuels and bioliquids (...) shall not be made from raw material obtained from land with high biodiversity value, namely: primary forests and other wooded lands, (...) areas designated by law or by the relevant competent authority for nature protection purposes or (...) for the protection of rare, threatened or endangered ecosystems or species (...), highly biodiverse grassland."
- "The increasing worldwide demand for biofuels and bioliquids, and the incentives for their use provided for in this Directive, should not have the effect of encouraging the destruction of biodiverse lands..."
- "Land should not be converted for the production of biofuels if its carbon stock loss upon conversion could not, ... be compensated by the greenhouse gas emission saving resulting from the production of biofuels or bioliquids..."

Carbon Stock[3]

- "Biofuels and bioliquids (...) shall not be made from raw material obtained from land with high carbon stock, namely (...) wetlands, namely land that is covered with or saturated by water permanently or for a significant part of the year; continuously forested areas, namely land spanning more than one hectare with trees higher than five meters and a canopy cover of more than 30 %, (...); land spanning more than one hectare with trees higher than five meters and a canopy cover of between 10 % and 30 % (...)"
- "Land should not be converted for the production of biofuels if its carbon stock loss upon conversion could not, ... be compensated by the greenhouse gas emission saving resulting from the production of biofuels or bioliquids..."

1.6 Life Cycle Assessment of energy and fuels

The increased awareness of the importance of environmental protection, and the possible impacts associated with products, both manufactured and consumed, has increased interest in the development of methods to better understand and address these impacts. One of the techniques being developed for this purpose is Life Cycle Assessment (LCA)[22].
LCA is the process of evaluating the total effects that a product has on the environment over its entire existence, starting with its production and continuing through to its eventual disposal. Accounts the energy and resource inputs, as well as the polluting outputs to land, water and air that result from the

[3]The amount of carbon stored within an area of land[9]

production of a product. Essentially is a decision-making tool [31]. In the following Figure 1.4 it can been seen a basic scheme of a general LCA [10]:

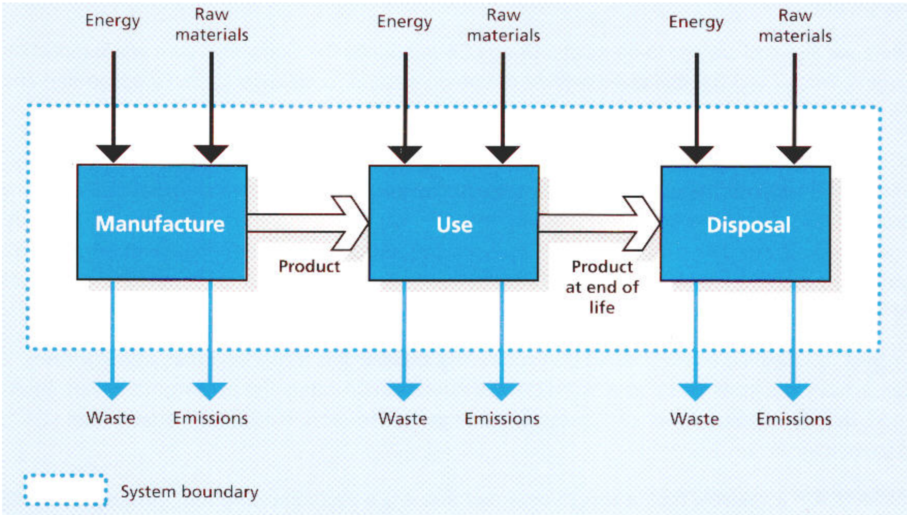


Figure 1.4: LCA Basic Scheme [10]

Evaluating an entire product's LCA is a very complex and extensive process. Therefore for this work borders for the LCA were established, otherwise this thesis would have had much more than the 80 pages limit. In the chapter 3 is presented a more detailed explanation of the LCA norms and characteristics applied, in this case, to the sugarcane ethanol.

1.7 Thesis objectives

The main scope of this work is to propose guidelines and an LCA methodology for biofuels, applied to ethanol from sugarcane. For that, the following goals were attained:

- Find which processes exist in the production of ethanol.
- Analyze different LCA studies of Brazilian sugarcane ethanol, in what fossil energy consumption and GHG emissions is concerned;
- Adjust these studies to the same units and criteria so that they can be compared;
- Identify the major differences and why they occur;
- Find how much energy is required and how much pollutants are emitted.
- Identify the activities that consume more energy and that cause more GHG emissions;
- Identify the strongest points of each study and the incomplete or less well done parts.

1.8 Structure

In chapter 1, the Introduction is made, where the context of the research is presented followed by a small caracterization of the transport sector, biofuels, road transport fleets, ligislation, and life cycle assessment. The thesis objectives and structure are presented in the final sections of chapter 1.

Then, in chapter 2, an overall study of Brazilian sugarcane ethanol is made: characteristics, blends and already some considerations of its LCA.

In chapter 3, the life cycle methodology is presented, inclunding the system bounderies, functional unit, and allocation issues. The studies gathered about ethanol LCA are presented, discussed and their caracteristics are compared.

In the Results chapter every detail and values of each study are presented, compared and fully analyzed.

Finally, chapter 5 presentes the conclusions and guidelines for similar studies.

Chapter 2

Ethanol

Bioethanol (many times just referred as ethanol) is a biofuel that can be made from various plants or organic matter (biomass)[1]. Ethanol can be produced from sugarcane (Brazil is the world's largest sugarcane ethanol producer and a pioneer in using ethanol as a motor fuel[12]) or from corn (corn is the leading U.S. crop and serves as the feedstock for most domestic ethanol production[1]), among other less common options. Sugarcane is mainly produced in the South-Center region of Brazil, because it's a region with the most favourable conditions for sugarcane production, with a good mix of warm temperatures and abundant rainfall [33]. Ethanol can be used in internal combustion engines for road vehicles in two ways[12]:

- **Blended with gasoline**, at levels ranging from 2 to 27 percent to reduce petroleum use, boost octane ratings and cut tailpipe emissions (more than 95% of U.S. gasoline contains up to 10% ethanol[1]). Other blends are also available, which the most common is the E85 (51%-83% ethanol), but this high blended fuel kinds can only be used in flex-fuel vehicles (E85 cannot be legally used in conventional gasoline-powered vehicles [1]).
- **Pure ethanol** – a fuel made up of 85 to 100 percent ethanol depending on country specifications. This fuel can also be used in flex-fuel vehicles, but not on conventional vehicles.

2.1 Hydrous ethanol vs anhydrous ethanol

There are two types of ethanol: hydrous and anhydrous. The difference between the two relates to the amount of water present in each one [11]:
- **Hydrous Ethanol** has in its composition 95.1% to 96% of ethanol and the rest is water.
- **Anhydrous Ethanol** (also called pure ethanol or absolute ethanol) has at least 99.6% of alcohol content. Anhydrous ethanol is almost pure ethanol.

The two types of ethanol follow the same manufacturing process until they are fermented. From fermentation hydrous ethanol arises at a rate of approximately 95% ethanol. While anhydrous ethanol goes through a dehydration process (that occurs in the distillation process), which involves evaporating water after separating it from the alcohol. In practical terms, the difference between the two is that hydrous ethanol is sold as pure ethanol (E100), while anhydrous ethanol is the ethanol which is blended with gasoline. According to Novacana [11] hydrous ethanol is the most common ethanol sold in Brazil.

2.2 Ethanol blends

Some of the current available fuels that include ethanol in the mix are presented in Table 2.1 [1].

Table 2.1: Ethanol Blends

Fuel	Blend	Side Notes
E10	*10% ethanol* *90% gasoline*	E10 doesn't qualify as an alternative fuel under the Energy Policy Act of 1992
E15	*10%-15% ethanol* *85%-90% gasoline*	E15 doesn't qualify as an alternative fuel under EPAct. E15 can be used in flexible fuelvehicles.
E85	*51%-83% ethanol* *rest gasoline*	E85 can be used in flexible fuel vehicles. It cannot be legally used in conventional gasoline-powered vehicles.
E100	*100% ethanol*	Brazil is the only country so far using E100 [11]

The ethanol-gasoline blending has been considered several times so far. So *why is (anhydrous) ethanol blended with gasoline?* Some of the main reasons have already been mention in chapter 1, in the section biofuel's advantages. Nevertheless here the main advantages of blending ethanol with gasoline [11]:

1. To increase the fuel's octane number. Like it was mentioned before, the higher the octane number of a fuel the smaller the chances of knocking will be. Higher octanes in the fuel the engine can work at higher compression rations without "knocking", than, extracting more mechanical energy - higher efficiency. The thermal efficiency is slightly increased due to the increased combustion speed, and tailpipe emissions of CO and HC are reduced due to the improved combustion process.

2. To reduce the pollutant emissions at local level. In vehicles powered with higher amounts/shares of ethanol, emissions of CO and HC are reduced due to the improved combustion process.

Now, other pertinent question. *Why blending ethanol instead of using only pure ethanol fuel?*

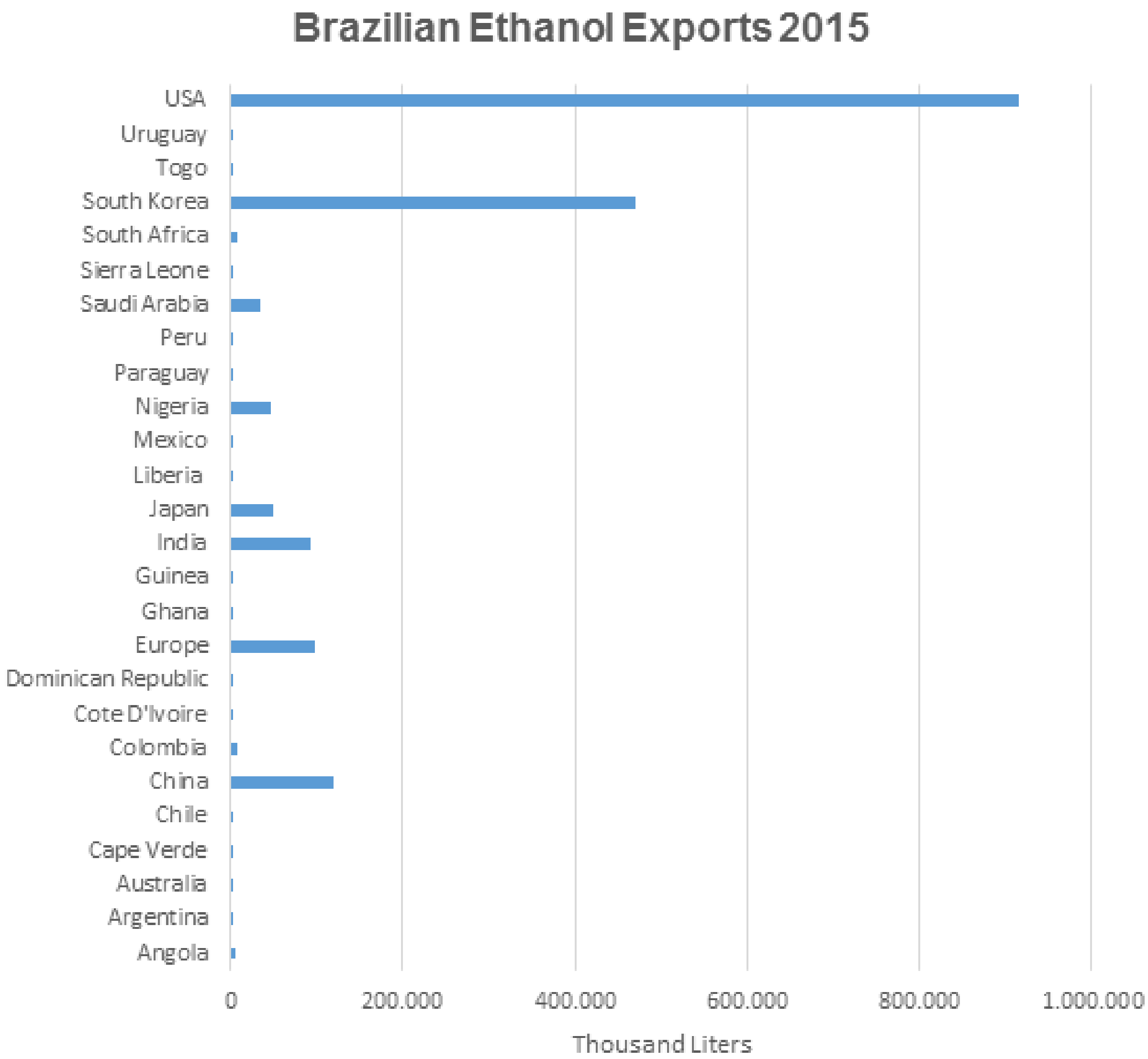
As mentioned before, there are some disadvantages in the use of biofuels, also mentioned in chapter 1, like the vehicle issues due to anhydrous ethanol's water affinity that may lead to corrosion and lubrication problems in the engine. But there are other aspects that haven't been mentioned. Below $13°C$ hydrous ethanol (E100) loses its ability to generate combustion, becoming unusable as fuel[11]. However, this problem (which is most frequently in cold strat events) can be reduced by blending ethanol with some amount of gasoline, as well as implementing apropriate ignition control systems [11].

2.3 Ethanol vs Bioethanol

So, what's the difference between **ethanol** and **bioethanol**?
Much of the ethanol produced in the world is actually a petroleum product. It is easily made by the hydrolysis of ethylene, a major petrochemical and it's called petroleum-derived ethanol (synthetic ethanol). Bioethanol, or "renewable ethanol," comes from renewable sources. Bioethanol and synthetic ethanol are chemically indistinguishable, since they are both the same compound: C_2H_5OH. The only difference between the two is the isotopic composition of the carbon atoms [7]. So, the ethanol considered in this work is, of course, bioethanol. But for a simplistic reason many articles and sites just refer to it as ethanol. Of course that by using the term "bioethanol", no doubts will exist in what's the source type of the considered ethanol.

2.4 Ethanol from Brazilian sugarcane

So far general aspects and fundamentals of ethanol were discussed. But in this work only one bioethanol is studied: the Brazilian sugarcane ethanol. In Brazil sugarcane is the main feed-stock of ethanol production. One the major milestones in Brazilian ethanol history was the "PROÁLCOOL" program in 1975, which established and consolidated the use of hydrated ethanol as fuel, in a response to the 70's oil crisis. In consequence of that program, in July 1979 the first car 100% alcohol was produced in Brazil (the Fiat 147).
Brazil produces sugarcane ethanol, not only for its own needs, but it also exports. In Figure 2.1 [14] a list of the exports is shown:



Only included countries with 2015 data. Same criteria for Europe.

Figure 2.1: Brazilian Ethanol Exports 2015 [14]

2.5 Life cycle analysis of ethanol from sugarcane

Some of the main aspects of the sugarcane ethanol LCA are now discussed. The WTG stage (see chapter 3) is the boundary studied in this thesis and it is divided in two distinct stages:

- **Feed-Stock Production & Transportation** corresponds to the sugarcane production and then transport to the conversion plant;
- **Feed-Stock Conversion** corresponds to the processes that "transforms" the sugarcane into ethanol.

In Figure 2.2 a basic scheme of the LCA bounderies applied to ethanol produced from sugarcane can be seen. This scheme shows a plant that produces both sugar and ethanol. The electricity and thermal energy generated in the boiler, from the co-product bagasse (biomass), is usually used to power the factory, therefore no fossil energy is needed.

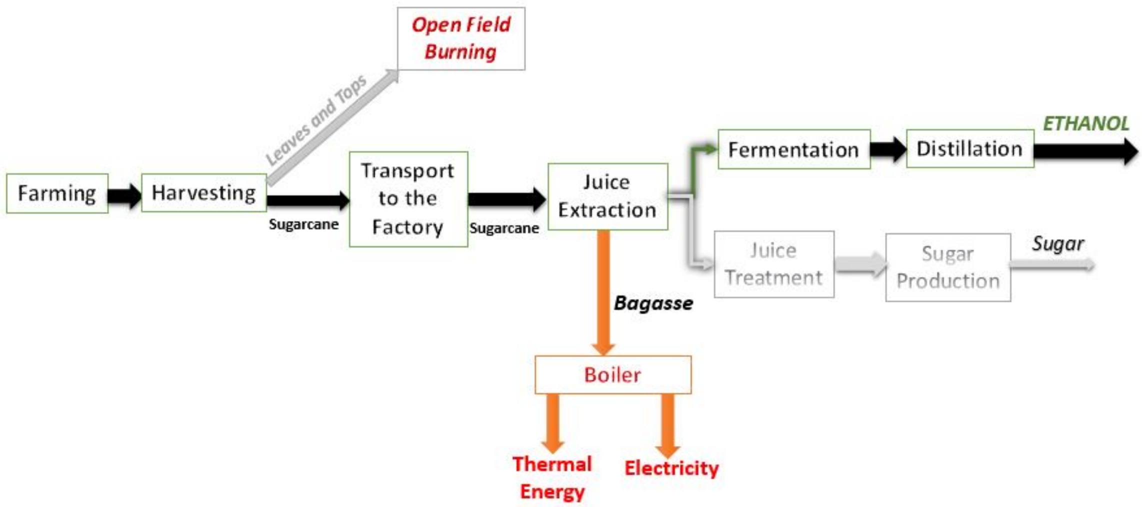


Figure 2.2: Sugarcane Ethanol Pathway

This study stops before the stations or storage to supply fuel to the road vehicles. Basically the only part of the WTP stage (see section 3.4) that isn't covered in this work is the ethanol transportation to the fuel pumps. Therefore is a WTG analysis (see section 3.4) and not a WTP (see section 3.4).

Bagasse is the residue of sugarcane after the juice from the sugarcane has been extracted. Because of its high carbon content, it serves as an excellent source of process fuel in sugarcane mills[29]. Some studies assume that bagasse is combusted in a biomass boiler to produce steam to meet the plant demand for steam and to generate electricity with a steam turbine to meet the plant requirement for electricity and for electricity export.

Some studies consider sugar production, others don't. According to [37] sugarcane mills can be classified into three different groups: sugar mills, for sugar production only; sugar mills with adjacent distilleries, which produce sugar and ethanol; and autonomous distilleries for ethanol production only.

2.5.1 (In)Direct Land-Use Change

Direct and *DirectIndirect Land-Use Change* are very important concepts for biomass fuels in what emissions and energy consumption are concerned. Many studies don't take them into consideration, but nevertheless they must be discussed.

According to [33], if crops for biofuels come from land which was not previously planted with row-crops (e.g. grazing land, pasture or forest) there will be a *Direct Land Use Change* (LUC), which may cause significant releases of carbon from the soil. About ILUC, according to the European Comission [2] when biofuels are produced on existing agricultural land, the demand for food and feed crops remains, and may lead to someone producing more food and feed somewhere else. This can imply *Indirect Land Use Change* (by changing e.g. forest into agricultural land).

So, if LCA studies rarely take into account LUC and ILUC energy consumption and emissions, does it mean they are not important? They are important, but unfortunately still very uncertain, since complex economic modelling is required. Understanding of these broader aspects is growing, but such is the level of uncertainty that they are not easy to include in a quantified way.

Chapter 3

Methodology

In this next chapter the LCA concept and its norms according to ISO (International Organisation for Standardisation) are presented, and some important aspects such as functional unit and allocation are explained. The fuel's LCA stages and the system boundaries considered for this thesis are discussed, as well as an idea proposed for an LCA analysis concerning the classification of the life cycle assessment into a three level scheme.

The GHG emissions calculation according to the *Directive 2009/28/EC of the European Parlament and of the Council*[32] are presented and finally an overview of each sugarcane ethanol studies is made. In this last sub-chapter, key parameters are compared as well as the different energy and emissions types for every operation of the sugarcane ethanol manufacture.

3.1 Life cycle assessment - Norms according to ISO

NOTE: In case of any doubt about some specific term, check *Glossary* in the "LCA Related" section.

According to the *ISO 14040: Environmental management — Life cycle assessment — Principles and framework* [22] LCA is one of several environmental management techniques, e.g. risk assessment, environmental performance evaluation, environmental auditing and environmental impact assessment, and might not be the most appropriate technique to use in all situations. LCA typically does not address the economic or social aspects of a product, but the life cycle approach and methodologies described in this International Standard can be applied to these other aspects. LCA can assist in [22]:

– Identifying opportunities to improve the environmental performance of products at various points in their life cycle;

– Informing decision-makers in industry, government or non-government organizations (e.g. for the purpose of strategic planning, priority setting, product or process design or redesign);

– The selection of relevant indicators of environmental performance, including measurement techniques;

– Marketing (e.g. implementing an eco labelling scheme, making an environmental claim, or producing an environmental product declaration).

LCA addresses the environmental aspects and potential environmental impacts (e.g. use of resources and the environmental consequences of releases) throughout a product's life cycle from raw material acquisition through production, use, end-of-life treatment, recycling and final disposal (i.e. cradle-to-grave) [22].

There are four phases in an LCA study [22] :

1. **Goal and scope definition phase** (The goal states: the intended application; the reasons for carrying out the study; the intended audience, i.e. to whom the results of the study are intended to be communicated; and whether the results are intended to be used in comparative assertions intended to be disclosed to the public.
   The scope defines: the product; the functional unit; the system boundary; allocation procedures; impact categories and methodology of impact assessment; assumptions; limitations; initial data quality requirements; type and format of the report required for the study);

2. **Inventory analysis phase** (It is an inventory of input/output data with regard to the system being studied. It involves collection of the data necessary to meet the goals of the defined study);

3. **Impact assessment phase** (The purpose of LCIA (Life Cycle Impact Assessment) is to provide additional information to help assess a product system's LCI results so as to better understand their environmental significance.);

4. **Interpretation phase** (The final phase of the LCA procedure. The results are summarized and discussed as a basis for conclusions, recommendations and decision-making in accordance with the goal and scope definition).

In the next section some crucial elements of an LCA are deeply explained: the functional unit and allocation. Explained and applied to this thesis case study.

3.2 Functional Unit

The functional unit describes and quantifies properties of a product. These properties can be: the functionality, appearance, stability, durability, ease of maintenance etc.., and are determined by the requirements in the market in which the product is to be sold[25]. **The primary purpose of a functional unit is to provide a reference to which the inputs and outputs are related.** This reference is necessary to ensure comparability of LCA results [22]. For a better understanding, here is an example [22]: *In the function of drying hands, both a paper towel and an air-dryer system are studied. The selected functional unit may be expressed in terms of the identical number of pairs of hands dried for both systems. For each system, it is possible to determine the reference flow, e.g. the average mass of paper or the average volume of hot air required for one pair of hand-dry, respectively. For both systems, it is possible to compile an inventory of inputs and outputs on the basis of the reference flows. At its simplest level, in the case of paper towel, this would be related to the paper consumed. In the case of the air-dryer, this would be related to the mass of hot air needed to dry the hands.*

In Table 3.1 more functional unit examples are presented:

Table 3.1: Functional Unit Examples

Machine/Product/System	***Functional Unit***
Washing machine	*1kg of washed clothing*
Food	*Calories*
Passenger transportation	*Passenger per kilometer*

In this work, pathways of production for the same fuel (ethanol) are being compared. There is one functional unit (FU): MJ of produced ethanol. Both energy consumption and GHG emissions are related to the FU and for a matter of comparison they have the following units:

For emissions comparison: grams of CO_2 equivalent emissions emitted per mega Joule of produced ethanol (gCO_2eq/MJ) .

For fossil energy consumption comparison: the quantity of fossil energy expended in mega Joules (MJ) per each MJ of produced ethanol (MJ_{fossil}/MJ)

Basically the CO_2 equivalent emissions and fossil energy consumption are compared, for the same amount of produced ethanol.

3.3 Allocation

Allocation is the appropriate division of the process impact factors (e.g.: energy consumption, GHG emissions) between the main product and the system co-products[1]. It's used, for example, in situations where the studied system generates more than one product. [34].

For example, in this work sugarcane ethanol is being analyzed. From sugarcane (the feed-stock) there are two main products created: sugar and ethanol. Some factories just produce ethanol, others

[1] Every product generated apart from the main product. Includes residues.

just sugar and others both. When studying the ethanol manufacturing process, if sugar is also one of the process products, the GHG emissions of the entire process can't be attributed only to Ethanol manufacture. Therefore, it is necessary to find a way to calculate the amount of emissions attributed to sugar production and to ethanol production. And that is allocation.

There are several allocation types: (economical, based on physic or chemical properties, environmental, etc...)

The general calculation procedure for allocation is resumed in equation 3.1 and it consists on the following[34]:

- Find a relation between the co-products and the input data (D_i);
- Determine the value of the Allocation Factor (F_i) for each co-product of the system;
- Multiply every data about emission or consumption (D_i) for the factor F_i. That should represent the environmental aspects of the inventory (I_i) to be attributed to each co-product of the system.

$$I_i = D_i \times F_i \tag{3.1}$$

Allocation can occur basically in three types of systems: 1. System with multiple inputs; 2. System with multiple outputs (products and co-products); 3. Recycle System.

EXAMPLE

For a better understanding of the allocation concept let's give an example based on this thesis' subject. As it can be seen in Figure 3.1, in this case study the main input is sugarcane and there two main outputs: ethanol and sugar.

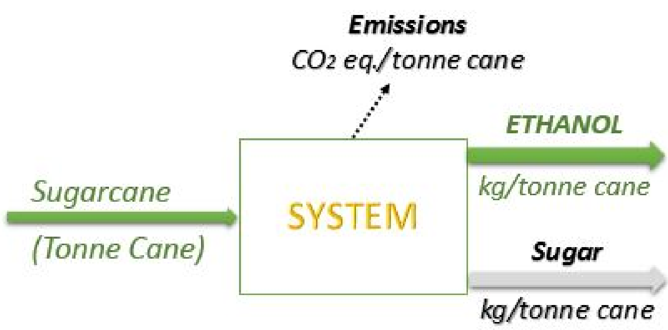


Figure 3.1: System Allocation Example

Assuming, for example, that a system produces emissions of: $23\ gCO2\ eq.\ per\ tone\ of\ cane$. How many of these emissions are responsible for the ethanol production?

A mass allocation based on the amount of produced ethanol can be made. The "mass relevance" of each product is governed by the following equation:

$$MassAllocation = \frac{m_x}{\sum m} \tag{3.2}$$

It's more common to use *liters* as the unit for ethanol production, but in these calculations the same units must be used, so assuming that the system produces: 400 kg of ethanol per tone of cane and 300 kg of sugar per tone of cane, the relevance of ethanol and sugar will be:

$$ETHANOL : \frac{400}{400 + 300} = 57\% \tag{3.3}$$

$$SUGAR : \frac{300}{400 + 300} = 43\% \tag{3.4}$$

CONCLUSION: For the total emissions, the ethanol production is responsible for $23 \times 0.57 = 13.11$ *gCO2 eq. per tone of cane*. Ethanol's allocation factor (F_i) is 57%.

Allocation can also be used to determine the total amount of produced sugar and ethanol in a country, as it can be seen in one of the analyzed studies (Seabra study [37]).

3.4 System boundaries

A complete LCA analysis of any product can be a real complex and long study, so boundaries must be defined. Different products can have different division and different boundary types. This study is about fuels , which are used in road vehicles, and the most common way to divide a fuel's LCA is in the two following stages[36]:

-**Well-to-Pump** (WTP): consideration of the resource recovery and extraction, transport, treatment, conversion or refining to the final form of energy/fuel, and finally the delivery to the gas pump.

-**Pump-to-Wheels** (PTW): consideration of the use of the fuel in the vehicle from the gas pump to the wheels (vehicle operation activities). This involves the vehicle efficiency and operation.

The combination of the WTP and PTW stages, is called the **Well-to-Wheels** (WTW). For this thesis only the WTP was studied, with a slight difference: the fuel transport to the fuel pumps wasn't taken into consideration. Only feed-stock manufacture, transport to the factory and production was considered. In other words, the Well-to-Gate stage was the one studied in this thesis, as shown in Figure 3.2 [15]:

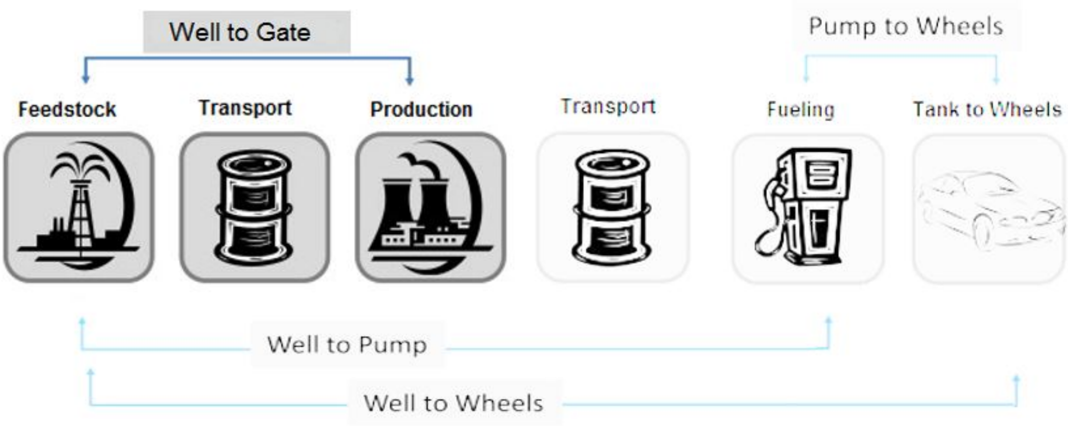


Figure 3.2: Well-to-Gate

In Figure 3.3 [29] a basic scheme of the LCA boundaries applied to the sugarcane ethanol pathway can be seen. This study begins in the sugarcane farming and end in the manufacture of ethanol.

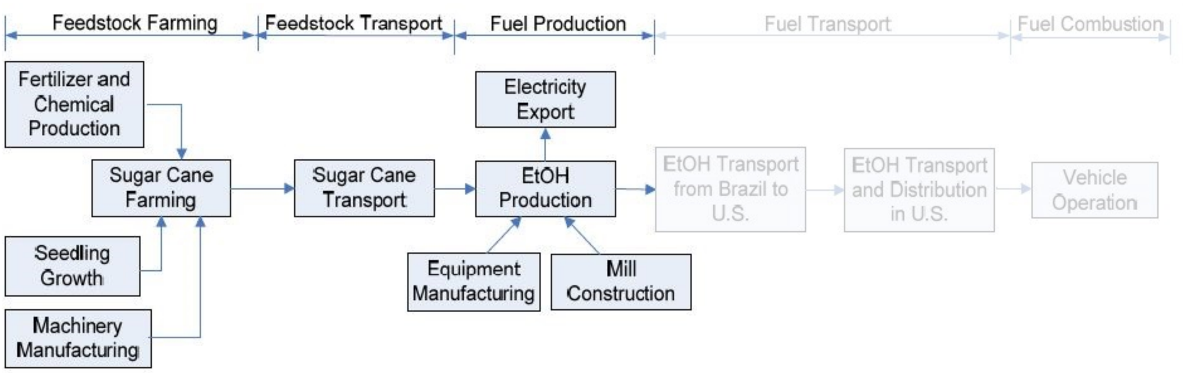


Figure 3.3: Well-to-gate borders as considered in this research work

3.5 Life Cycle Assessment Levels

Before analyzing and comparing the sugarcane ethanol studies, something really important must be refered: the way the studies were analyzed! In order to facilitate not only the individual analysis, but also the comparison between studies, a structure was implemented. Each study is divided in **3 different categories**: Resources Consumption, Energy Consumption and Emissions. Each one of these categories are also divided in **3 Levels**: Level 1, Level 2 and Level 3. Important referring that these levels idea was inspired in the reference [28]. In Figure 3.4 an overall scheme of the LCA levels is shown:

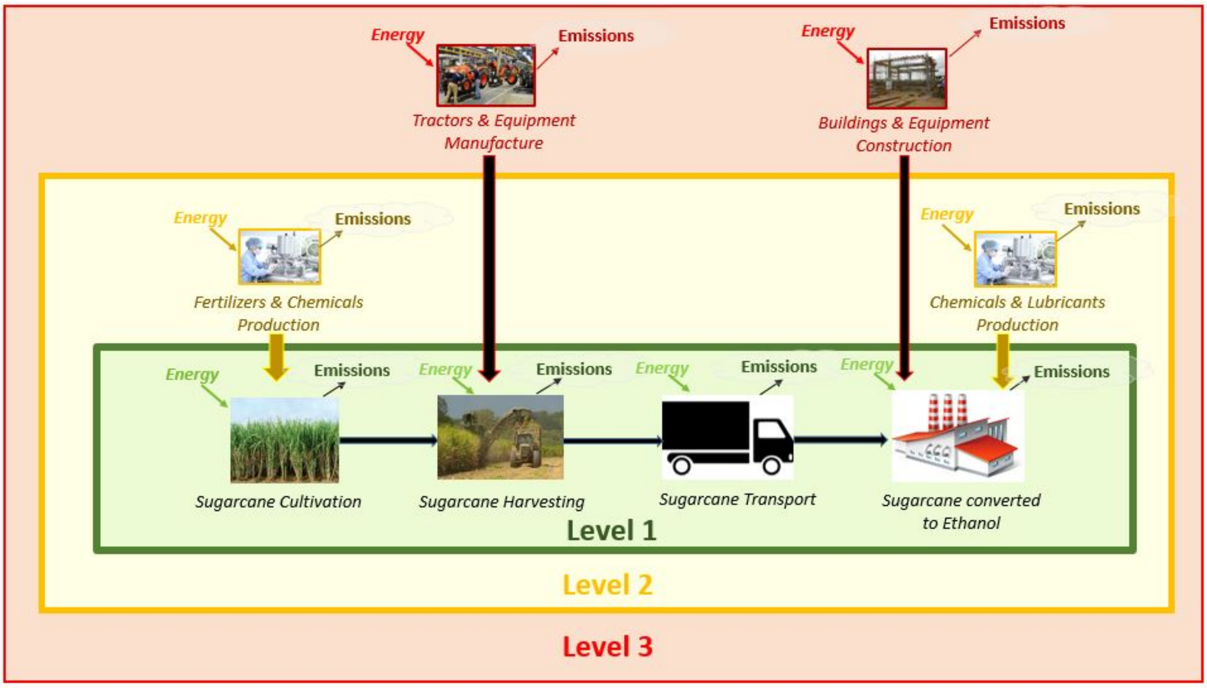


Figure 3.4: LCA Levels

3.5.1 Resources consumption

Human resources weren't considered in this study, only material resources needed for each operation.

- Level 1 – Resources like: water, fuel (for the functioning of the machinery directly involved in the processes), fertilizers and chemicals. Basically all the resources that are needed for the direct developing processes.
- Level 2 – Resources needed for the manufacturing of the Level 1 Resources.
- Level 3 – Resources needed for the manufacture, construction and maintenance of equipment and buildings/factories.

3.5.2 Energy consumption

The energy consumed in MJ/FU is focused in the fossil energy consumption (fuel oil and diesel). Studies may refer electricity or thermal energy, but only the share produced from fossil energy is considered.

- Level 1 – Only the direct consumption of external fuels (direct energy inputs) is considered.
- Level 2 – Additional energy required for the production of resources used in the agricultural and industrial processes.

- Level 3 – Additional energy necessary for the manufacture, construction and maintenance of equipment and buildings.

3.5.3 GHG Emissions

Only GHG [2] are compared in gCO2eq/FU: CO_2, CH_4 and N_2O.

- Level 1 – Emissions related to the direct consumption of external fuels and electricity (direct energy inputs).
- Level 2 – Emissions from the production of chemicals and materials used in the agricultural and industrial processes
- Level 3 – Emissions from the manufacture, construction and maintenance of equipment and buildings.

3.6 GHG emissions calculation

According to the *Directive 2009/28/EC of the European Parliament and of the Council*[32], the GHG emissions from the production and use of transport fuels and biofuels can be calculated from equation 3.5:

$$E = e_{ec} + e_l + e_p + e_{td} + e_u – e_{sca} – e_{ccs} – e_{ccr} – e_{ee} \quad (3.5)$$

E	=	total emissions from the use of the fuel;
e_{ec}	=	emissions from the extraction or cultivation of raw materials;
e_l	=	annualized emissions from carbon stock changes caused by land-use change;
e_p	=	emissions from processing;
e_{td}	=	emissions from transport and distribution;
e_u	=	emissions from the fuel in use;
e_{sca}	=	emission saving from soil carbon accumulation via improved agricultural management;
e_{ccs}	=	emission saving from carbon capture and geological storage;
e_{ccr}	=	emission saving from carbon capture and replacement;
e_{ee}	=	emission saving from excess electricity from cogeneration.

GHG emissions from fuels, E, are expressed in terms of grams of CO_2 equivalent.

GHG emission's saving from biofuels shall be calculated as equation 3.6:

[2]GHG taken into account shall be CO_2, N_2O and CH_4. For the purpose of calculating CO_2 equivalence, those gases shall be valued according to a 100 year equivalence factor: CO_2 = 1; N_2O = 298; CH_4= 23

$$SAVING = (E_F – E_B)/E_F \tag{3.6}$$

Where:

E_B	=	total emissions from the biofuel or bioliquid;
E_F	=	total emissions from the fossil fuel comparator (gasoline) production.

According to the Directive [32] the value of the GHG emission savings must be approximate to 71% for sugarcane ethanol production pathway, if produced with no net carbon emissions from land-use change. There are for sure land-use change emissions, but since the analyzed studies don't approach land-use change emissions this is a perfect parameter to be used. But note that this is a value for Brazilian sugarcane ethanol exported and consumed in Europe. According to the UNICAMP report [24] E is approximately 86% for sugarcane ethanol produced and consumed in Brazil. The difference in these values is due to intercontinental transport and lower efficiency of European engines using ethanol [24]. The fossil fuel comparator, E_F, shall be the latest available actual average emissions from the fossil part of petrol and diesel consumed in the Community as reported under Directive 98/70/EC. If no such data are available, the value used shall be $83,8\, gCO_{2_{eq}}/MJ$.

For bioliquids used for electricity production, E_F shall be $91\, gCO_{2_{eq}}/MJ$.

For bioliquids used for heat production, E_F shall be $77\, gCO_{2_{eq}}/MJ$.

For bioliquids used for cogeneration, E_F shall be $85\, gCO_{2_{eq}}/MJ$.

More considerations:

- This Directive[32] doesn't take into account emissions from the manufacture of machinery and equipment. In other words, **Emissions Level 3 aren't accounted!**
- Emissions from the extraction or cultivation of raw materials, e_{ec}, include emissions from the extraction or cultivation process itself; from the collection of raw materials; from waste and leakages; **and from the production of chemicals or products used in extraction or cultivation**. Emissions from processing, ep , include emissions from the processing itself; from waste and leakages; **and from the production of chemicals or products used in processing**. The bolded factors correspond to **Level 2 Emissions!**
- Capture of CO_2 in the cultivation of raw materials is excluded.
- Emissions from the fuel in use, e_u , shall be taken to be zero for biofuels and bioliquids.
- Emissions from transport and distribution, e_{td} , shall include emissions from the transport and storage of raw and semi-finished materials and from the storage and distribution of finished materials.

- Emission saving from excess electricity from cogeneration, e_{ee} , shall be taken into account in relation to the excess electricity produced by fuel production systems that use cogeneration (except where the fuel used for the cogeneration is a co-product other than an agricultural crop residue). The GHG emission saving associated with that excess electricity shall be taken to be equal to the amount of GHG that would be emitted when an equal amount of electricity was generated in a power plant using the same fuel as the cogeneration unit.

In Table 3.2, some typical values for the emission factors for the sugarcane ethanol, according to [32], can be seen:

Table 3.2: Emimission Factors Values for SugarCane Ethanol

Emission Factor	**Typical GHG emissions (gCO2eq/MJ)**	**Default GHG emissions (gCO2eq/MJ)**
e_{ec}	14	14
e_p–e_{ee}	1	1
e_{td}	9	9
Total for cultivation (e_{ec}), processing (e_p–e_{ee}), transport and distribution(e_{td})	**24**	**24**

3.7 Sugarcane ethanol studies

An extent literature review was made to understand the different approaches to the sugarcane ethanol LCA and its real application. The data found in the LCA studies is going to be real important to determine the amount of GHG emissions, energy consumed and which activities more contribute to the increase of these. Four studies were analyzed: Macedo[28], Seabra[37], Wang[29] and a study from Concawe[33]. From the several studies found these were the chosen to be part of this thesis, because they are very complete in what ethanol LCA is concerned, while other studies just focus briefly on the LCA and present some resumed data.

Each study has its own division, rules and units, basically its own criteria. So first, each study criteria was verified and then adapted to the **LCA levels** (section 3.5). This was applied for each study and in the end the results were compared. Before moving, a quick remind: the feed-stock is sugarcane, so in some of the following tables:

- **Feed-stock production & transportation** corresponds to the sugarcane production and then transport to the factory;

- **Feed-stock conversion** corresponds to the processes that “transforms” the sugarcane into ethanol

Also referring that all energy contents used are on LHV basis. Specifically for bagasse the LHV of the dry matter content of the material is considered.

In Table 3.3 the overall characteristics of ”Macedo”, ”Seabra”, ”Wang” and Concawe studies can be seen. Macedo, Seabra and Wang are approach specificaly Brazilian sugarcane ethanol, so they have more details of ethanol’s LCA. They were compared among them and also in the end with some data from Concawe study. Concawe doesn’t present enough detailed data to allow the same comparison with the other studies, but the few existant data was presented and compared (see *Appendix A* for more details).

NOTE[13]: *There are two weight units that can be easily confused:* ***ton*** *and* ***tonne****.* ***Ton*** *is a british and american measure, while a* ***tonne*** *is a metric measure.* ***Ton*** *is also different in the US and in the UK.*
- 1 british ton = to 2,240 pounds or 1,016.047 kg;
- 1 american ton = 2,000 pounds = 907.1847 kg;
- 1 tonne = 1 metric ton = 1,000 kg (in US)

Table 3.3: Ethanol Studies - Overall Characteristics

	Studies			
Characteristics	***Macedo***	***Seabra***	***Wang***	***Concawe***
Authors	Isaías C. Macedo; Manoel Regis Lima Verde Leal; João Eduardo Azevedo Ramos da Silva	Joaquim E.A. Seabra; Isaías C. Macedo; Helena L. Chum; Carlos E.Faroni and Celso A.Sarto	Michael Wang, May Wu, Hong Huo and Jiahong Liu	R. Edwards; J-F. Larivé; J-C. Beziat
Year of the Study	2004	2011	2007	2011
Brazilian Region	——	Center-South	——	Center-South
Allocation	——	TRS Allocation to determine sugar and ethanol’s production (Not relevant for the study)	——	——
Borders	Well-to-Wheels	Well-to-Wheels	Well-to-Wheels	Well-to-Wheels

3.7.1 Macedo Study

There are several authors, but for a question of convenience this study will be referred as "Macedo Study" [28]. It was released in 2004, but it uses data from previous years: sugar cane yield data are averages for harvest seasons 1998/99 to 2002/03; energy consumption in the sugar cane ethanol production is 2002 data; utilization and associated energy consumption for the production of chemicals and materials for industrial sector refer to the 2002/2003 crushing season. This study has two very good aspects. First of all, the inspiration for the **LCA 3 Levels Criteria** came from this study. The other thing is: they represent two distinct scenarios in this study:

- **Scenario 1:** based on the average values of energy and material consumption;
- **Scenario 2:** based on the best values being practiced in the sugar cane sector (minimum consumption with the use of the best technology in use in the sector).

Since this study is from 2004, the values from Scenario 2 were used, because they will probably match better the "average" values from nowadays.

3.7.2 Seabra Study

Once again there are several authors, but for a question of convenience this study will be referred as "Seabra Study" [37]. This study was the main reason for the searching and learning about allocation, since it's the only study that refers it. Knowing allocation's importance and relevance in this study was of course mandatory. "Seabra" considers the production of sugar, anhydrous ethanol and hydrous ethanol and it uses a mass allocation method, by measuring the TRS[3]. In Figure 3.5 it can be seen the allocation data used in this study:

Table 5. Overall ATR balance in the Brazilian Center-South Region in 2008.

Product[a]	Production[b] (Mt or hm³)	ATR factor[c] (kg/kg or L)	ATR[d] (Mt)	Mix
Sugar[e]	27.1	1.0495	28.4	**40%**
Hydrous ethanol	16.7	1.6913	28.2	**39%**
Anhydrous ethanol	8.5	1.7651	15.1	**21%**

[a] In 2008, total sugarcane production for sugar and ethanol in the Center-South Region was 500.2 M t.[4]
[b] From MAPA.[4]
[c] Converts final products into ATR equivalent. This analysis was based on ATR factors given by Consecana-SP.[31]
[d] ATR = Production x ATR factor.
[e] Considered as white sugar.

Figure 3.5: Seabra - Allocation Data [37]

Attention: The study refers that in 2008, 500.2 Mt of Sugarcane were produced. It's so easy to misunderstand *Metric Ton* with *MegaTonne*. After consulting this study's source [30], **Mt** is in fact **MegaTonne**. So: $500.2\ Mt = 500.2 \times 10^9\ tonne$.

[3] Total Recovered Sugar. ATR in portuguese

After learning about allocation, reading carefully this study and its main source (*Anuário Estatístico da Agroenergia 2012* [30]) and talking via e-mail with professor Joaquim Seabra himself, a conclusion was reached that this allocation was not relevant for this thesis pourpose. This allocation had only the goal of calculating the total amount of produced ethanol and sugar in Brazil, so that it could be known exactly how many emissions and energy had been released and spent for each product's production. Since this thesis is about knowing the emissions and energy consumed per megajoule of produced ethanol, knowing the total amount of produced ethanol has no relevance.

The data presented in this study about energy consumption and emissions are for sugar and anhydrous ethanol production separately. No manipulation of the data can be made (manipulation means changing allocation values and with that change understand the variation in energy and emission values due to ethanol production), since it could only be possible with data from a specific factory that would produce both products. From a specific factory, because, according to professor Joaquim Seabra, these values differ a lot from factory to factory (technology and processes configuration). Also, there's a certain difficulty in the total separation of the processes, since they are generally integrated.

In spite of allocation being no relevant for this thesis, "Seabra" study was a challenge not only because of the allocation issue, but also because it only presented the results of energy consumption and emissions for sugar and anhydrous ethanol production. Hydrous ethanol production results are not present in this study.

By checking this study's source [30] it can be found that: $LHV_{Anhydrous} = 22.34MJ/liter$ and $LHV_{Hydrous} = 20.85MJ/liter$. Anhydrous ethanol has a distillation process (hydrous hasn't), but considering that the study doesn't specify anything about each production process, let's assume hydrous and anhydrous are the same in what energy consumption and emissions are concerned. It's not a perfect assumption since according to professor Joaquim Seabra, hydrous and anhydrous ethanol don't have the same energy consumption values (the difference differs from factory to factory, due to dehydration technology mainly), but since there is no more data available this assumption is the best approach. The study has the following data [37]:

Table 7. Fossil energy use and GHG emissions from sugar production (2008).

	Fossil energy use (kJ/kg)	GHG emissions (g CO_2eq/kg)
Sugarcane farming	1109	85
Trash burning		48
Field emissions[a]		85
Agr. inputs production	508	48
Sugarcane transportation	237	18
Sugar production	37	31
Credits		
Electricity[b]	–754	–46
Bagasse[c]	–416	–35
Total	**721**	**234**

Table 8. Fossil energy use and GHG emissions in the anhydrous ethanol life cycle (2008).

	Fossil energy use (kJ/MJ)	GHG emissions (g CO_2eq/MJ)
Sugarcane farming	88	6.8
Trash burning		3.8
Field emissions[a]		6.7
Agr. inputs production	40	3.8
Sugarcane transportation	19	1.4
Ethanol production	4	2.6
Ethanol T&D	22	1.8
Tailpipe emissions		0.8
Credits		
Electricity[b]	–60	–3.7
Bagasse[c]	–33	–2.7
Total WTW	**80**	**21.3**

Figure 3.6: Seabra - Results Data [37]

Only anhydrous ethanol values were used for this study. But one interesting fact was checked. According to professor Joaquim Seabra, energy consumption values for sugar and ethanol production are very similar. Knowing that with one tonne of sugarcane $138\ kg\ of\ sugar$ are produced [30] or $82\ litersofethanol$ [30], the values from Figure 3.6 can be easily converted to kJ of fossil energy per tonne of sugarcane. And it is confirmed, the values for sugar and ethanol production are similar (approximately 150,000 kJ of fossil energy spent per tonne of sugarcane).

3.7.3 Wang Study

”Wang study” [29], as it will be called from now on, analyzes ethanol produced in Brazil and then exported to the USA. But since this study has a Well-to-Gate boundary, Wang study data can be used.

Wang also combines data from previous ethanol studies (and it’s the only one that specifies all the pollutants from the ethanol LCA). For this study the concept of ”carbon dioxide equivalent” had to be learned and understood. Carbon dioxide equivalent is a measure used to compare the emissions from various GHG based upon their global warming potential (GWP). For example, the GWP for methane over 100 years is 25. This means that emissions of one million metric tons of methane is equivalent to emissions of 25 million metric tons of carbon dioxide[4]. In other words, this concept allows to convert the pollutants quantities into CO_{2eq}.

Wang is also the only study that: makes a comparison between ethanol and petroleum gasoline; that considers the thermal energy needed in the ”feed-stock conversion” phase; that specifies the fossil energy types consumed for ethanol production.

3.7.4 Concawe Study

”Concawe study” [33] is a ”well-to-wheels Analysis of Future Automotive Fuels and Powertrains in the European Context”. Concawe is an European organization, more specifically is a division of the European Petroleum Refiners Association [5]. In spite of being a study for the European context it can still be used, because only the WTG Brazilian sugarcane data presented here is needed. A good advantage of this study is that presents data from many other fuels, so it allows to make a quick comparison between sugarcane ethanol and other ethanol types and gasoline. In Figure 3.7 a scheme of the Concawe study can be seen. Only the first two steps were considered: ”production and conditioning at source” and ”transformation at source”.

Figure 3.7: Concawe Scheme [33]

To better understand and also confirm that these two steps are the WTG analysis, this is what the study refers about each one [33]:

- Production and conditioning at source includes all operations required to extract, capture or cultivate the primary energy source. In most cases, the extracted or harvested energy carrier requires some form of treatment or conditioning before it can be conveniently, economically and safely transported.

-Transformation at source is used for those cases where a major industrial process is carried out at or near the production site of the primary energy (e.g. gas-to-liquids plant).

The study also considers that the notional time horizon for the study is about a decade ahead: 2015-2020. The technologies considered are those that have the potential to become commercially available in that time frame. The same applies to supply/demand, availability and potential for substitution of conventional fuels.

About emissions, Concawe also considers GWP.

A downside of this study is that, because it focus on so many fuels, it doesn’t specify all the details of ethanol production. Moreover, this study focus also on the concept of total primary energy. The other studies focus a lot in fossil fuel usage only, except for electricity from the net generation (where all sources must be considered). But Concawe refers total primary energy, which means fossil and renewables are considered in every stage. The downside is that it is not explicit where and how many fossil energy is used, so it was difficult to compare it with the other studies. On the other hand, GHG emissions can be compared with no problem.

Finally, for sugarcane ethanol Concawe presents also 2 scenarios: 1) credit for surplus bagasse and 2) no credit for surplus bagasse. The two scenarios are identical with the difference that scenario 2) doesn't consider external uses for the surplus bagasse. So this was the scenario considered for comparison pourposes.

3.7.5 Data Comparison

Each study presents its own data, units and parameters. Assembling all this data in one single model was one of the steps of this work, so that a correct comparison between them would be possible. The conversion steps can be seen in the *Appendix A*. Like mentioned before, only Macedo, Seabra and Wang were compared in every WTG detail. The comparison began with some basic parameters.

Table 3.4: Key Parameters

Key Parameters	**Macedo**	**Seabra**	**Wang**	**CONCAWE**
Cane Productivity [tonnecane/hectare]	106	86.7	-	-
Liters of ethanol per tonne of sugarcane	97.3	82	91	86
Allocation	NO	YES (but not relevant)	NO	NO
Co-Products				
Electricity [kWh/tonnecane]	-	41[10]	51.9	-
Bagasse [kg/tonnecane]	140	140	140	140
Surpluses				
Electricity [kWh/tonnecane]	16.83[11]	10.7	23.1	-
Bagasse [kg/tonnecane]	21	8.7	0	-

Cane productivity is one parameter of the process' efficiency. For the same amount of fuel and fertilizers used per hectare, if more tonnes of cane are produced, then the process is more efficient. In other words, more productivity means that the process demands less resources for the same amount of produced cane. Looking to Table 3.4 data we see that Macedo has a huger cane productivity than

[10] Using the surplus value they refer, plus the energy they consider is saved by using electricity instead of fossil fuels
[11] Average electricity produced. Macedo refers that the bought electricity is almost irrelevant, and that all produced electricity is consumed. So in the overall energy balance - generated and consumed energy - the electricity has a zero value.

Seabra, and in Table 3.5 we see that Macedo uses less diesel fuel and less fertilizers and chemicals for each tone of produced cane in the feed-stock production stage.

Referring that Macedo is the only study that refers a technique used in Brazil that is called ”ratooning”. Ratooning is a practice of growing a crop from the stubbles of previous crop[21]. Ratoon saves cost on preparatory tillage and planting material, but only one ratoon should be taken because incidence of pests and diseases increases and deterioration of soil takes place[21]. Macedo refers and presents data for 5 ratoons, which shows a clear decrease in the sugarcane production (90 tone/ha in the first ratoon and 78 tone/ha in the second). The value for productivity presented in Table 3.4 is of a new cane plantation (before ratooning takes place).

The amount of liters of ethanol produced per tonne of sugarcane is another efficiency parameter. Seabra value for ”liters of ethanol produced per tonne of sugarcane” presented in Table 3.4 is the value for 100% ethanol production. This is the ”comparison value”, considering that there is no allocation in this scenario. The more liters of ethanol are produced per tonne of cane used, the more efficient the system is. In fact, this parameter has a huge impact on the energy consumption and emissions, as it can be seen in chapter 4 (Results).

There can be a little misunderstanding between co-products and surpluses. The factories use bagasse that comes from the sugarcane to generate heat and electricity. Bagasse and electricity are, therefore, co-products. The main product of the system is ethanol; bagasse and electricity, that are also generated in the process, are co-products or ”extra-products”. Part of the bagasse and electricity are consumed in the factory, and the excess that isn’t used in the factory can be sold. Those excesses are the surpluses. Now, some studies see only those surpluses as co-products, because the surpluses are in fact what remains by the end of the process. But in this analysis, it is assumed that the co-products (bagasse and electricity) are the total amount generated along the process, and the surpluses the excess. Something like this:

$$coproducts = consumed\ coproducts\ in\ the\ factory + surpluses \tag{3.7}$$

About co-products, all studies refer a specific value of $280\ kg$ of bagasse that exists per each tone of sugarcane. Those $280\ kg$ have a 50% moisture content, so in reality we got $140\ kg$ of dry bagasse.

The surpluses are the excess and are important, because they are accounted as produced energy. Electricity surplus can be exported to the powergrid and bagasse can be sold as biomass fuel. In Macedo study it’s referred that from the $140\ kg$ of bagasse produced per tone of cane, approximately 15% isn’t burned in the boilers ($140 \times 15\% = 21$), which means it can be used for other applications like selling to the net. But as it is refered in the study these 15% are the best estimative, because the average value at the time was approximately 8%. Using that value, we would obtain $11.2\ kg$ of bagasse, a really close value to the one Seabra refers. These percentages differ because of the efficiency and quality of the equipment. The more efficient, the less bagasse is needed in the boiler to achieve the same power. Macedo doesn't refer anything about the total amount of electricity generated, it just considers the electricity that covers the factory needs.

Also noticing that according to Macedo, a factory can increase the production of surplus electricity by increasing the amount of bagasse burned in the boilers, therefore decreasing the excess bagasse. This can explain why Wang considers zero bagasse surplus and practically the double amount of electricity surplus of Seabra and Macedo. Also noticing that Wang is the only study that considers electricity generation efficiency, that Wang considers the value of 30%. Nevertheless, this can also be a parameter that explains some differences between studies.

One thing that immediately is seen in Table 3.5, is that no study refers water consumption. This is a huge flaw considering the importance of this natural resource. Water should always be accounted in the consumed resources.

Table 3.5: Resources Quantity - Level 1

	Resources		**MACEDO**	**SEBRA**	**WANG**	**CONCAWE**
Feed-Stock Production & Transportation	Diesel Fuel [Liters/tonnecane]		1.56	3.87	1.30	-
	Fertilizers and Chemicals [g/tonnecane]	N	783	777	1091.7	363
		P_2O_5	165	249	120.8	181
		K_2O	792	980	193.6	363
		$CaCO_3$	-	5183	5337.70	1815
		Herbicides	-	44	26.90	-
		Insecticides	-	3		0
		Acaricides	-	0.02	2.20	0
		Fungicides	-	0.01		0
		Other Defensives	-	0.96	-	-
	Water [Liters/tonnecane]		-	-	-	-
Feed-Stock Conversion	Chemicals and Lubricants [g/tonnecane]	Lubricants	13.37	10	-	-
		Sulfur	-	1.36	-	-
		Lime	930	880	-	907.30
		Sulfuric Acid	880.77	600.14	-	725.84
		Soda	-	65	-	-
		Neutralization Soda	-	170.31	-	-
		Antibiotic	-	0.75	-	-

About diesel consumption. Diesel is the fossil fuel used in all operations of feed-stock production and transportation. Concerning specifically about transportation, all studies consider an average distance of 20 km from the farms to the factories and every study refers diesel trucks as the transportation vehicle. In Seabra and Macedo the diesel consumed was calculated through the amount of energy consumed in sugarcane farming and transportation. Having diesel's LHV was necessary for every study and for a matter of comparison the same LHV for diesel was used in the three studies. Macedo is the only that presents a value for diesel's LHV, $LHV_{Macedo} = 11414\ kcal/liter = 47.8\ MJ/liter$, so this value was used. Focusing now about fertilizers and chemicals of feed-stock production and transport stage. As it was mentioned previously, the higher the productivity the less resources are needed per tonne of sugarcane produced.

NOTE: *Level 2 and 3 Resources are not presented in any study!*

Now the 3 Levels of energy consumption and emissions are going to be deeply seen, more specifically the energy types in Tables 3.6, 3.7 and 3.8, and also emission types in Tables 3.9, 3.10 and 3.11, exactly as they are refered in each study.

Table 3.6: Energy Consumption Type – LEVEL 1

		Energy Type		
	Operation Type	**Macedo**	**Seabra**	**Wang**
Feed-Stock Production & Transportation	Agricultural Operations	*Diesel Fuel*	*Diesel Fuel*	*Diesel Fuel*
	Transportation to the Factory	*Diesel Fuel*	*Diesel Fuel*	*Diesel Fuel*
Feed-Stock Conversion	Production	*Electricity and Thermal*	*Fossil Energy*	*Electricity and Thermal*

Table 3.7: Energy Consumption Type – LEVEL 2

		Energy Type		
	Operation Type	**MACEDO**	**SEABRA**	**WANG**
Feed-Stock Production & Transportation	Fertilizers	*Fuel Oil*	*Fossil Energy*	——
	Lime			——
	Herbicide			——
	Pesticide			——
	Seeds			Fuel Oil
Feed-Stock Conversion	Chemicals & Lubricants	*Fuel Oil*	-	Fuel Oil

Table 3.8: Energy Consumption Type – LEVEL 3

		Energy Type		
	Operation Type	MACEDO	SEABRA	WANG
Feed-Stock Production and Transportation	Equipment (Tractors, Harvesters and Trucks)	*Fuel Oil*	-	*Fuel Oil*
Feed-Stock Conversion	Buildings	Electric and Thermal[13]	-	Electric and Thermal
	Equipment	Electric and Thermal[13]	-	Electric and Thermal

Table 3.9: Emissions Type - LEVEL 1

		Emissions Type		
	Operations	MACEDO	SEABRA	WANG
Feed-Stock Production and Transportation	Sugarcane Farming andTransport	*GHG*	*GHG*	*GHG*
	Trash Burning	*Metane and N_2O*	*GHG*	*CO, CH_4, NOx, N_2O, PM2.5, PM10, VOC, SOx*
	Field Emissions[14]	*N_2O*	*GHG*	*GHG*
Feed-Stock Conversion	Production	*Methane*	*GHG*[15]	*Metane and N_2O*

Table 3.10: Emissions Type - LEVEL 2

	Operation	MACEDO	SEABRA	WANG
Feed-Stock Production and Transportation	Indirect Land Use Change	-	-	-
	Agr. Inputs Production	*GHG*	*GHG*	*GHG*
Feed-Stock Conversion	Chemicals and Lubrificants Production	*GHG*	-	-

[13] 90% of Brazil's electricity comes from Hydro Power Plants. (30% of Electric and 70% of Thermal, of the total energy required)
[14] Field emissions are emissions from the soil due to fertilizers, residues and limestone application
[15] Emissions from Bagasse burning in boilers

Table 3.11: Emissions Type - LEVEL 3

	Operation	**MACEDO**	**SEABRA**	**WANG**
Feed-Stock Production and Transportation	Equipment	*GHG*	-	-
Feed-Stock Conversion	Building and Equipment	*GHG*	-	-

Avoided emissions

One more aspect must be discussed: the avoided emissions. The concept of avoided emissions can be used for different situations. For example, in the calculation of GHG emissions by the European directive [32] there's a parameter, e_{ee}, that is the emission saving from excess electricity from cogeneration systems. Many ethanol factories use cogeneration systems where they use the co-product bagasse as fuel and generate thermal and electric power. The avoided emissions, e_{ee}, correspond to the emissions that would be emitted if the same amount of electricity was produced in a power plant using fossil fuel. Wang study refers avoided emissions, but doesn't present values relevant for this thesis. Seabra refers and presents specifically how many CO_{2eq} emissions are avoided by the use of bagasse instead of fuel oil and by the use of cogeneration electricity instead of electricity produced in natural gas plants. Macedo refers avoided emissions by using surplus bagasse instead of fuel oil in other industries (orange juice, pulp and paper).

Chapter 4

Results

In this section are presented graphs and data about the energy consumption and emissions for each study. Other important aspect, crucial for this analysis, is the percentage of electricity produced from fossil fuels (Figure 4.1):

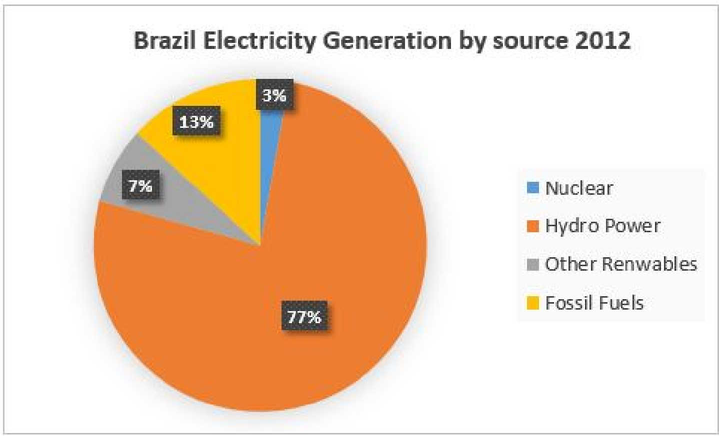


Figure 4.1: Brazil electricity generation by source[6]

Ethanol production factories, according to the studies, are self-sufficient in electricity demands. Nevertheless, if for some extraordinary reasons, electricity from the national grid is required for the feed-stock conversion stage, this data will be considered. This data was used in Level 3, because electricity is necessary in Level 3 energy consumption. To make the comparison fair, these electricity sources' values were used for every study. Also, the following results of each study are based on the ethanol production efficiency of each one. In the section 4.8 an analysis is made where the same efficiency is assumed for every study and with that analyzing the differences.

4.1 Fossil energy consumption

Concerning the amount of fossil energy consumed and specifically the percentage of fossil energy consumed per Level, **it's important to refer that the following values are related to the FU of 1 MJ of the ethanol produced by the pathway**, not to the output of each particular operation. Also, these values represent the MJ of fossil energy expended, in other words the fossil energy losses. Example: assuming operations A and B as the total operations required to produce ethanol, if Operation A demands 0.02 $MJ_{fossil}/MJ_{ethanol}$ and Operation B demands 0.05 $MJ_{fossil}/MJ_{ethanol}$, this means that a total of 1.07 MJ of fossil energy were used in the process to produce 1 MJ of ethanol. Thus, 0.07 MJ were Operations A and B total energy losses to produce 1 MJ of ethanol, meaning that globally 1.07 MJ were needed to achieve the 1 MJ of ethanol.

Also, to make a more fair comparison between studies, the same LHV for diesel and ethanol was considered in every study . In Figure 4.2 the values of fossil energy consumption for Level 1 are presented:

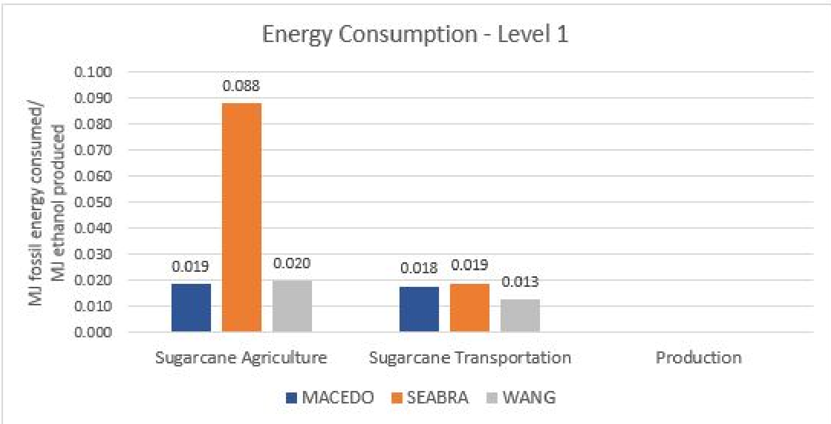


Figure 4.2: Fossil Energy Level 1

Analyzing this graph, immediately it's clear that fossil energy consumption in **sugarcane agriculture** is much higher in Seabra. As it can be seen in Table 3.5 Seabra considers a diesel consumption much higher than the remaining studies (more than the double), so this makes sense. But the question is why this huge difference in diesel consumption?

First of all, Seabra considers 48% of mechanical harvesting, which means that during the harvesting of the sugarcane 48% is assured by machines and the rest by manual labour. Macedo, on the other hand, assumes 35% of mechanical harvesting. Just there Seabra has to consume more fossil energy. Doing an approximation of considering sugarcane agriculture energy consumption 13% lower in Seabra a value of $0.077\ MJ_{fossil}/MJ_{ethanol}$ is reached. Still very high compared to the other studies. So more reasons must affect this. Reasons such as technologies used, land type (format, declivity,...), trucks course along the field, can affect dramatically the diesel consumption. Less efficient technologies, lands with greater declivity and huger distances taken by the machinery during sugarcane farming and harvesting will increase the diesel consumption.

Sugarcane transportation reveals smaller differences. Every study also considers diesel fuel and an average distance of $20km$ from the field to the mill. Wang has a lower energy consumption on this stage, 28% lower that Macedo and 31% than Seabra. Once again, vehicle type and efficiency can affect energy consumption.
Other important aspect is that Macedo includes several activities in the "transportation". Macedo englobes sugarcane, seed cane, filter mud cake, vinasse and fertilizers transportation. The study is very well detailed in its annexes, so it was possible to separate and just consider the sugarcane transportation for this work. It's important to refer this for two reasons:
1) Wang study also discusses Macedo, and supposes that the high value of energy consumption in the transportation stage is probably because Macedo includes the energy embedded in manufacturing of the trucks. Which is not true. Macedo considers Level 3 energy consumption in a separate section. The high value of energy consumption in the transportation stage, is because Macedo englobes sugarcane, seed cane, filter mud cake, vinasse and fertilizers transportation.
2) Macedo is the only study that considers chemicals and fertilizers transportation, which is a Level 2 operation.

Finally the **production of ethanol**. All studies consider cogeneration, more specifically, producing heat and electricity from bagasse. Bagasse is the residue of sugarcane after the juice has been extracted and it is a co-product that can be used as a fuel (biomass). Because of its high carbon content (46.3 wt% on a dry matter basis), it serves as an excellent source of process fuel in sugarcane mills[29]. The studies only refer that most of the factories use bagasse, and therefore, are self-sufficient in what energy is concerned in the production phase. So Macedo and Wang have no values for fossil energy consumption in the production phase. Seabra presents a really small value, but it should also be zero, because and quoting: "Because bagasse is used for energy there is no demand for fossil fuels in the industrial phase" [37]. That small value has probably to do with the chemicals production for the industrial phase, so this last assumption was added to this study.

In Figure 4.3 the fossil energy consumption related to the Level 2 can be seen:

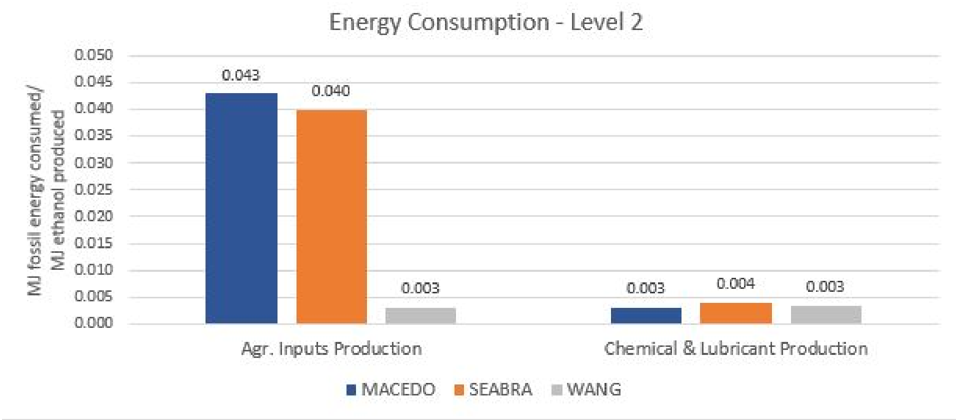


Figure 4.3: Fossil Energy Level 2

Energy consumption Level 2 is divided in agricultural inputs production - which includes fertilizers, chemicals and seeds production - and in chemical and lubricants' production, from the feed-stock conversion stage.

Concerning first on **agricultural inputs**, Macedo and Seabra present really close values. Wang presents a much smaller value, and this is because it only considers seeds production and not the energy embedded in the production of chemicals and fertilizers.

About **chemicals and lubricants' production**. The same assumption made in the Level 1 fossil energy consumption for the Seabra study was applied in this section: the value presented in Seabra about "ethanol production" is in fact related to the production of chemicals and lubricants. And as it can be seen the Seabra value is really close to the values from Macedo and Wang.

In Figure 4.4 the fossil energy consumption related to the Level 3 can be seen:

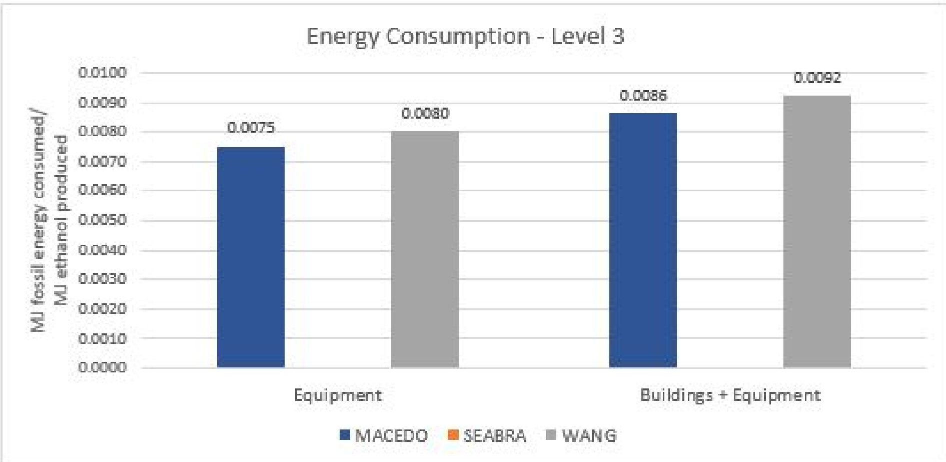


Figure 4.4: Fossil Energy Level 3

Seabra does not mention Level 3. Macedo considers an estimative of thermal (70%) and electric (30%) energy used in this Level. Using the 30% that corresponds to the electricity plus the 13% for fossil fuel usage (see Figure 4.1), the total fossil energy usage from electricity is reached. Now, about fossil energy usage to generate thermal energy, Macedo is not 100% clear about this, because it doesn't expose the relevance of each sector (e.g. mining, ceramic, cement, steel and iron) that contributes for this Level. Nevertheless, an estimative was made based on the percentages of renewable thermal energy used in each sector, and a value of 30% for renewable thermal energy usage was reached. The remaining 70% are from fossil energy, because fortunately Macedo specifies the different energy sources. So, using 70% of fossil energy usage for thermal energy generation added to the fossil energy used for electricity and these values are reached for Macedo. Macedo is Wang's source for these values, therefore the similarity of values. The small differences have probably to do with conversion factors.

4.1.1 Level's percentage of energy consumption

Each individual operation was shown, now percentages related to the levels are presented in Figures 4.5, 4.6 and 4.7.

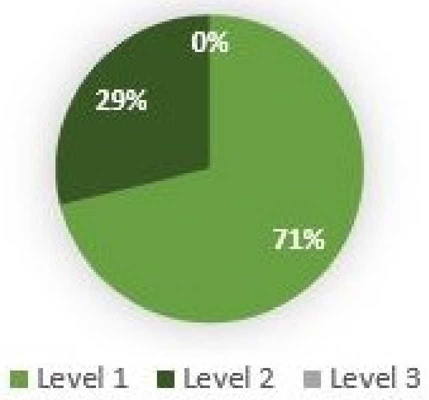


Figure 4.5: Fossil energy consumption by levels - **Seabra**

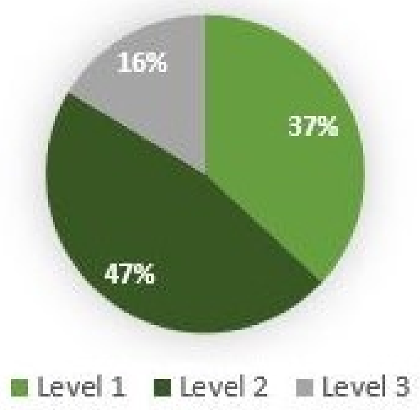


Figure 4.6: Fossil energy consumption by levels - **Macedo**

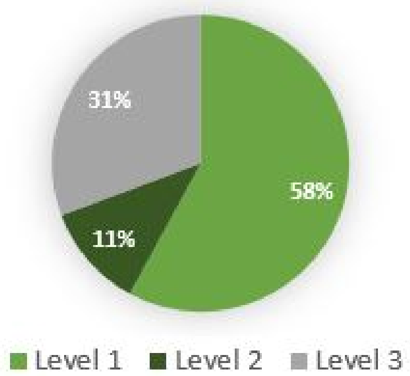


Figure 4.7: Fossil energy consumption by levels - **Wang**

At a first sight Level 1 seems the main responsible for fossil energy consumption. Seabra does not mention Level 3, therefore it was not accounted. Wang is an incomplete study in what Level 2 is concerned. Macedo, from what was analyzed previously, is by far the most complete study. And according to Macedo, Level 2 is the main responsible for fossil energy consumption. Which means that all the chemicals and lubricants needed for ethanol production need a lot of fossil energy to be manufactured. Assuming Macedo as the most reliable source, Level 2 is the main Level of fossil energy consumption, and if measures should be taken to decrease fossil energy consumption it should start here in this Level.

4.2 Emissions

As it is shown in the following images, and remembering what was refered previously about LUC and ILUC, the studies do not take them into consideration. In Figure 4.8 the emissions related to Level 1 operations can be seen:

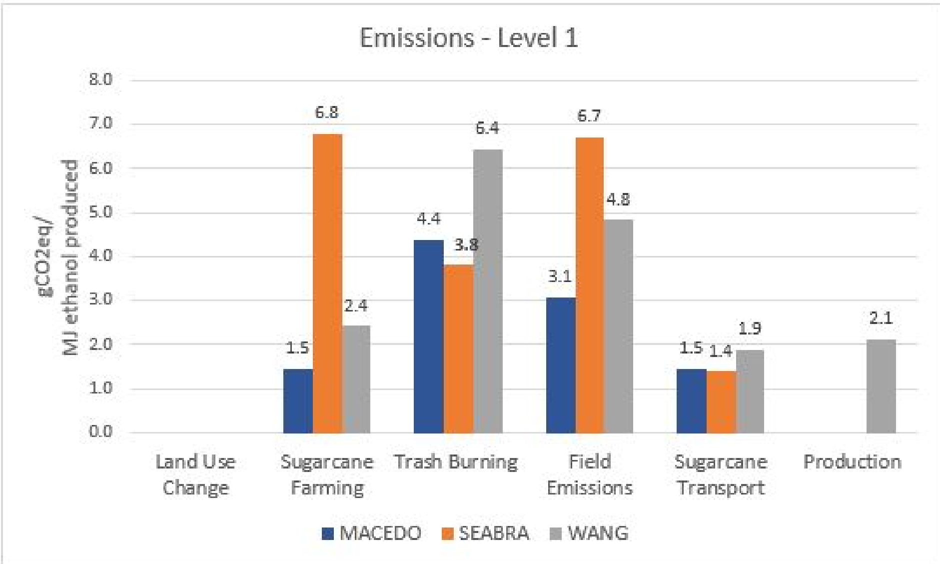


Figure 4.8: Emissions Level 1

Note: Macedo includes sugarcane farming and sugarcane transport in one single dataset. And there's no way to know the percentages that belong to each category. For this situation, and to present some reliable data, an approximation was made. Considering that the amount of diesel is practically the same in both activities, an equal split for the emissions was made.

The values of GHG emissions of the operations of section 4.1 (fossil energy consumption) should be coherent and proportional with the use of fossil energy usage considered by each study. For example, energy consumption in sugarcane agriculture was much higher in Seabra, and as it can be seen in Figure 4.8 the GHG emissions are much higher in **sugarcane agriculture** for Seabra. But for example the emissions of **sugarcane transport** in Wang are higher, which in a first instance doesn't make sense since Wang considers a lower fossil energy consumption in this operation. First of all, like mentioned in the previous note, Macedo doesn't specify which portion of emissions are responsible for agriculture and which are for transport. Like it was mentioned an approximation was made, but it's not 100% guaranteed that the value is correct (it can be higher). Other possible explanation for the high value presented in Wang for sugarcane transport is the technology considered in each study: older trucks pollute a lot more.

About **trash burning emissions**. Sugarcane leaves and tops are typically burned in the field before and after harvest [29]. Seabra considers 35% of unburned harvested cane, while Macedo and Wang consider 20%. This is one very important factor in why the emissions are lower in Seabra.

For the **field emissions** the results from Table 3.5 (resources quantity) must be checked. Since field emissions are emissions from the soil duo to fertilizers and chemicals, the results from Figure 4.8 make sense if Seabra considers more fertilizers consumption. By checking Table 3.5 that is confirmed. By adding all the fertilizers quantities it can be seen that Seabra considers a total of 7237 grams of fertilizers per tone of sugarcane produced, Macedo considers 1741 g/tonne and Wang 6773 g/tone. These quantities aren't exactly proportional to the GHG field emissions, but that is due to the fact of some fertilizers being more pollutant than others. According to the report [20] the nitrogen fertilizer usage increases the emissions of N_2O, which has a very high GWP (it has a GWP of 298 and CH_4, for example, has a GWP of 25). Which means that more usage of N fertilizer, the more N_2O will be emitted and the more will be the GHG emissions. As it can be seen in Table 3.5 the values for N fertilizer usage are very similar between studies, therefore, in spite of the smaller usage of fertilizers, Macedo hasn't that much of a difference in the GHG field emissions.

Now about emissions due to the **ethanol production**. Macedo considers zero GHG emissions in this stage, because it assumes the carbon released in the boiler is uptaken by the sugarcane. Seabra mentions a value for the ethanol production like it can be seen in Figure 3.6. But, like it was mentioned in section 4.1 (fossil energy consumption) probably what Seabra mentions as "production" is probably the production of chemicals for the industrial phase, therefore those emissions will also correspond to the manufacture of the chemicals and to the production of ethanol, therefore emissions in this stage aren't accounted. Wang doesn't consider that, therefore it presents a value for the GHG production emissions, which can indicate a good estimate on the values for this stage.

In Figure 4.9 the emissions related to Level 2 operations can be seen:

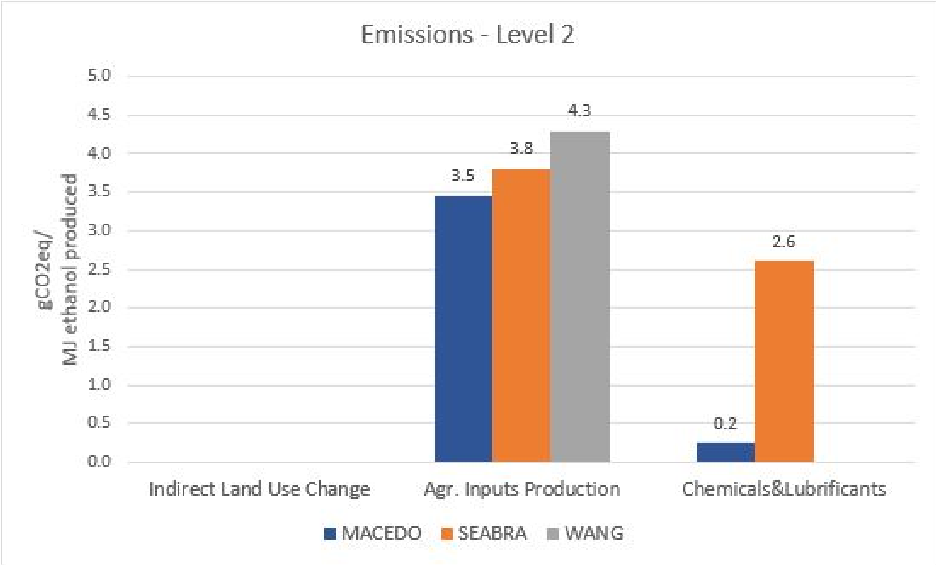


Figure 4.9: Emissions Level 2

As mentioned before, ILUC is not considered in any study. Reminding section 4.1, the GHG emissions should be somehow proportional to the fossil energy usage. But that doesn't happen, especially in the chemicals and lubricants section.

The values of Figure 4.9 are similar for the agricultural inputs and very different for the chemicals used in the industrial phase. Wang has the highest value of emissions for the agricultural inputs, which can be explained by this: in spite of just considering the energy consumption of the seeds' preparation, probably it considered the entire agricultural inputs manufacturing emissions. This is not wrong, since Wang refers the usage of many agricultural inputs. Wang also doesn't consider Level 2 emissions for the feed-stock conversion stage, therefore it was not accounted.

Overall the main reason for the existent differences can be the total amount of fertilizers and chemicals usage considered by each study. As seen in Table 3.5 (resources quantity), Macedo considers much less fertilizers during agriculture and it also considers less chemicals quantity in the industrial phase than Seabra. But still, why such small differences in the agricultural inputs and such a huge difference in the chemicals for the industrial phase? That probably has to do with the fertilizer/chemical itself, since different fertilizers/chemicals will have different manufacturing processes with different emissions quantities.

In Figure 4.10 the emissions related to Level 3 operations can be seen:

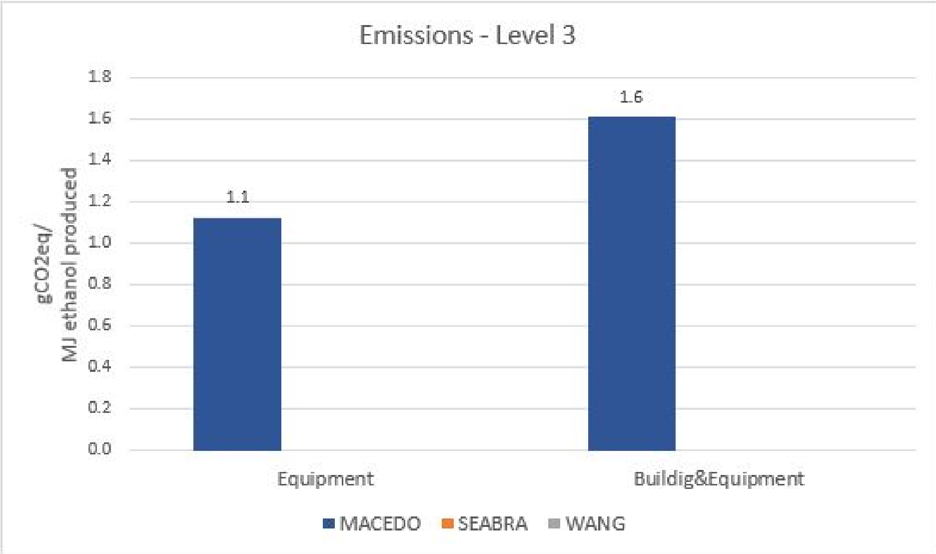


Figure 4.10: Emissions Level 3

Macedo is the only study that presents data in this section. No comparison can be made, but considering that not even the European directive considers Level 3 emissions, having one study with this info is great. It allows to make an estimative of which Level is the larger responsible for emissions.

4.2.1 Level's percentage of GHG emissions

Like done for energy consumption, the percentage values for the emission's levels is shown in Figures 4.11, 4.12 and 4.13.

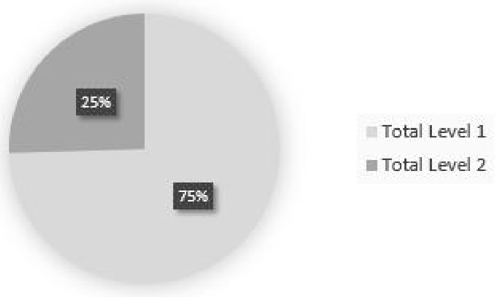


Figure 4.11: GHG emissions by levels - **Seabra**

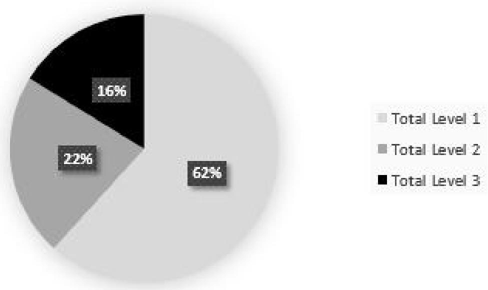


Figure 4.12: GHG emissions by levels - **Macedo**

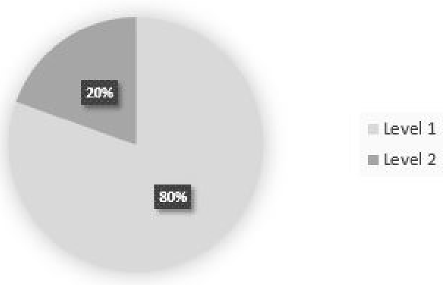


Figure 4.13: GHG emissions by levels - **Wang**

No doubt here, Level 1 is by far the main responsible for the GHG emissions. And like it was seen previously, sugarcane farming, trash burning and field emissions are the main responsibles inside this Level. Level 1 is the Level that must be improved in what GHG emissions is concerned.

4.3 Overall comparison

After checking individually energy consumption and GHG emissions, agglomerated data can be seen in Figure 4.14. The dots that correspond to Level 1 are connected. As well as the dots that correspond to Level 1 plus Level 2, and finally the dots that correspond to the sum of all Levels. This is just to get an idea of the trend of the potential range associated to the consideration of each level.

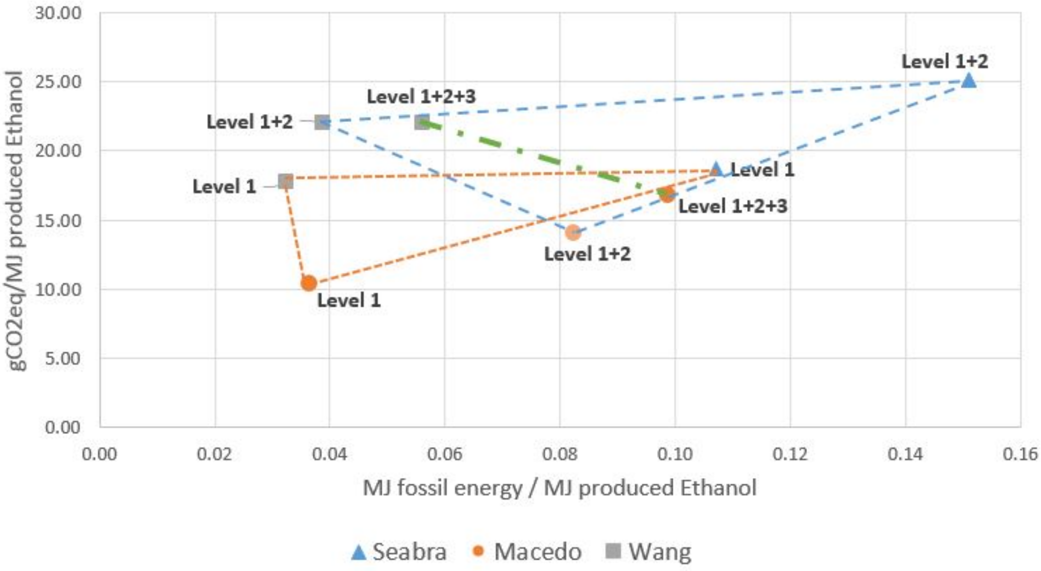


Figure 4.14: Overall Comparison

4.4 Concawe study comparison

Like mentioned before, Concawe study [33] is an European study and it presents an overall dataset for several fuels. Concawe presents a lot of sugarcane ethanol information, but it isn't as detailed as the other studies of this thesis in what energy consumption and GHG emissions is concerned. Nevertheless it contains enough data so that some comparisons can be made. The first one in the total amount of fossil energy expended in the WTT pathway of the ethanol. Since is WTT the study also considers the expended energy to transport ethanol to Europe and was not analyzed in this study, but yet a comparison can be made , because **the values presented by the other studies should be smaller than the one presented by Concawe**. Another aspect is known, this fossil energy expended value presented in Concawe is just for Level 1 range. The total Level 1 fossil energy consumption values are presented in Table 4.1:

Table 4.1: Level 1 fossil energy consumption - Concawe comparison

Fossil energy expended (MJ/MJproduced ethanol			
Concawe	Macedo	Seabra	Wang
0.040	0.036	0.107	0.032

Macedo and Wang values are really close to the Concawe value. The smaller value has to due with the fact that Macedo and Wang values don't consider the fossil energy expended in transportation to Europe. Seabra value is really much higher, which indicates it may not to be the most reliable value.

Concawe also presents data about Level 2 fossil energy consumption.

Table 4.2: Concawe fossil energy consumption LEVEL 2

	Fertilizers& Chemicals	**Fossil energy consumption MJ/MJ**	$\sum$ **Concawe fossil energy consumption MJ/MJ**	$\sum$ **Other studies fossil energy consumption MJ/MJ**
Feed-Stock production	N	0.0083	$\sum = 0.0134$	$\sum_{Macedo} = 0.043$ $\sum_{Seabra} = 0.040$ $\sum_{Wang} = 0.003$
	P_2O_5	0.0012		
	K_2O	0.0019		
	CaO	0.002		
Feed-Stock Conversion	Lime	0.0024	$\sum = 0.0041$	$\sum_{Macedo} = 0.003$ $\sum_{Seabra} = 0.003$ $\sum_{Wang} = 0.003$
	Sulfuric acid	0.0017		

Reminding the results of section 4.1, it can be seen that the Level 2 fossil energy consumption value presented by Concawe in the **feed-stock conversion** stage is very similar to the values presented by the other studies.

The same doesn't happen for the value presented in the **feed-stock production** stage. The value is much lower than the ones presented by Macedo and Seabra. But considering that Concawe also consideres a much lower consumption of agriculture resources (check Table 3.5) it makes sense the fossil energy used is also lower.

GHG emissions comparison

Concawe study also presents the GHG emissions for each operation of ethanol's pathway. A comparison was made to verify the resemblance between the study's and the Concawe values. These values are presented in Table 4.3:

Table 4.3: GHG emissions Level 1 comparison with Concawe values

	Emissions gCO2eq/MJ			
	Macedo	Seabra	Wang	**Concawe**
Sugarcane agriculture	8.91	17.30	13.69	**14.45**
Road transport	1.46	1.40	1.88	**0.85**
Production (Avoided Emissions)[25]	-11.35	-6.40	0.00	**-9.84**

For the emissions of **sugarcane agriculture** the emissions due to trash burning and field emissions were also considered. Since Concawe[33] doesn't mention aspects like the share of mechanical and manual harvesting, the smaller values of Macedo can have to do with the fact that Macedo considering more manual harvesting than Concawe.

About **road transport**, Concawe considered a smaller energy consumption and by consequence it also considers a smaller value for GHG emissions. Once again Concawe it's not clear about the road transportation distance. If the value is smaller than the 20 km considered by the other studies that it's explained the smaller GHG emissions.

For the **avoided emissions** it was considered the value presented by Macedo that in reality represents the avoided emissions by using bagasse instead of fuel oil in other industries. It's not the avoided emissions for using bagasse instead of fuel oil in the ethanol production, but for a matter of comparison it was mentioned here. And by surprise it has the smaller relative error of the avoided emissions. Wang doesn't consider avoided emissions, therefore the zero in Table 4.3.

4.5 Renewability

Knowing the the fossil energy consumed and the total energy consumed is a great way to see the renewability of an operation and/or of a pathway. Unfortunately the analyzed studies don't reveal enough data to make this renewability check possible for all operations. Nevertheless, some operations have this data and can be compared. Also, Concawe study also presents a value for total energy consumption and fossil energy consumption. In spite of being a WTT study (and not WTG), the value is presented.

[25] The negative values are the conventional way to present the values of avoided emissions. The concept of avoided emissions is better explained at the end of chapter 3

For the manufacture of machinery and buildings, Macedo presents values of energy generated by electricity and thermal energy. These values are approximations based on energy consumed by sectors (e.g. mining, ceramic, cement, stell and iron) that contribute for this manufacture. And it is specific that 70% of the total energy consumed corresponds to thermal energy and 30% to electricity. Like mentioned in section 4.1, 13% of Brazilian electricity is generated from fossil fuels. About fossil energy usage to generate thermal energy, an estimative was made based on the percentages of renewable thermal energy used in each sector, and a value of 30% for renewable thermal energy usage was reached and the remaining 70% are from fossil fuels. So the fossil energy (FE) consumed is reached from total energy (TE) by equation 4.1:

$$FE = TE \times 30\% \times 13\% + TE \times 70\% \times 70\% \tag{4.1}$$

Table 4.4: Fossil energy share from Level 3 operations - Macedo

Operation	**Total Energy Consumption (MJ/MJethanol)**	**Fossil Energy Consumption (MJ/MJethanol)**	***Fossil Energy Share***
Agriculture equipment manufacture	29.20	15.45	***52.9%***
Buildings + Equipment from conversion stage	33.48	17.71	
Total Level 3	**62.68**	**33.16**	

For these operations fossil fuel usage reprented an approximated share of 52.9%., which leaves a good value of 47.1% for renewables usage. Another interesting aspect of renewability is related to the total energy consumed in the ethanol factories. Only Wang presentes values for the total energy consumed in that stage and those values are presented in Table 4.5:

Table 4.5: Wang total energy consumption in production stage

	Study Values	**Normalized Values**
	MJ/tonnecane	*MJtotalenergy/MJ*
Electricity	100.8	0.052
Thermal energy	1188	0.619
TOTAL	1288.8	0.671

The electricity and thermal energy are produced through bagasse combustion. The $0.052 MJ_{total}/MJ$ and the $0.619 MJ_{total}/MJ$ are really high values of energy consumption (the highest value of fossil energy consumption in this thesis is $0.043 MJ/MJ$, correspondent to the Level 2 of Macedo study). Basically here are presented $0.671 MJ/MJ$ that are produced through biomass and not through fuel oil, which represents not only zero fossil consumption, but also really lower GHG emissions.

4.6 European directive comparison

Reminding equation 3.5, to calculate the biofuel emissions according to the European directive [32]:

$$E = e_{ec} + e_l + e_p + e_{td} + e_u - e_{sca} - e_{ccs} - e_{ccr} - e_{ee} \tag{4.2}$$

Where:

e_{ec} includes: sugarcane farming, trash burning, field emissions (Level 1) and agricultural inputs production (Level 2);

$e_l = 0$, since no land-use change emissions are considered;

e_p includes: production (Level 1) and chemicals&lubricants production (Level 2);

e_{td} includes: transportation to the factory (Level 1) plus the distribution to the fuel stations (this last one is out the WTG analyzes);

$e_u = 0$, because ethanol is a biofuel;

e_{sca}, e_{ccs} and e_{ccr} are considered zero, since no information about these are given;

e_{ee} includes: emissions saving from excess electricity produced in cogeneration systems, instead of using electricity from power plants.

In Table 4.6 are presented the values of every parameter for each study analyzed in this thesis, as well as the relative error between the default values of the parameters presented by the European directive [32] and the ones of each study:

Table 4.6: Emission parameters of each study

	Emissions (gCO2eq/MJ)				***Variation between studies and directive (%)***		
	Seabra	**Macedo**	**Wang**	**Default values of European directive**	*Seabra*	*Macedo*	*Wang*
e_{ec}	21.10	12.37	17.99	14.00	*50.71*	*-11.65*	*28.47*
e_l	0.00	0.00	0.00	-	-	-	-
e_p	2.60	0.24	2.13	-	-	-	-
e_{td} [18]	1.40	1.46	1.88	9.00	-	-	-
e_u [19]	-	-	-	0.00	-	-	-
e_{sca}	-	-	-	-	-	-	-
e_{ccs}	-	-	-	-	-	-	-
e_{ccr}	-	-	-	-	-	-	-
e_{ee}	3.70	-	-	-	-	-	-

Only e_{ec} parameter can be compared, since the transportation parameter, e_{td}, in the directive includes emissions from the distribution of the fuel to the pumping stations in Europe, which is out of the WTG boundary. Nevertheless being able to compare one parameter is already really good and, as it can be seen, Macedo has the lowest relative error. This is a good indication that Macedo has more reliable data. Seabra on the other hand has the highest error, probably to do with the really high emissions (and energy consumption) of the agriculture operation.

Macedo considers avoided emissions thanks to the use of bagasse in other industries, but since e_{ee} are the avoided emissions thanks to the excess electricity from cogeneration, two distinct scenarios for Macedo were made: $e_{ee} = 0$ and e_{ee} equal to the avoided emissions from bagasse usage in other industries.

The default value assumed by the directive [32] for e_{td} it also accounts for the emissions due to the transportation to Europe. Once again, two distinct scenarios were assumed: $e_{td} = 9$ for the case where ethanol is exported to Europe and e_{td} equal to values presented by each study. In this last scenario the emissions from transportation to the pump weren't considered.

Finally, assuming $e_u = 0$ for all studies and $E_f = 83.8\ gCO2eq/MJ$ the following results presented in Table 4.7 were reached. Scenario 1 is an approximation of the ethanol produced and consumed in Brazil and Scenario 2 is an approximation for ethanol produced in Brazil and exported to Europe.

[18] These values are only related to the WTG analyzes
[19] Emissions related to the vehicle in function were not analyzed

Table 4.7: Emissions and emission savings according to the European directive formula

	Scenario 1 e_{td}= value from studies		Scenario 2 $e_{td} = 9$	
	E $gCO2eq/MJ$	**GHG savings** $(E_f - E)/E_f \times 100\%$	**E** $gCO2eq/MJ$	**GHG savings** $(E_f - E)/E_f \times 100\%$
Seabra	21.40	74.46	29	65.40
Macedo	14.07	83.21	21.61	74.21
Wang	22.00	73.75	29.12	65.25
Macedo w/e_{ee}	2.73	96.75	10.27	87.75

Reminding what was refered in section 3.6, the GHG savings must be approximately 71% for the ethanol exported to Europe and approximately 86% for ethanol produced and consumed in Brazil. Macedo is by far the study more close to these values, which reforces the idea of being the most reliable study. Still analyzing Macedo, it can be seen that if the emissions saved by using bagasse in other industries are considered, the GHG savings are really high (96.75% and 87.75%), much higher than the values assumed in section 3.6.

4.7 Zero trash burning

According to Wang study [29] open-field burning practice of sugarcane leaves and ”leftovers” will be gradually phased out. So, imagining that this practice was already gone how would that affect the emissions' Levels share? In Figures 4.15, 4.16 and 4.17 are the emission Levels share considering zero emissions of trash burning.

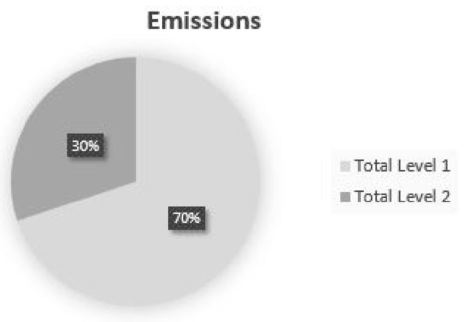


Figure 4.15: Emissions by levels without trash burning - **Seabra**

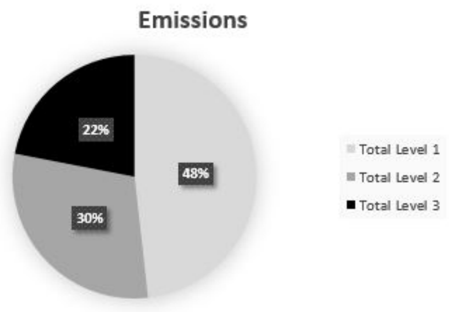


Figure 4.16: Emissions by levels without trash burning - **Macedo**

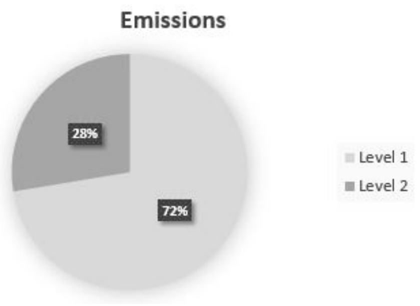


Figure 4.17: Emissions by levels without trash burning - **Wang**

In this scenario Level 1 continues to be the main responsible for the GHG emissions. Nevertheless ending the open-field burning represents a decrease of 42%, 20% and 36% in the Level 1 GHG emissions for Macedo, Seabra and Wang respectively. Considering all Levels, it represents a decrease of 26%, 15% and 29% of the GHG emissions for Macedo, Seabra and Wang respectively. These values are quite significant, which means that ending the open-field burning is indeed an excellent practice to reduce the GHG emissions of the sugarcane ethanol pathway.

4.8 Pathway efficiency

So far the presented results had into account each study efficiency, and by **efficiency it's meant the total amount of produced ethanol from one tonne of sugarcane**. Macedo is the study with the highest efficiency, considering 97.32 liters of ethanol produced with 1 tonne of sugarcane. Efficiency is mainly related to the technology and practices of each pathway. An analysis was made: considering the exact same data of each study, their efficiency will be changed. And by only changing efficiency, how will the fossil energy consumption and GHG emissions change? For this simulation, and knowing that Macedo has the highest efficiency, Seabra and Wang were the ones tested. In other words, let's manipulate Seabra's and Wang's efficiency assuming that now they have Macedo's efficiency of 97.32 liters/tonne of cane.

Seabra has originally an efficiency of 82 liters per each tonne of sugarcane produced. Assuming now the 97.32 liters/per tonne of cane, this represents an increase of 18.68% of the efficiency. By changing the efficiency it can be found that fossil energy consumption and GHG emissions of every operation of the pathway decreases 15.74%.
Wang has originally an efficiency of 91 liters per each tonne of sugarcane produced. Assuming now the 97.32 liters/per tonne of cane, this represents an increase of 6.95% of the efficiency. By changing the efficiency it can be found that fosil energy consumption an GHG emissions of every operation of the pathway decreases 6.49%.
All the previous data is resumed in Table 4.8:

Table 4.8: Efficiency analysis

Study	**Original efficiency** ***(Liters/tonnecane)***	**Maximum potential efficiency (Macedo)** ***(Liters/tonnecane)***	**Efficiency Increase concernin max. eff. (%)**	**Decrease in fossil energy consumption and GHG emissions if max. eff. is considered (%)**
Seabra	82	97.32	18.68	15.74
Wang	91	97.32	6.95	6.49

A better study would have to be made about if more efficient technologies have less environmental impact. Reminding the analysis in section 4.2, Macedo - the study with better efficiency results - presents less GHG emissions. Which makes sense, because better efficiency implies less consume of fossil energy to achieve the same amount of ethanol. Improving the technology of every operation of ethanol's pathway can be a huge improvement in the fossil fuel depletion situation and also in the environmental GHG emissions. Probably the only huge obstacle for this is the economical factor, but this would have to be analyzed in future work.

Chapter 5

Conclusions

Different sugarcane ethanol LCA studies were analyzed, presenting different values for resources consumption, energy consumption and GHG emissions. One of the goals of this thesis was identifying the reasons for these differences. It was found that they can be influenced by the year of study, the analyzed region and also by other factors such as: the share of mechanical and manual labour, the technology and configuration of the procedures in the agriculture stage and in the factory where the sugarcane is converted to ethanol, the vehicles' type used in transportation stage (older vehicles will consume and pollute more), resources types and quantities used.

One great achievement was the evaluation of the impact categories divided in three levels. This allows not only to call for attention that an LCA is not just Level 1 based (an easy mistake to be made), but also it helps to focus efforts in three different categories, improving the overall analyzes. Level 1, which concerns the direct operations of the pathway, was found to be the major responsible for fossil energy consumption and GHG emissions from two studies, with values from 0.032 to 0.107 MJ of expended fossil energy to produce 1 MJ of ethanol and 17.7 to 18.7 grams of CO_2eq emitted per each 1 MJ of produced ethanol. But for the most reliable study of this thesis - Macedo - the main responsible for energy consumption was Level 2, which concerns the production of resources used in the agricultural and industrial processes, with a total value of 0.046 MJ of expended fossil energy to produce 1 MJ of ethanol. The main responsible for GHG emissions according to Macedo is Level 1, with a value of 10.4 grams of CO_2eq per each 1 MJ of produced ethanol. The operation more responsible for the Level 1 emissions is the open-field burning of the remains/trash of the sugarcane, but fortunately according to the Wang study this practice will be abolish from Brazil. Level 3, which concerns the manufacture of equipment and buildings necessary for Level 1 operations, is the less detailed level and some studies don't even consider it. Macedo referes this Level, and according to it Level 3 is responsible for the emission of 2.7 grams of CO_2eq emitted per each 1 MJ of produced ethanol and it expends 0.017 MJ of fossil energy to produce 1 MJ of ethanol.

Finally, a set of guidelines were created and are presented in the next section - these guidelines are also a resume of some important topics to be considered in these kind of studies.

5.1 Guidelines

In this section, some guidelines are given with the intention of guiding following researchers in similar studies, highlighting topics that are usually discarded but demonstrated in this study to have great importance.

LEVEL 1 - Sugarcane agriculture, transportation and conversion to ethanol in the factory are the main operations of sugarcane ethanol production.

Agriculture:

- Which and how many fuels, fertilizers and seeds are needed? The fertilizers will have an impact in field emissions, so knowing which type and how many are used will be very useful to calcutate field emissions.
- What is the percentage of manual and mechanical harvesting?
- Does that specific field pratice trash burning? If so, how many leaves and tops are burned? This is important for emissions calculation.
- How much water is it needed in agriculture stage?
- Even if the factory uses cogeneration, how many GHG emissions are emitted? Attention, some studies may consider zero GHG emissions because of the carbon uptaken by sugarcane.
- Is it possible to replace any of the chemicals for natural fertilizers?

Transportation:

- Which fuel is needed for this operation?
- What is the distance travelled by vehicles from the field to the mill?
- Type of vehicle used and its age?

Ethanol Production

- Does the factory use the co-product bagasse in a cogeneration system? If not, which fuels are needed to power the factory?
- Which chemicals are needed?
- Does the factory produces sugar and ethanol, and uses allocation?

LEVEL 2 - Englobes operations involved in the manufacture of Level 1 resources.

- Which and how many fuels, fertilizers, chemicals and seeds are needed? Different reources will have different manufacture processes.
- Distance travelled of fertilizers and chemicals to the agriculture fields and ethanol production factories. Are the fertilizers imported? Fertilizers with small GHG emissions manufacture can represent huge GHG emissions if they travel great distances.

LEVEL 3 - Operations involved in the manufacture of machinery and buildings.

- Which machinery and buildings are used in Level 1 operations?
- For each machinery and buildings, how many and which types of energy were used in their manufacture? If info is hard to find check which materials were needed and then research for each material sector info. If electric and thermal energy were needed in any operation, check the percentages of fossil and renewable energy needed to generate them.
- description Is the machinery imported? If so, which distance does it travel?
- Is there any machinery, more recent that the ones used, that has lower values of energy consumption and GHG emissions in its manufacture process?

Finally, how many liters of ethanol are produced with one tonne of sugarcane? Knowing the pathway's efficiency is crucial, to determine the impact of emissions and energy consumption.

5.2 Future Work

Some topics for future work are presented below. Although not included in this study, there are several issues that should be adressed.

- No economic analyzes was made in this assignment. This is something valuable for future work in order to assess the pathway financial viability.
- Fossil fuel's manufacturing is Level 2 data and it must be included, although in comparative terms, if the fuel provenance is the same, has no influence in the results.
- A detailed analyzes in how to decrease GHG emissions and energy consumption in ethanol WTG stage (ex: replacing older equipment, using renewable energy equipment, better sugarcane harvesting strategies,...).
- Making a detailed WTG analysis in other ethanol types (e.g. corn ethanol, sugar-beet ethanol,...), and then compare the results with this study. Diferent resources should produce different impacts.
- Include Direct and Indirect Land Use Change data. What is the impact caused by LUC and ILUC emissions? Is it significant? Also, research if it's a viable and sustainable practice to change forest into agriculture lands and at which rate this happens.

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Appendix A

Studies Details

Used values for energy conversion:

Diesel's LHV : $11,414\ kcal/liter = 47.8\ MJ/liter$ [28]
Ethanol's LHV: $21.1\ MJ/liter$ (middle value from the LHV values of anhydrous and hydrous from [30])

1 kcal = 0.00419 MJ
MJ/MJ $\rightarrow$ MJ of fossil energy expended to produce one MJ of ethanol
gCO2eq/MJ $\rightarrow$ gCO2eq emitted per each MJ of produced ethanol

A.1 Macedo Study

Macedo's efficiency: *490100 kcal/tonnecane = 97.32 liters of ethanol/tonnecane*
Cane productivity: *106 tonnecane/ha*

Table A.1: Macedo Resources Level 1 - details

	Inputs	**Values From theStudy**	**NormalizedValues**
		Several Units	g/tonnecane
Feed-Stock Production	N	*83 kg/ha*	783
	P_2O_5	*17.5 kg/ha*	165
	K_2O	*84 kg/ha*	792
Feed-Stock Conversion	Lubricants	*13.37 g/tonnecane*	13
	Lime	*930 g/tonnecane*	930
	Sulfuric acid	*9.05 g/L ethanol*	881

Table A.2: Macedo fossil energy consumption details

			Values From the Study	**Normalized Values**
		Operation	*kcal/tonnecane*	MJ/MJ
Feed-Stock Production	Level 1	Sugarcane Farming	*9097*	0.019
		Sugarcane Transportation	*8720*	0.018
	Level 2	Agr. Inputs Production	*21074*	0.043
	Level 3	Equipment manufacture	*6970*[22]	0.008
Feed-Stock Conversion	Level 1	Production	*0*	0
	Level 2	Chemicals & Lubrificants	*1520*	0.003
	Level 3	Buildings + Equipment manufacture	*7990*[22]	0.009

Table A.3: Macedo emission details

			Values From the Study	**Normalized Values**
		Operation	*kgCO2eq/tonnecane*	gCO2eq/MJ
Feed-Stock Production	Level 1	Sugarcane Farming (&Transport)[23]	*6*	1.5
		Trash Burning	*9*	4.4
		Field Emissions	*6.3*	3.1
		Sugarcane Transport[23]	-	1.5
	Level 2	Agr. Inputs Production	*7.1*	3.5
	Level 3	Equipment manufacture	*2.3*	1.1
Feed-Stock Conversion	Level 1	Production	*0.0*	0.0
	Level 2	Chemicals&Lubrificants production	*0.5*	0.2
	Level 3	Building&Equipment manufacture	*3.3*	1.6

[22] These values from the study weren't directly converted. Like mentioned in section 4.5, these values include fossil and renewable energy.

[23] Macedo presents the emissions values in one single data. Like mentioned in section 4.2 an approximation was made. Considering that the amount of diesel is practically the same in both activities, an equal split for the emissions was made.

A.2 Seabra Study

Seabra's efficiency: *82 liters of ethanol per each tonne of sugarcane.*

Table A.4: Seabra Resources Level 1 - details

	Inputs	***Values From theStudy***	**NormalizedValues**
		Several Units	g/tonnecane
Feed-Stock Production	N	*777 g/tonnecane*	777
	P_2O_5	*249 g/tonnecane*	249
	K_2O	*980 g/tonnecane*	980
	$CaCO_3$	*5183 g/tonnecane*	5183
	Herbicides	*44 g/tonnecane*	44
	Insecticides	*3 g/tonnecane*	3
	Acaricides	*0.02 g/tonnecane*	0.02
	Fungicides	*0.01 g/tonnecane*	0.01
	Other Defensives	*0.96 g/tonnecane*	0.96
Feed-Stock Conversion	Lubricants	*10 g/tonnecane*	10
	Sulfur	*156 g/tonnebagasse*	1.36
	Lime	*880 g/tonnecane*	880
	Sulfuric acid	7.4 g/L ethanol	606.8
	Soda	65 g/tonnecane	65.00
	Neutralization Soda	2.1 g/L ethanol	172.2
	Antibiotic	9.3 g/m^3 ethanol	0.763

Table A.5: Seabra fossil energy consumption details

			Values From the Study	**Normalized Values**
		Operation	*Several Units*	MJ/MJ
Feed-Stock Production	Level 1	Sugarcane Farming	*88*	0.088
		Sugarcane Transportation	*19*	0.019
	Level 2	Agr. Inputs Production	*40*	0.040
	Level 3	Equipment manufacture	-	-
Feed-Stock Conversion	Level 1	Production	*0*	0
	Level 2	Chemicals & Lubrificants production	*4*	0.004
	Level 3	Buildings + Equipment manufacture	-	-

Table A.6: Seabra emission details

			Values From the Study	**Normalized Values**
		Operation	*gCO2eq/MJ*	gCO2eq/MJ
Feed-Stock Production	Level 1	Sugarcane Farming	*6.8*	6.8
		Trash Burning	*3.8*	3.8
		Field Emissions	*6.7*	6.7
		Sugarcane Transport	*1.4*	1.4
	Level 2	Agr. Inputs Production	*3.8*	3.8
	Level 3	Equipment manufacture	-	-
Feed-Stock Conversion	Level 1	Production	*0*	0
	Level 2	Chemicals&Lubrificants production	*2.6*	2.6
	Level 3	Building&Equipment manufacture	-	-

A.3 Wang Study

Wang's efficiency: 91 liters of ethanol per each tonne of sugarcane.

Table A.7: Wang Resources Level 1 - details

	Inputs	***Values From the Study***	**Normalized Values**
		[g/tonnecane]	g/tonnecane
Feed-Stock Production	N	*1091.7*	1091.7
	P_2O_5	*120.8*	120.8
	K_2O	*193.6*	193.6
	$CaCO_3$	*5337.7*	5337.7
	Herbicides	*26.9*	26.9
	Insecticides	*2.2*	2.2
	Acaricides		
	Fungicides		

Table A.8: Wang fossil energy consumption details

			Values From the Study	**Normalized Values**
		Operation	Several Units	MJ/MJ
Feed-Stock Production	Level 1	Sugarcane Farming	*36019 Btu/tonnecane*	0.020
		Sugarcane Transportation	*24.40 MJ/tonnecane*	0.013
	Level 2	Agr. Inputs Production	*5573 Btu/tonnecane*	0.003
	Level 3	Equipment manufacture	*27583 Btu/tonnecane*	0.008
Feed-Stock Conversion	Level 1	Production	*1288.80 MJtotal energy/tonnecane*	0
	Level 2	Chemicals & Lubrificants production	*6.36 MJ/tonnecane*	0.003
	Level 3	Buildings + Equipment manufacture	*33.45 MJtotal energy/tonnecane*	0.009

Table A.9: Wang emission details

			Values From the Study	**Normalized Values**
		Operation	*kgCO2eq/tonnecane - (GHG emissions share)*	gCO2eq/MJ
Feed-Stock Production	Level 1	Sugarcane Farming	*(9%)*	2.4
		Trash Burning	*(24%)*	6.4
		Field Emissions	*(18%)*	4.8
		Sugarcane Transport	(7%)	1.9
	Level 2	Agr. Inputs Production	*(16%)*	4.3
	Level 3	Equipment manufacture	-	-
Feed-Stock Conversion	Level 1	Production	*4.09 - (17%)*	2.13
	Level 2	Chemicals&Lubrificants production	-	-
	Level 3	Building&Equipment manufacture	-	-

The only value that Wang reveals for emissions are the emissions due to bagasse burned in the boilers: 4.09 kgCO_2eq/tonnecane. In the end Wang presents a chart with shares of GHG emissions, and thanks to that it was possible to reach the remaining values. Knowing that the emissions in production represented 17% of total GHG emissions it was just a matter of calculating the rest. For the most observant readers, the remaining 9% are due to ethanol transport to the gas pumps, value which wasn't accounted for this work.