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SCHOOL OF INDUSTRIAL AND INFORMATION ENGINEERING

MASTER OF SCIENCE ENERGY ENGINEERING FOR AN EVIRONMENTALLY SUSTAINABLE WORLD

SUSTAINABLE EVALUATION OF JATROPHA OIL AS A BIOFUEL IN COLOMBIA

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Abstract

In the last decades the depletion of oil reserves has become a major source of discussion worldwide, since oil constitutes the most important primary energy source. This situation has led the oil industry to develop new and more advanced technologies in order to achieve better oil recovery and more efficient. As a consequence, the prices of oil have been pushed up. In the same way, the global warming also became a major priority around the world due to the fact that show how human activities have disturbed the natural cycles on earth and the urge to look for sustainability. In such panorama, global community has been looking for energy solutions which permit a gradual replacement of fossil fuels to avoid the dependence on them due to their elevated costs and damage to the environment. Biofuels show up as a solution to apply basically on the transportation and generation sectors. With biofuels, both problems can be attacked by reducing the dependence on fossil fuels and reducing as well the negative impacts on the environment

In Colombia, the energy security became a priority since major blackouts occurred in the early nineties and also due to the oil prices. Although Colombia is considered to be a net oil exporter, still is dependent on oil products imports such as diesel, which, considering the high prices, pushes the country towards alternative solutions like biofuels. The great advantage is that, Colombia has a great variety of environments and lands which permit vast agriculture. Today, Colombia is producing bioethanol from sugar cane and biodiesel from oil palm and has already established policies to promote and regulate this market. Nonetheless, the demand is still high and the projections for replacing fossil fuels are hard to achieve. Under this situation, new feedstocks are called to complement the actual production.

Jatropha biodiesel shows up as a potential feedstock for biodiesel production due to its advantages as an energy crop as well as to the good aptitude of the tree to be cultivated in Colombia. However, the knowledge on this plant is still in its starting point and it is still considered as a wild plant. The knowledge gap in this situation needs to be filled up correctly reason why mane studies have been done in this area. The present work aim is to reduce this gap from the energy and sustainability point of view. A model was designed to analyze the possible production of Jatropha biodiesel in different regions of the country focusing on the energy performance of the system starting from the cultivation till the production of the fuel to be commercialized. With the results of this model plus the results of some other works done in Colombia on this topic, a sustainable evaluation is executed in order to determine whether if it is a good practice or not to be applied in this Country.

Key words – Biodiesel, sustainability, Jatropha Curcas L., trans-esterification, net energy ratio, net energy balance, greenhouse gases, fertilization, global warming.

“No sacrifice. No victory”

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1. Introduction

In the last decades, the interest in developing biofuels has been increasing due to many factors. The most important of them are the concerns for both the energy security and the mitigation of greenhouse gas (GHG) emissions. Energy security is affected negatively by the declining of the fossil fuel reserves while the demand for energy keeps increasing, pushing up the market prices. Global warming is being boost up with the strong usage of conventional fuels encouraging governments and international organizations to work out policies and promoting researches that may diminish this impact.

These factors act as driving forces that have led the biofuel´s production of different feedstocks without a proper sustainability study of them. This situation is being created due to the knowledge gap upon their production and impacts which confine social, economic and environmental issues. Major concerns have been addressed in the field of food security due to the competition for land and crops demand as well as in the environmental area where the carbon stock[1] change dependent on the land use change (LUC)[2] may be negatively affected plus the intense use of agriculture resources like fertilizers and water.

The present document is intended to do a general review of the actual state of biofuels in the world and specifically of Jatropha biodiesel in Colombia focusing in the type of crops, technologies and sustainability issues. A worldwide comprehension on this matter will help to understand the feasibility of working with a specific biofuel in a particular country according to its characteristics and the experiences from other regions. In such way, an adequate sustainability evaluation of Jatropha oil as a biofuel in Colombia can be done contributing in the reduction of the knowledge gap in this area and funding a good base for further studies.

The general idea is to start from the universal stand point of view and gradually go deep into the particular case of Jatropha in Colombia. Accordingly, in the first part, a general description of the different biofuel feedstocks used in the world is presented taking care of their production, energy consumption, yields and efficiencies of the processes as well as the countries working on them. Then, a more detailed view is performed for Jatropha biodiesel in some countries in order to gradually approach to the specific aim of this document. This offers the opportunity to compare and analyze good practices that may be proposed in the future and serve as example for countries in the route of biodiesel developing. Finally, a detailed state of the art of Jatropha in Colombia is presented so that it can be used in the further evaluation of Jatropha biodiesel in this country.

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[1] The quantity of carbon contained in a “pool”, meaning a reservoir or system which has the capacity to accumulate or release carbon.

[2] LUC: As defined by the United Nations Climate Change Secretariat; land use, land use change and forestry (LULUCF) is “A greenhouse gas inventory sector that covers emissions and removals of greenhouse gases resulting from direct human-induced land use, land-use change and forestry activities.”

2. Biofuel feedstocks in the world

2.1. A general overview

Biofuel markets started due to the first oil crisis in the seventies where the prices of crude oil increased heavily (see % of GDP in Figure 1). After this period, the usage of oil as primary energy fell almost ten points and clearly there is a similar situation nowadays (see % of energy in Figure 1). Cost of oil is increasing heavily again pushing a decrease in oil consumption (see Figure 1). Back in the seventies, this situation pushed countries to develop an alternative oil supply dependent on a domestic production of crops, opening the doors to liquid biofuels in the energy panorama, in pursue of the so called energy security. Today, not only the climate change concern is pulling down oil demand but also the increasing costs of oil as we can see from Figure 1 [1].

Figure 1 – Oil share of energy and GDP (Source: BP world energy outlook booklet. January/2013)

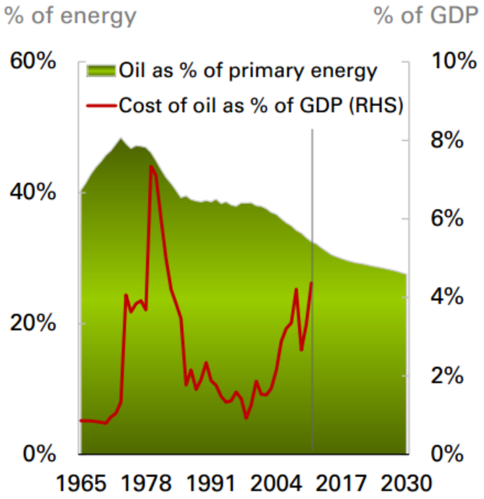
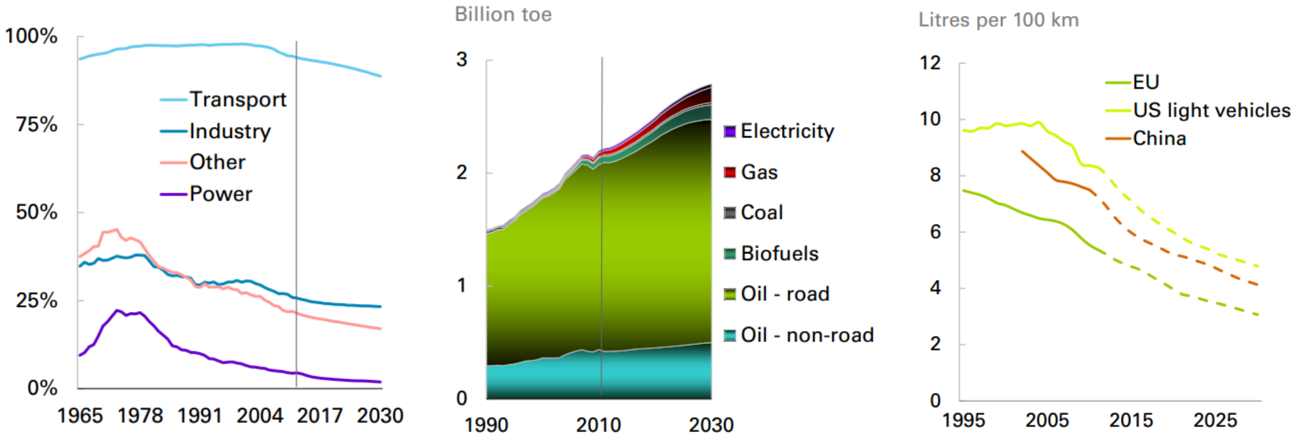


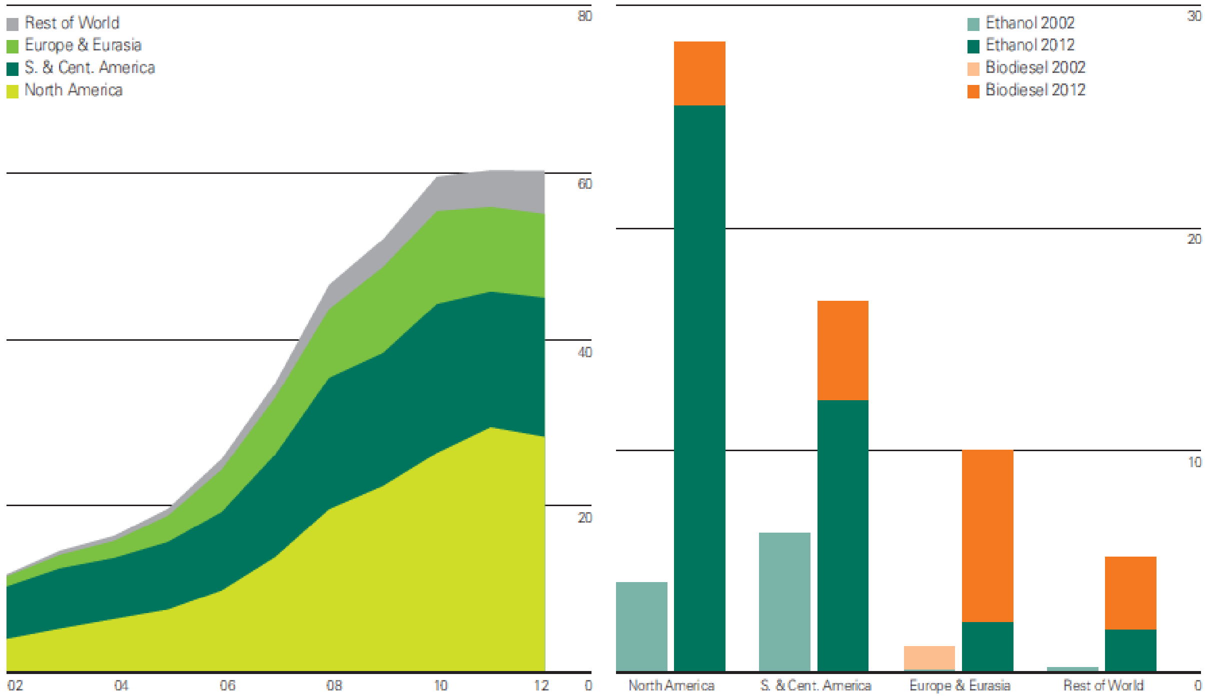
Figure 2 – Oil share per sector (left), transport demand by fuel (center) and fuel economy of new cars (right). (Source: BP world energy outlook booklet. January/2013)



The most affected sector is transportation where today's share is around 94%, demanding a diversification of its energy supply in order to be economically sustainable (see Figure 2 left). Increasing cost of oil makes this sector to look forward alternative solutions that may help to avoid their productivity and efficiency loss, matching also with the rising policies regarding pollutants emission control. It is expected a reduction of at least 5 points in the sector over the oil consumption by 2030 opening the doors to alternate solutions like liquid biofuels [1]. The growth tendency of energy for transport will slow down also due to new enhanced vehicles where fuel economy is an important fact plus the increasing share of biofuels in time (see Figure 2 center and right).

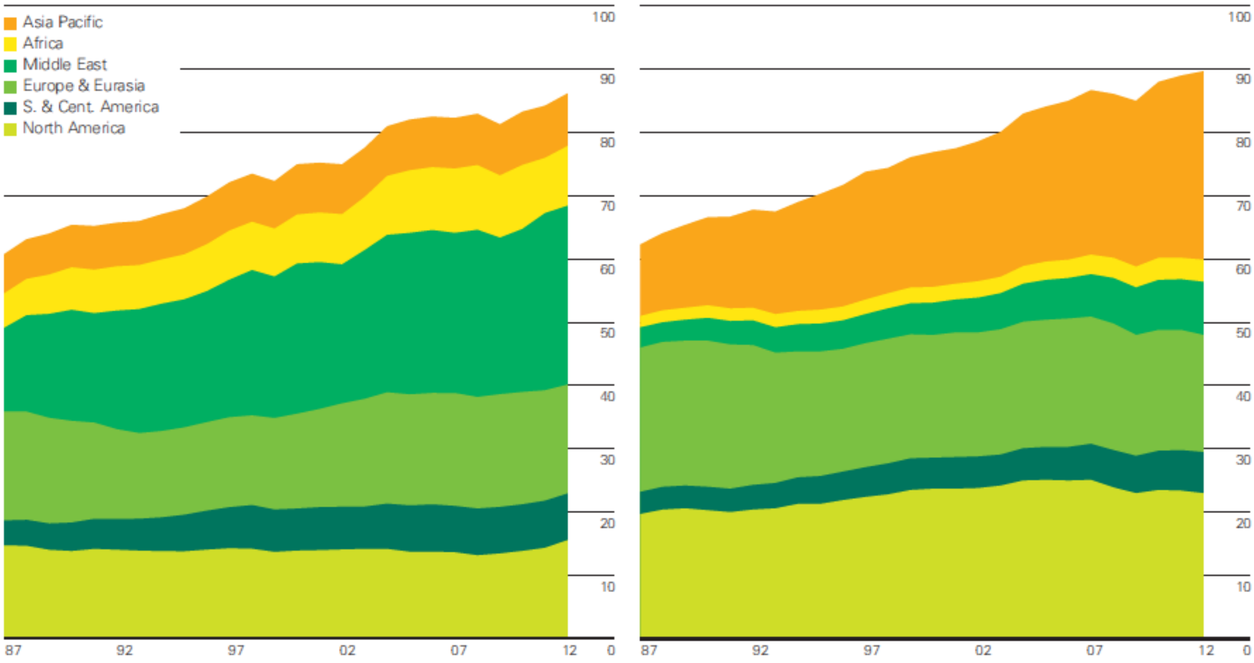
The worldwide trend of the last ten years in terms of biofuel production experienced a huge increase which exploded near 2005 when, as we saw before in Figure 1, the cost of oil started to rise. North America took the leadership and made a great effort in this growth trend followed by South and Central America (mainly drove by USA and Brazil accordingly), both of them with a large share on ethanol as showed in Figure 3 [2]. Europe also started to develop biofuels but in a smaller proportion due to its land and climate availability to grow energy crops that in general terms is very narrow (see Figure 3).

Figure 3 – World biofuels production in Million tonnes oil equivalent (Source: BP statistical review of world energy. June/2013)



Nonetheless of the increasing oil cost and the intensive growth of biofuels due to the latter, during the last two years there has been a slowdown in the biofuel production which, accordingly to the oil production in 2009, as biofuel slows down oil production started to show a new positive slope as well as in oil consumption (see Figure 3 and Figure 4). Before this point in time, it is clear that the oil production and consumption stopped just when the biofuel production slope began to rise strongly, showing the total interdependency between them. All of the above shows up as the path to answer the question: Why biofuels?

Figure 4 – Oil production (left) and consumption (right) by region in Million barrels daily (Source: BP statistical review of world energy. June/2013)



As a particular example, in 2011, a comparison on GHG emissions and energy consumption was executed in China for vehicles run with conventional fuels, electric cars and biofuel cars. The results were that for the current year, biofuel cars showed relatively lower GHG emissions and substantially lower fossil energy consumption. For the same case, a forecast showed that by 2020, thanks to the increasing development of biofuels in China, vehicles running on biofuels will have almost zero fossil energy consumption and GHG emissions [36].

2.2. The feedstocks worldwide

Countries choose their biofuel feedstocks among the most important crop in their country. Since then, the production of these liquid biofuels in the world is being centered on bioethanol and biodiesel, each of them used to blend liquid fuels, where the most remarkable examples today are oil palm in Malaysia and Indonesia, corn in the USA, rapeseed in the EU and sugarcane in Brazil [2].

2.3. Bioethanol

Basically, there are three mechanisms to obtain ethanol from nearly any biomass: fermentation from sugar, saccharification of starch and hydrolysis of cellulosic materials. It is already being used as a fuel additive in certain amounts or even alone. It has clear advantages over conventional fuels like gasoline due to its higher compression ratios, octane rating and increasing the potential to reduce emissions such as NO_x, CO and HC although, in rich blends, special modifications are required in the engine in order to resist to the possible effects of corrosion and polymer degradation caused by alcohols.

Nowadays, ethanol is very common as a biofuel worldwide. It is produced from crops like sugarcane, maize, wheat, sugar beets, etc. Sugar extraction may need high amounts of energy input which in some cases is supplied by a sustainable procedure of energy recovery from the wasted biomass.

All in all, these factors make ethanol a renewable source of energy that helps to reduce the fossil fuels demand. Some of the most important cases are exposed in the following lines focusing on their main characteristics, updated yields data and sustainability issues with a country case.

2.3.1. Sugarcane

Figure 5 – Sugar field (Source: sugarcanecollection.wordpress.com)

It is a perennial grass[3] that is grown in tropical climates and in several types of soils from which sugar is processed. Sugarcane demands a good disposal of water which makes it ideal for regions with high precipitations otherwise irrigation is necessary pushing into an environmental stress due to scarce water supply.

Ethanol from sugarcane has positive impacts due to the elimination of lead compounds from gasoline and the reduction of noxious compounds as well as the decline of CO_2 emissions since its production requires low fossil fuels. CO_2 emissions are almost balanced mainly by their re-absorption during harvesting and the generation of electricity with biomass (bagasse) from the production process avoiding grid usage and its corresponding CO_2 footprint. Fossil fuels are required only in labors of transportation of materials and mechanized harvesting as well as in fertilizers production required for soils.

On the other hand, the future large scale production pushed by the market may lead to destruction of biodiversity and degradation of soils which brings up the sustainability discussion in Brazil which is the largest producer in the world (see Figure 6) [4]. Also, land use change (LUC) of virgin ecosystems to energy crops is a high threat in terms of deforestation, extinction of species, land competition with food crops (being sugarcane also a food crop) and reduction of carbon stock change. LUC from pasture to sugarcane production may push livestock systems to the forest affecting negatively the Carbon stock change.

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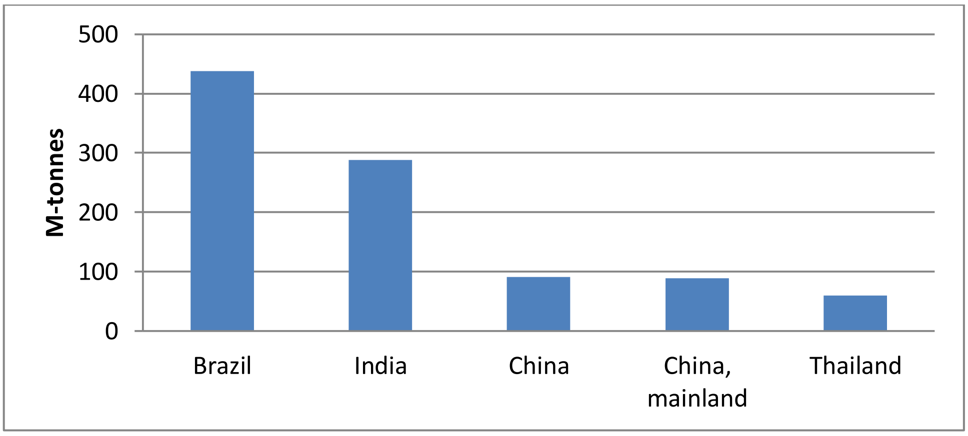
[3] Perennial is a plant that lives for more than two years and has little or no woody growth.

Ethanol is produced through fermentation of sugarcane and then blended with fossil fuels. The great majority of ethanol produced in the world is from sugarcane, mainly in Brazil and it has been used in cars as an octane enhancer and oxygenated additive to gasoline. Brazilian sugar yields amount to about 84.7% tonnes per hectare where 50% of the harvesting procedure is mechanized. It has resulted in positive economic, energetic and environmental indicators, primarily due to high agro industrial yield, recycling of by-products and bagasse energy recovery for electricity [5].

It is estimated that sugar cane is the world´s largest and efficient crop in terms of yield per unit of land. According to the Food and Agriculture Organization of the United Nations (FAO), to the year 2012 over 25,7 million Ha were harvested with a total production of 1,773,8 million tonnes[4] with Brazil being the largest producer in the world (almost 37% of world´s harvested area and 38% of world´s production). It is a source of a wide range of by-products including animal feed, cane wax and fertilizers (besides sugar and ethanol). As stated before, the resulting fibrous bagasse from the sugar extraction process is used in the heat and power generation making the carbon stock change almost neutral.

Figure 6 - Top 5 producers of sugarcane (average values 1992-2012.Source: FAOSTAT 14/11/2013)



In an analysis of GHG emissions and energy flows performed in 2008 for the Brazilian case from a 6 year period (2002-2008) and an expected period (2008 – 2020), taking into account the probable expansions, showed in general terms a sustainable impact. Two trend scenarios were studied setting boundaries around the sugarcane production and the ethanol production. The first one is according to the electricity scenario which follows the technological trend till 2008 where there is a usage of wastes from the process to produce surplus electricity. The second one is a more advanced scenario where the ethanol production is increased by means of hydrolysis of residues reducing the electricity surplus but increasing the ethanol productivity [6].

Large energy ratios were found based on the output energy to the input non renewable energy as reported in Table 1 (energy ratio) till 2008 and it was still expected a growth in this item. The CO_2 eq/m^3 are considerably reduced particularly in the first scenario as can be seen in Table 2 and emissions associated with LUC from croplands and pasture lands are also reduced in the period of study according to Table 3. These facts show the sustainability of this case in terms of energy economics and environment.

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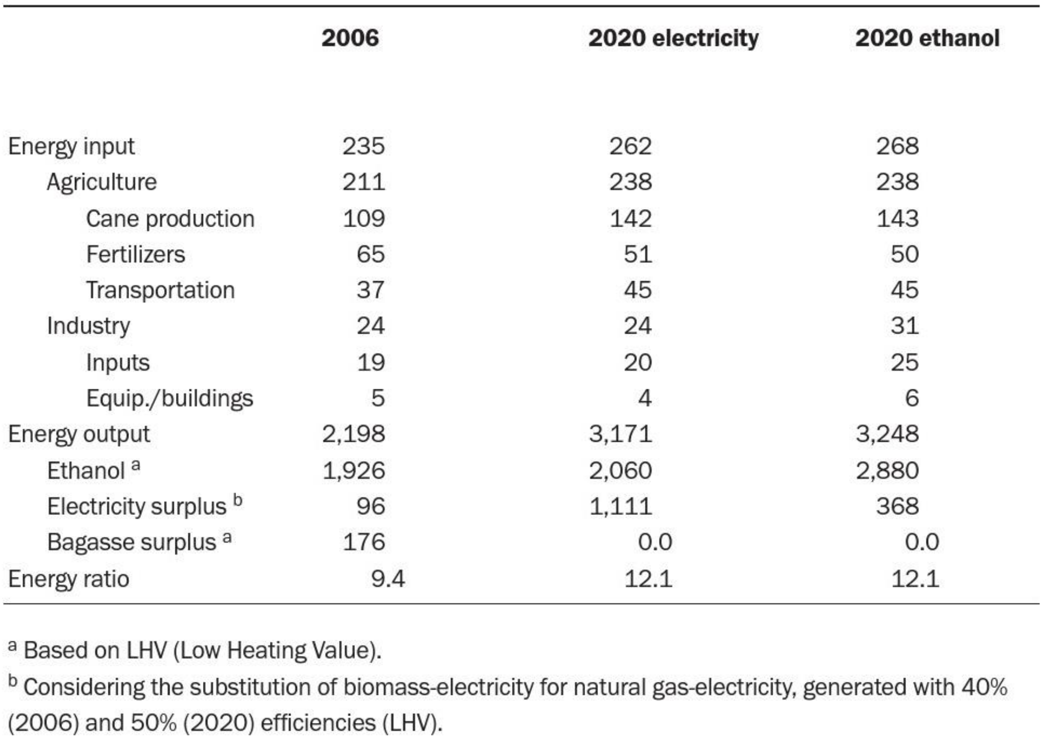
[4] Data retrieved from FAOSTAT 07/11/2013.

Table 1 – Energy balance in anhydrous ethanol production in MJ/t cane (Source: Peter Zuurbier, Jos van de Vooren, 2008. Sugarcane etanol: Contributions to climate change mitigation and the environment. p.100)

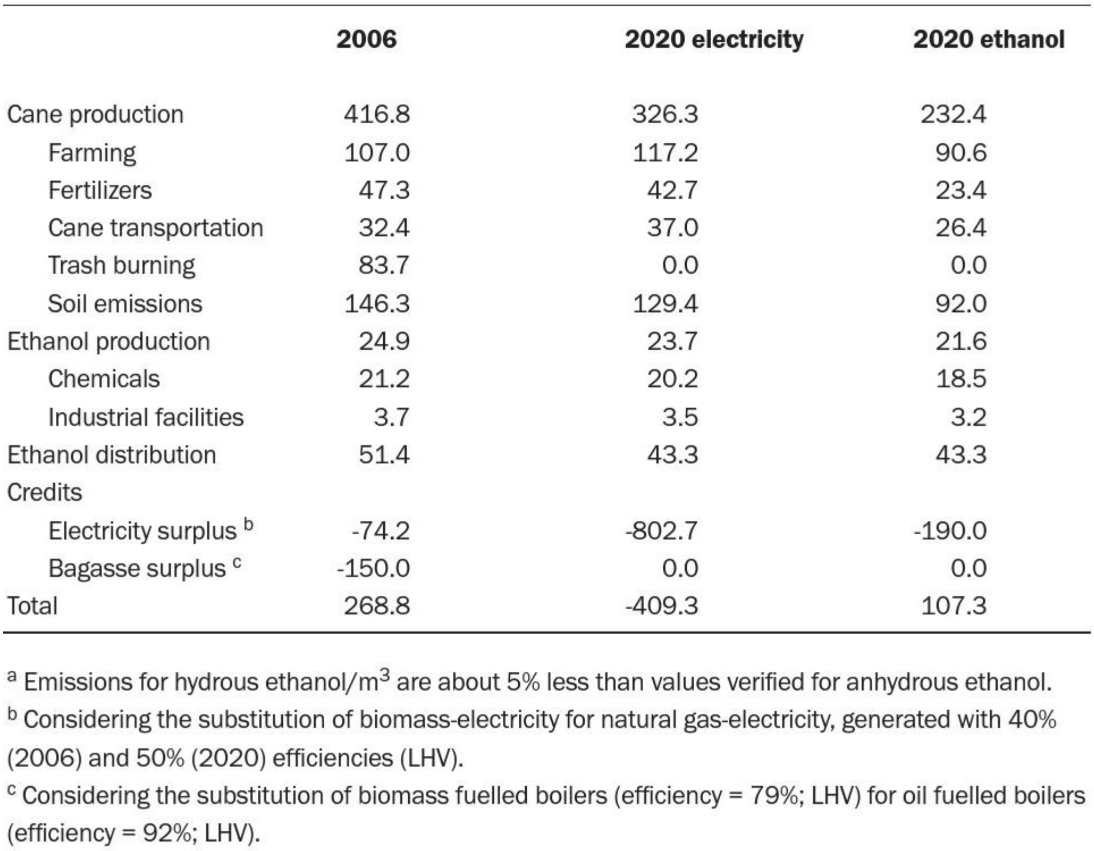


	2006	2020 electricity	2020 ethanol
Energy input	235	262	268
Agriculture	211	238	238
Cane production	109	142	143
Fertilizers	65	51	50
Transportation	37	45	45
Industry	24	24	31
Inputs	19	20	25
Equip./buildings	5	4	6
Energy output	2,198	3,171	3,248
Ethanol [a]	1,926	2,060	2,880
Electricity surplus [b]	96	1,111	368
Bagasse surplus [a]	176	0.0	0.0
Energy ratio	9.4	12.1	12.1

[a] Based on LHV (Low Heating Value).

[b] Considering the substitution of biomass-electricity for natural gas-electricity, generated with 40% (2006) and 50% (2020) efficiencies (LHV).

Table 2 – Total emission in ethanol life cycle in kg CO_2 eq/m^3 anhydrous[a] (Source: Peter Zuurbier, Jos van de Vooren, 2008. Sugarcane ethanol: Contributions to climate change mitigation and the environment. p.101)



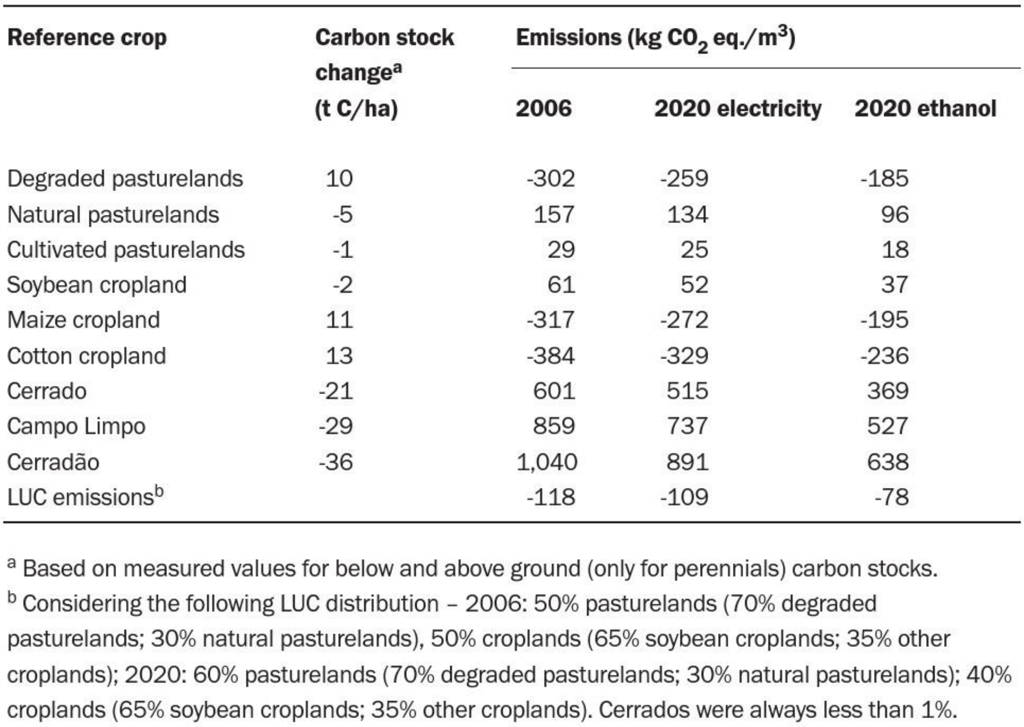
	2006	2020 electricity	2020 ethanol
Cane production	416.8	326.3	232.4
Farming	107.0	117.2	90.6
Fertilizers	47.3	42.7	23.4
Cane transportation	32.4	37.0	26.4
Trash burning	83.7	0.0	0.0
Soil emissions	146.3	129.4	92.0
Ethanol production	24.9	23.7	21.6
Chemicals	21.2	20.2	18.5
Industrial facilities	3.7	3.5	3.2
Ethanol distribution	51.4	43.3	43.3
Credits			
Electricity surplus [b]	-74.2	-802.7	-190.0
Bagasse surplus [c]	-150.0	0.0	0.0
Total	268.8	-409.3	107.3

[a] Emissions for hydrous ethanol/m^3 are about 5% less than values verified for anhydrous ethanol.

[b] Considering the substitution of biomass-electricity for natural gas-electricity, generated with 40% (2006) and 50% (2020) efficiencies (LHV).

[c] Considering the substitution of biomass fuelled boilers (efficiency = 79%; LHV) for oil fuelled boilers (efficiency = 92%; LHV).

Table 3 - Emissions associated with LUC to unburned cane (Source: Peter Zuurbier, Jos van de Vooren, 2008. Sugarcane etanol: Contributions to climate change mitigation and the environment. p.106)



Reference crop	**Carbon stock change[a] (t C/ha)**	**Emissions (kg CO_2 eq./m^3)**		
		2006	**2020 electricity**	**2020 ethanol**
Degraded pasturelands	10	-302	-259	-185
Natural pasturelands	-5	157	134	96
Cultivated pasturelands	-1	29	25	18
Soybean cropland	-2	61	52	37
Maize cropland	11	-317	-272	-195
Cotton cropland	13	-384	-329	-236
Cerrado	-21	601	515	369
Campo Limpo	-29	859	737	527
Cerradão	-36	1,040	891	638
LUC emissions[b]		-118	-109	-78

[a] Based on measured values for below and above ground (only for perennials) carbon stocks.

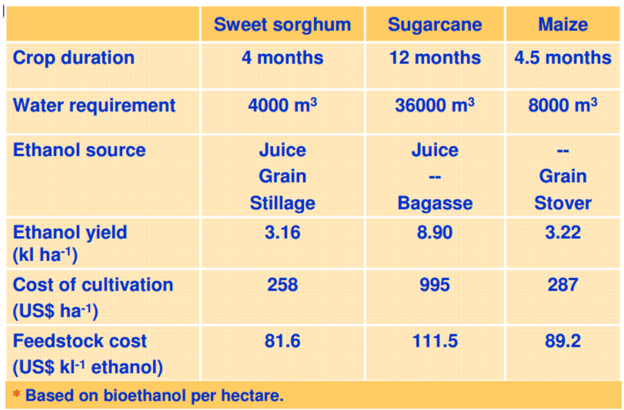
[b] Considering the following LUC distribution – 2006: 50% pasturelands (70% degraded pasturelands; 30% natural pasturelands), 50% croplands (65% soybean croplands; 35% other croplands); 2020: 60% pasturelands (70% degraded pasturelands; 30% natural pasturelands); 40% croplands (65% soybean croplands; 35% other croplands). Cerrados were always less than 1%.

2.3.2. Sweet Sorghum

Figure 7 – Sweet sorghum field (Source: http://www.sweetfuel-project.eu/)

It is one of a variety of sorghum plants which has higher sugar content than the other ones. It is similar to the grain sorghum but with stalks rich in sugar from which ethanol is produced. It is the closest competitor to sugar cane when talking about of yield potential per unit of land, although there is a strong yield variation within the producers around the world, from Table 4 it can be seen that the growing period, ethanol yield, cost of cultivation and water requirements are much lower than those of sugarcane [7]. United States is the largest producer followed by India and Nigeria according to FAO (see Figure 8) and it is the fifth most grown cereal in the world.

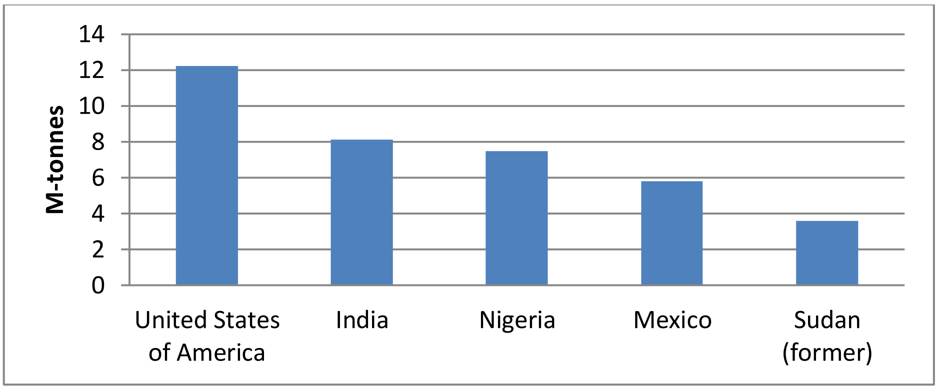
Table 4 – Data retrieved from ICRISAT for Indian case on May 2007.



	Sweet sorghum	Sugarcane	Maize
Crop duration	4 months	12 months	4.5 months
Water requirement	4000 m^3	36000 m^3	8000 m^3
Ethanol source	Juice Grain Stillage	Juice -- Bagasse	-- Grain Stover
Ethanol yield (kl ha^{-1})	3.16	8.90	3.22
Cost of cultivation (US$ ha^{-1})	258	995	287
Feedstock cost (US$ kl^{-1} ethanol)	81.6	111.5	89.2

* Based on bioethanol per hectare.

Figure 8 – Top 5 producers of sorghum (average values 1992-2012 Source: FAOSTAT 07/11/2013)



Sweet sorghum is an annual grass crop which makes it a plant with shorter growth cycles than sugarcane [3].It is known for its versatility on a variety of soils and water conditions and it is very appropriate in tropical areas where it is not too easy to grow sugarcane and risk of drought is present. In fact, it requires low water supplies which makes it very friendly to this resource and also has high resistance to flooding. Due to its low demand on soil quality, nitrogen fertilizers are poorly necessary.

A good characteristic about this plant is the potential to extract from it both, first and second generation bioethanol, fertilizers from the residues, animal and human food, eliminating the possibility of land use competition between these commodities. Also there is space to produce electricity by means of the fibrous residues as in sugarcane. In the southern region of Africa for example, bioethanol shows relatively high potential to be exploited as well as it is considered as a staple[5] crop in the region and traditionally used as animal feed [8]. In the Chinese case, if all the common grain sorghum were replaced by sweet sorghum the productive potentials of ethanol could meet 63.2% to 84.9% of E10 demand and, under their policies of bioethanol production based only on non-grain plants, this matches adequately with their actual needs of energy and food security [9].

The major drawback of this plant is that it is important to be processed as soon as possible because of its imminent sugar content drop in a short period of time. This puts substantial constraints upon

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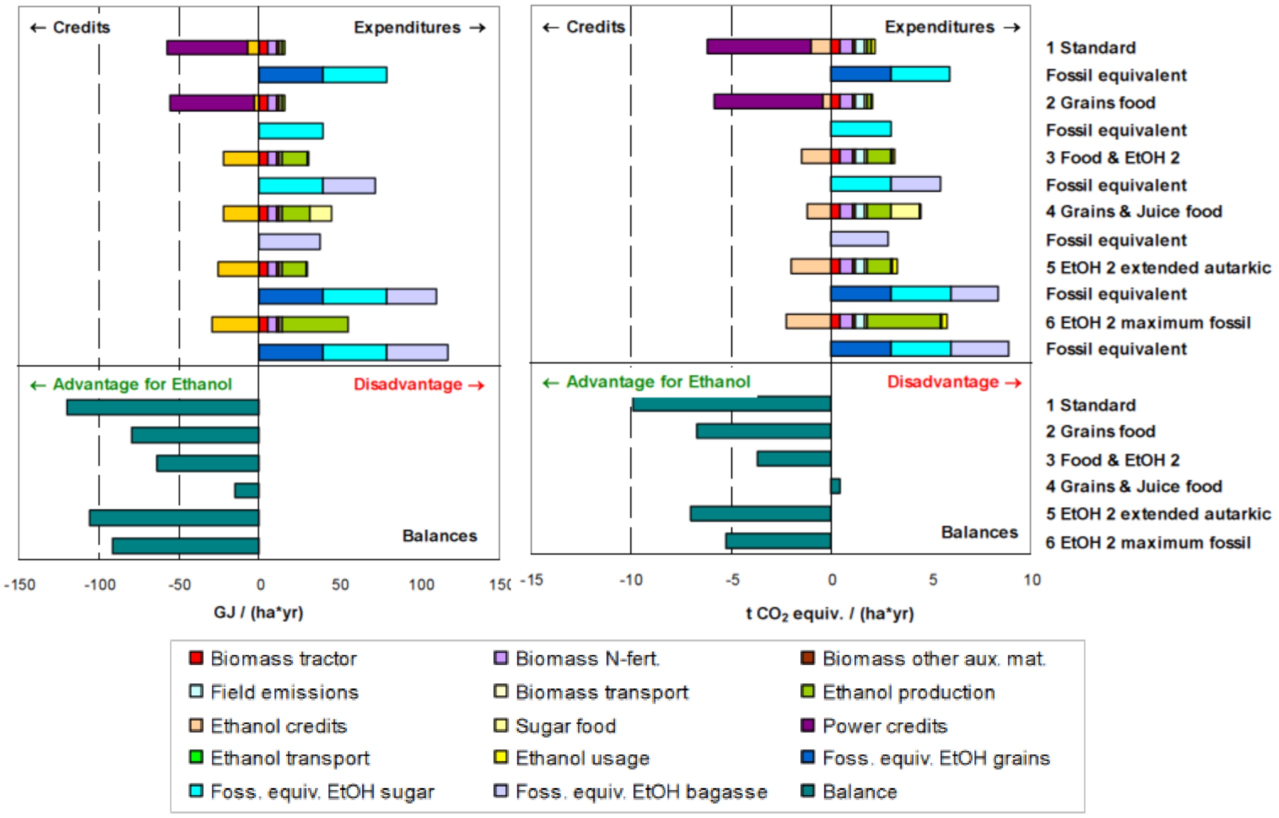
[5] Staple crop is a food considered to be consumed in such quantities that makes it a dominant portion of the basic diet in a determined region or population.

storage and transportation as it is required a quick processing and harvesting camps relatively near to the sugar extraction plants are vital. Also, due to its bulkiness form, it contributes to the storage and transportation limitations imposed by the time variable. A study performed in USA showed that almost 20% of the fermentable sugars can be lost in 3 days at room temperature because of activities of contaminating bacteria [10].

Figure 9 – Results of the life cycle comparison between Sweet Sorghum first and second generation bioethanol and conventional fuel regarding fossil energy savings (left) and GHG saving (right). Upper part: detailed expenditures and credits. Lower part: Resulting advantages and disadvantages for sweet sorghum bioethanol.



An energy and GHG emissions assessment was commended by FAO (2009) for sweet sorghum and its main conclusions were that this plant can contribute significantly to the reduction of fossil fuels dependence and to the mitigation of GHG. In general terms and taking into account the possibility to obtain food, biofuel and energy at the same time, it shows clear advantages over fossil fuels and their impact. Figure 9 shows a combination of raw material usage from sweet sorghum into 6 scenarios producing first and second generation bioethanol, food, bioelectricity and fertilizers. The combination was performed according to final product of each part of the raw material (leaves, grains and bagasse) as just mentioned, including the most important steps of the production process from fertilizers and harvesting to transportation electricity production and final bioethanol production [11].

The assessment also concluded that due to the low water requirement it is good for arid areas as well as the low fertilizer demand gives the plant an advantageous position for bioethanol production, taking care of the possible consequences that may show up under intensive practices. It also points out that thanks to the avoidance of food and fuel competition it is a very promising crop.

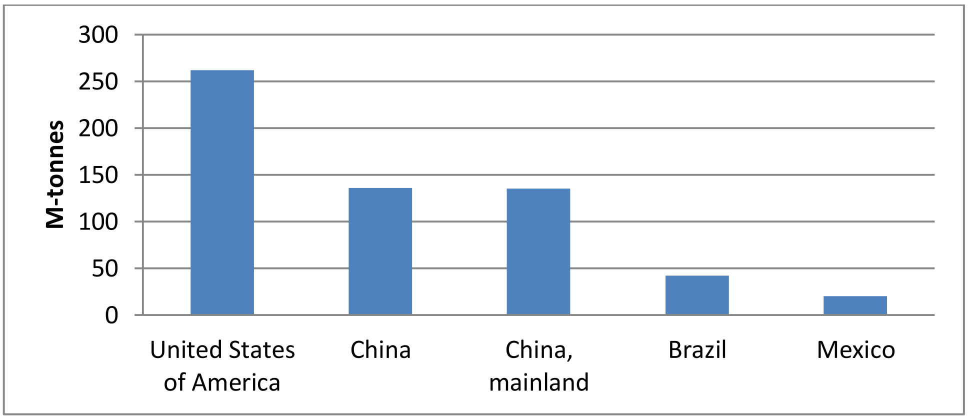
2.3.3. Maize

Figure 10 – Maize field (Source: http://agripb.gov.in/home.php?page=maize)

It is a large grain plant classified as a tall grass originating in the Americas from which after its discovery spread around the globe. It has a solid stem and large narrow leaves. The stalk produces ears which contain the grain that is basically the most popular food throughout the world. Ethanol is produced by means of fermentation and distillation of the milled maize kernel to be then blended with gasoline. There are two types of plants that produce maize ethanol: wet milling plants and dry milling plants. It is used as livestock feed, human food and raw material in industry, which creates direct competition with maize ethanol.

Maize is grown in many locations but mostly in temperate climates. The United States is the top producer with around 40% of world's production followed by China, Brazil and Mexico (see Figure 11). According to FAO reports, it is the largest feedstock for liquid biofuel and USA is also the leader in maize ethanol production which also has pushed the country to affect food prices [3].

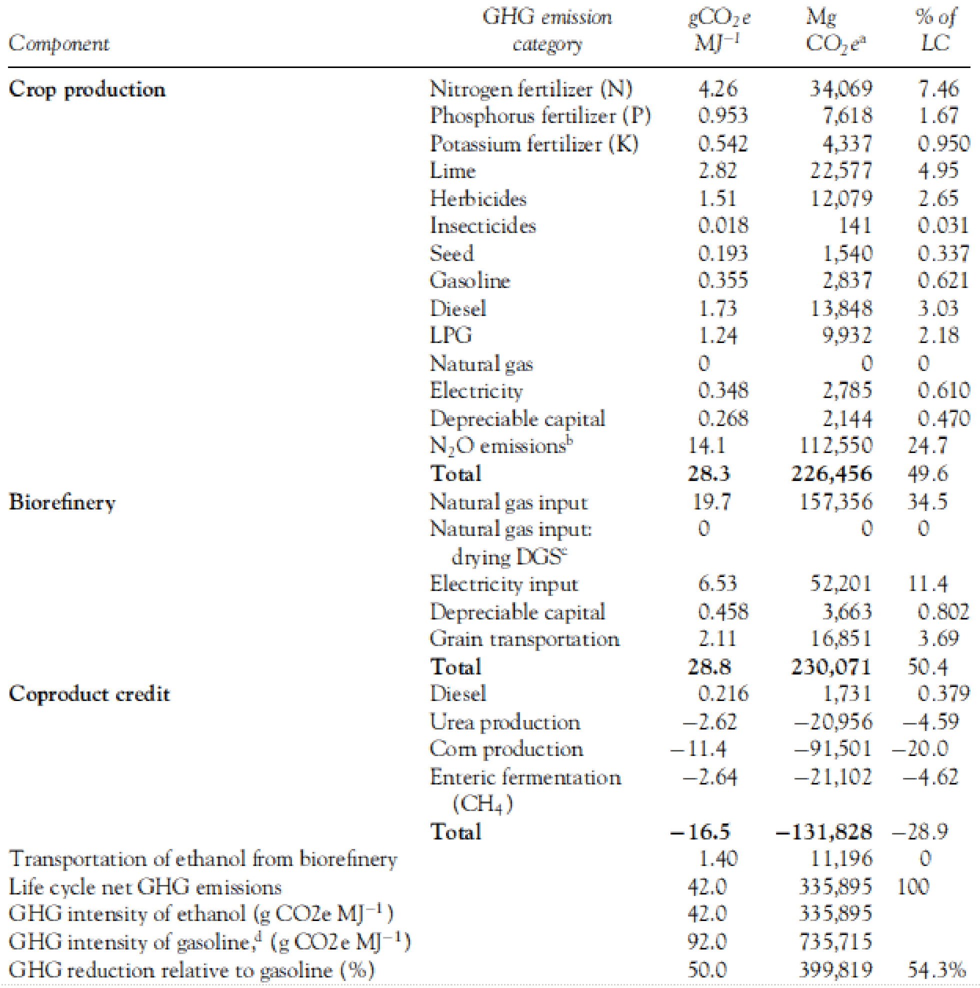
Figure 11 - Top 5 producers of maize (average values 1992-2012 Source: FAOSTAT 25/11/2013)



Maize is a highly productive crop, even more than any other cereal, but its productivity is based on high requirements of fertilizers and pesticides. In USA, the number of maize farming acres remained considerably stable compared to the maize yield per acre between 1980 and 2006. This clear increase in the maize yield comes from better seed variety and much better farming practices while a reduction in fertilizers is noticeable [12]. Nonetheless, the usage of fertilizers and pesticides is very high related to other crops which make maize ethanol be the one with highest demand on these mankind resources as well as more expensive than sugarcane ethanol for example, comparing maize ethanol yields per unit of land to those of sugarcane, maize offer lower ethanol yields [3].

In addition, bearing in mind the advantages of using oxygenated fuels and the relatively low water consumption plus the possible CO_2 sequestration of the farming fields, there are concerns about the negative impacts of maize ethanol. In USA many studies in the area have thrown positive results in GHG emissions but avoiding the LUC issues associated to the conversion of important carbon sinks into crops displaced by maize or maize itself [13]. For example, in a natural gas powered bio refinery in Iowa, USA, GHG intensity was performed settling the boundaries to the crop production and the bio refinery itself, throwing positive results (54.3%) in terms of GHG reduction relative to gasoline (see Table 5) [14]. In this case, although there is a high GHG reduction, there is no sufficient information about LUC to conclude that the general balance of GHG is positive with respect to fossil fuels. According to FAO, maize ethanol has low GHG emissions savings [3].

Table 5 – Greenhouse gas (GHG) emissions inventory of the corn ethanol life cycle (LC) for a dry mill bio refinery in Iowa (Source: p.69 [14])



Component	*GHG emission category*	*gCO₂e MJ⁻¹*	*Mg CO₂e*[a]	*% of LC*
Crop production	Nitrogen fertilizer (N)	4.26	34,069	7.46
	Phosphorus fertilizer (P)	0.953	7,618	1.67
	Potassium fertilizer (K)	0.542	4,337	0.950
	Lime	2.82	22,577	4.95
	Herbicides	1.51	12,079	2.65
	Insecticides	0.018	141	0.031
	Seed	0.193	1,540	0.337
	Gasoline	0.355	2,837	0.621
	Diesel	1.73	13,848	3.03
	LPG	1.24	9,932	2.18
	Natural gas	0	0	0
	Electricity	0.348	2,785	0.610
	Depreciable capital	0.268	2,144	0.470
	N_2O emissions[b]	14.1	112,550	24.7
	Total	**28.3**	**226,456**	49.6
Biorefinery	Natural gas input	19.7	157,356	34.5
	Natural gas input: drying DGS[c]	0	0	0
	Electricity input	6.53	52,201	11.4
	Depreciable capital	0.458	3,663	0.802
	Grain transportation	2.11	16,851	3.69
	Total	**28.8**	**230,071**	50.4
Coproduct credit	Diesel	0.216	1,731	0.379
	Urea production	−2.62	−20,956	−4.59
	Corn production	−11.4	−91,501	−20.0
	Enteric fermentation (CH_4)	−2.64	−21,102	−4.62
	Total	**−16.5**	**−131,828**	−28.9
Transportation of ethanol from biorefinery		1.40	11,196	0
Life cycle net GHG emissions		42.0	335,895	100
GHG intensity of ethanol (g CO2e MJ^{-1})		42.0	335,895	
GHG intensity of gasoline,[d] (g CO2e MJ^{-1})		92.0	735,715	
GHG reduction relative to gasoline (%)		50.0	399,819	54.3%

From the energetic point of view, maize ethanol has a high consumption of primary energy in the farming process and in the ethanol production process. Farming requires high quantities of chemicals which are fossil energy bearers as well as the harvesting machinery used that requires fossil energy to work. On the other hand, ethanol production plants are powered by other sources of energy like natural gas, coal or biomass in the USA [12].

In a well to wheels analysis[6] (comparing gasoline with ethanol) in the USA for different types of production plants, a clear reduction is observed in the fossil energy use. The analysis was split in two parts, a well to pump section (WTP) which comprises the processes (harvesting or extraction, refinery and transportation to pumps) and then a pump to wheels section (PTW) which basically is the consumption of fuel in vehicles (see Figure 12). Clearly there is a reduction on fossil fuel usage even though farming and production are high energetic costs.

Figure 12 – Well to wheels fossil energy use of ethanol and gasoline (Btu per million Btu of fuel produced and used) Source: p.9 [12]

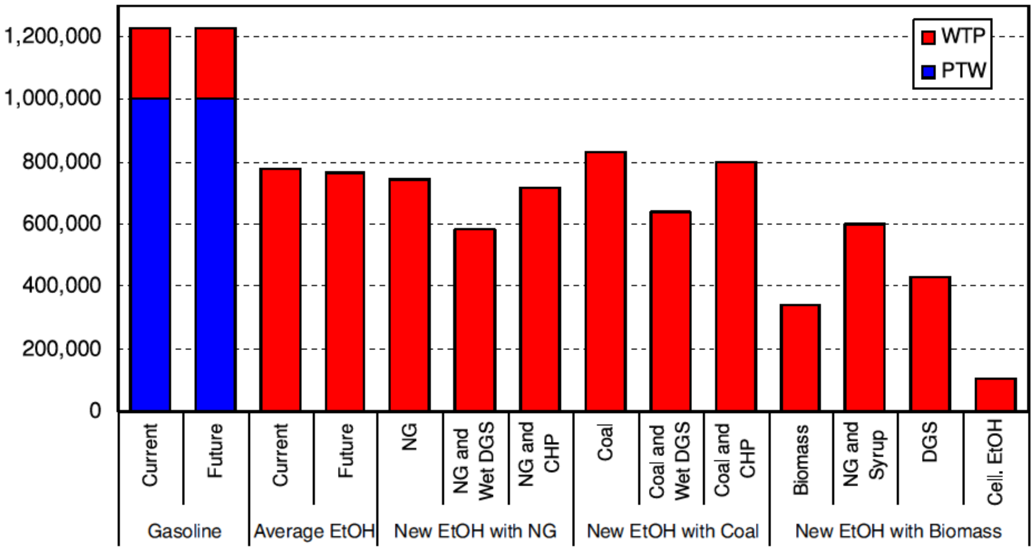
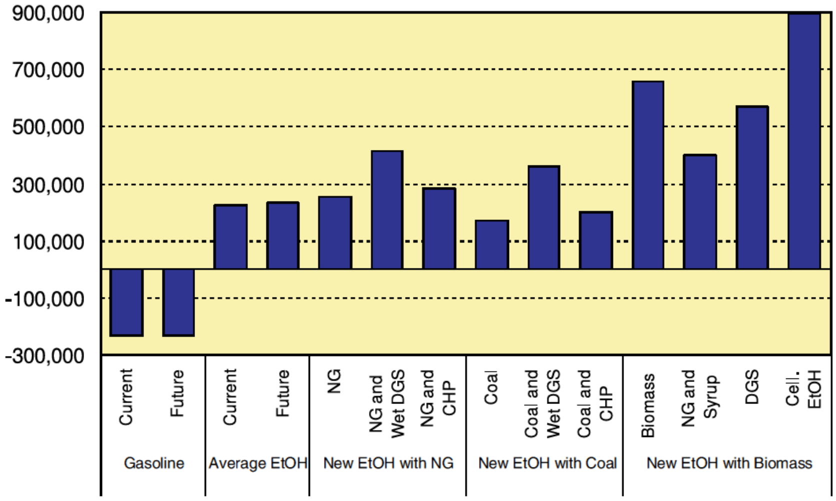


Figure 13 – Fossil energy balance per million Btu of ethanol and Gasoline (1 million Btu in ethanol minus fossil Btu used to produce ethanol and the fossil Btu embedded in ethanol). Source: p.10 [12]



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[6] It is a specific Life cycle assessment (LCA) for transport fuels. It is used to assess the total energy consumption or the energy conversion efficiency and environmental impact emissions of a fuel from its origin (well) to its final consumption (wheels).

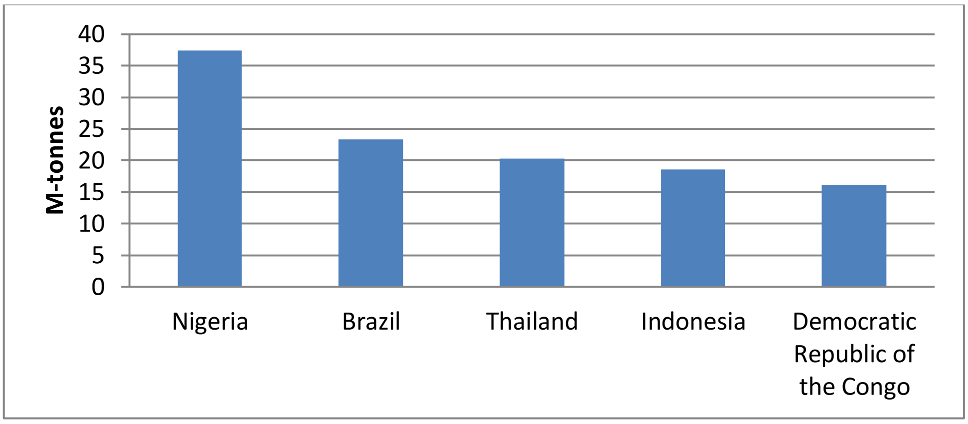
As a final result of the study stated before, there is a positive energetic balance in all the maize ethanol harvesting and production processes (see Figure 13), which makes it a sustainable energy source. The energy produced embedded in the final fuel with respect to the one used to produce it leaves a positive difference. Still, in the environmentally area, its sustainability is to be discussed in more detail due to the scarce information on LUC and the agriculture intensity of maize, specifically in the USA case which is the largest maize ethanol producer in the world.

2.3.4. Cassava

Figure 14 – Cassava species (Source: http://www.agenciabrasil.gov.br/media/imagens/2008/01/25/1732JC129.jpg/view)

It is a perennial, tuberous[7] and edible crop which is cultivated in the tropic and subtropics areas, principally in Africa but also in Latin America and Asia. It is from its numerous tuberous roots made up of starch that the main cassava products are extracted from, due to their high nutrients (major source of carbohydrates) and energy contents. It is a very drought tolerant crop which has a good capacity to overcome pests and diseases as well as to be grown in both sands and clays with limited fertility. In developing countries, it is an important stable crop (almost 12% of daily calories per capita in sub Saharan Africa) [3]. Nigeria is the largest producer in the world followed by Brazil, Thailand and Indonesia (see Figure 15).

Figure 15 - Top 5 producers of cassava (average values 1992-2012 Source: FAOSTAT 28/11/2013)



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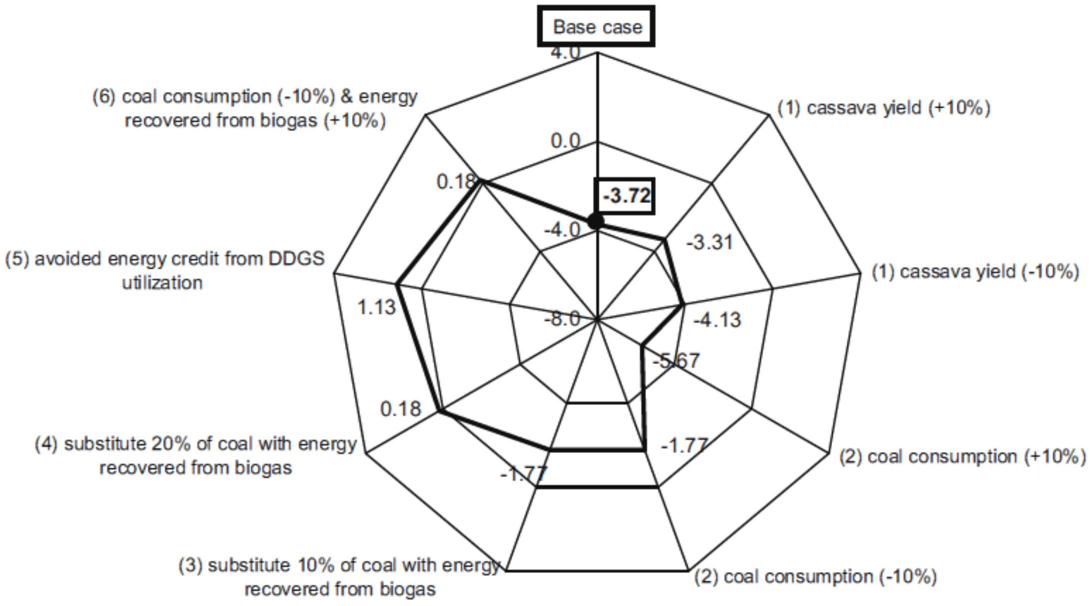
[7] Plants which have developed structures were they store nutrients for the dry or cold seasons.

Basically, ethanol is produced from cassava by means of the following processes: milling and mixing for a following saccharification and fermentation to then refine by distillation. The final product is a 99.5% ethanol with co-products like CO_2, animal feed, biogas and manure [15]. As in the case of sweet sorghum, this crop also has the major drawback of sugar drop once harvested, which imposes and immediate process of sugar extraction avoiding as much as possible storage and transportation periods.

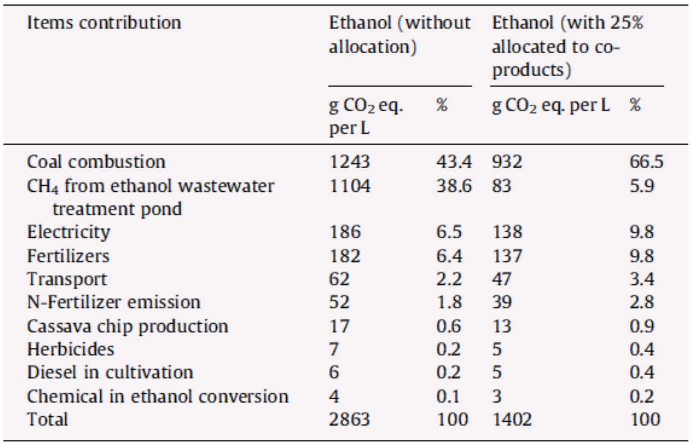
An example of relatively low efficiency is Thailand which, to the year 2008, was taking advantage of their relatively high cassava production to produce their own bioethanol, following a national policy to reduce their high dependence on fossil fuels. A life cycle of energy and environmental analysis was performed starting from the agricultural stage till the ethanol conversion stage. It showed up that the energy input to the process was higher than that one produced and embedded in ethanol, producing a poor energy ratio (less than the unity) [15]. This was mainly caused by the usage of fuels like coal in the ethanol conversion and the waste of co-products with any energy recovery on them. The study was conducted to show how alternative solutions could help to increase this ratio, for example using biogas to replace 20% of coal required (see Figure 16).

Figure 16 – Sensitivity analysis of factors related to the net energy gain in Thailand (Source: S115 [15])



Nonetheless in the Thai case, the energy ratio remains low compared to other biofuels and shows how, in order to gain positive results from ethanol fuel production, special attention should be take on the high fossil energy consumers of the entire process. As a consequence, the environmental impacts are not reduced due to the coal usage. As it can be seen from Table 6, a reduction could be achieved in the case of using some of the energy wasted in the co-products of cassava ethanol production. The use of biogas from wastewater for energy production greatly affects GHG emissions and shows a path to real sustainability of cassava ethanol in Thailand but greater efforts are required [16].

Table 6 – Life cycle GHG emission of 1 L anhydrous ethanol production in Thailand (Source: S116 [15])



Items contribution	Ethanol (without allocation)		Ethanol (with 25% allocated to co-products)	
	g CO_2 eq. per L	%	g CO_2 eq. per L	%
Coal combustion	1243	43.4	932	66.5
CH_4 from ethanol wastewater treatment pond	1104	38.6	83	5.9
Electricity	186	6.5	138	9.8
Fertilizers	182	6.4	137	9.8
Transport	62	2.2	47	3.4
N-Fertilizer emission	52	1.8	39	2.8
Cassava chip production	17	0.6	13	0.9
Herbicides	7	0.2	5	0.4
Diesel in cultivation	6	0.2	5	0.4
Chemical in ethanol conversion	4	0.1	3	0.2
Total	2863	100	1402	100

In addition, the amount of fresh water embodied in each ton of crop is relatively high compared to the amount of sugarcane in Thailand which, in a country moving towards bioenergy, puts high stress on this resource causing a possible scarcity [17]. Similar situation was described in another study in the sense of sustainable use of water resource in Nigeria for the production of cassava ethanol [18].

Another disadvantage may rise from the fact that intensive agriculture of cassava requires high amounts of fertilizers and harvesting machinery. As already discussed before, fertilizers demand huge amount of energy as well as high GHG emissions may appear, plus the fossil energy used to power the agricultural machines. Also LUC should be taken into account in case of intense agriculture to obtain a sustainable energy resource that matches with the objective of fossil fuel reduction.

2.4. Biodiesel

It is made out of vegetable oils mainly through a process of trans-esterification in which the oil extracted from the plant is mixed at adequate temperatures and pressures with methanol to produce fatty acid methyl ester (FAME) and glycerin, being FAME the biodiesel itself. In order to match with higher conversion efficiencies this process is done with the presence of a catalyzer medium which decreases the activation energy of the reaction. Crude vegetable oil could be used directly into the engine but a poor engine performance has been proven due to the low volatility of the oil extracted and the high viscosity [32]. Trans-esterification of triglycerides and esterification of free fatty acids (FFA)[8] show up as processes to improve the fuel quality and to match them to the standards required (see Table 7).

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[8] Fatty acids are derived from triglycerides of the vegetable oil and when they are not attached to other molecules are called "free". FFA can be esterified through and acidic catalyst to yield more biodiesel.

Table 7 – Specification of biodiesel for US, European countries and India (Source: p.399 ref. [32])

Sl. no.	Properties	EN 14214-2008	IS 15607-2005	ASTM D 6751-09
1.	Density @15 °C, kg/m^3	860–900	860–900	n.s.
2.	Kinematic viscosity at 40 °C, cSt	3.5–5.0	2.5–6.0	1.9–6.0
3.	Flash point, °C, *min*	101	120	93
4.	Sulfur, ppm, *max*	10	50	15
5.	Carbon residue, % by mass, *max*	0.3	0.05	0.05
6.	Sulfated ash, % by mass, *max*	0.02	0.02	0.02
7.	Water content, ppm, *max*	500	500	500
8.	Total contamination, ppm, *max*	24	24	n.s.
9.	Copper corrosion, 3 h at 50 °C, *max*	1	1	3
10.	Cetane number, *min*	51	51	47
11.	Acid value, mgKOH/g, *max*	0.5	0.5	0.5
12.	Methanol, % by mass, *max*	0.2	0.2	0.2
13.	Ester content, % by mass, *min*	96.5	96.5	n.s.
14.	Linolenic acid methyl ester, % by mass, *max*	12	n.s.	n.s.
15.	Polyunsaturated (≥ 4 double bonds) methyl esters, % mass, *max*	1	n.s.	n.s.
16.	Monoglyceride, % by mass, *max*	0.8	n.s.	n.s.
17.	Diglyceride, % by mass, *max*	0.2	n.s.	n.s.
18.	Triglyceride, % by mass, *max*	0.2	n.s.	n.s.
19.	Free glycerol, % by mass, *max*	0.02	0.02	0.02
20.	Total glycerol, % by mass, *max*	0.25	0.25	0.24
21.	Phosphorus, ppm, *max*	4	10	10
22.	Sodium and potassium, ppm, *max*	5	To report	5
23.	Calcium and magnesium, ppm, *max*	5	To report	5
24.	Iodine value, gI_2/100 g, *max*	120	To report	n.s.
25.	Oxidation stability at 110 °C, h, *min*	6	6	3
26.	Cloud point, °C	n.s.	n.s.	To report
27.	Distillation T90 AET, °C, *max*	n.s.	n.s.	360
28.	Cold soak filtration test, s, *max*	n.s.	n.s.	360 (and 200 for use in temperature below −12 °C)

n.s: not specified.

In detail, the process starts after the harvesting point when the crops are cleaned, dried and then the oil is extracted from the plant. Oil pretreatment may be required to increase the conversion rate and then trans-esterification takes place. The general trans-esterification reaction is one mole of triglyceride reacts with 3 moles of methanol to produce 3 moles of FAME and one of glycerin. Then a purification process is performed in which glycerol is separated from the FAME as well as the excess of methanol used in the main reaction, usually by means of water since it solves all the compounds except FAME. As by-products, glycerin is purified for other industrial processes and recovered methanol is recycled into the main process. Also, after the oil extraction from the plants, the remaining solid part (cake) may be used as fertilizer or depending on the plant characteristics the residues may be used as fuel in a boiler for power generation cycles or combined heat and power cycles (CHP).

In general, the energy requirements of the entire process comprise the energy embedded in the agricultural stage (harvesting machines, fertilizers), the energy used in the oil extraction process (milling machines) and the one used in the conversion step (the reaction needs to be warmed and continuously mixed with methanol which, in addition, might come from either a renewable source or a fossil source). As a consequence, energy balances should be run so to evaluate the real sustainability of the biodiesel production based on the amount of primary energy per energy in the final fuel.

The main advantage of biodiesel is the possibility to replace 100% of the fossil diesel fuel reducing both the fossil energy dependence and the pollutants formation during combustion thanks to its higher cetane number (oxygenated fuel) and lower sulphur content. However, to achieve this, modifications should be done on the engines so that the materials are fully compatible with this fuel as well as the engine performance optimized to the biofuel physic and chemical properties. In the GHG scenario, reduction is expected in the sense that CO_2 is to be used in the photosynthesis process of the energy crops bearing in mind the previous discussion on ethanol and GHG emissions due LUC.

In 2012, United States was the leading producer followed by Argentina, Brazil, Germany and France in a variety of crops while in a regional scale Europe is clearly the leader producer [19]. In the following lines, special attention is given to the most important biodiesel crops in the world with their basic characteristics, environmental and energetic advantages, sustainability issues as well as some producer countries are briefly stretched out.

2.4.1. Rapeseed

Figure 17 – Rapeseed field (Source: http://oiltransit.org/products/rapeseed-oil/)

Rapeseed is a plant that grows in temperate regions, cultivated for the production of biodiesel, edible vegetable oil and animal feed. It is grown during the winter season and provides a good coverage of the soil limiting Nitrogen to run out. The plant bears four petaled yellow flowers in spikes where each of them contains many seeds, carries of the oil. According to FAO, Canada is the highest producer in the world followed by China, India and France (see Figure 18). Nonetheless, EU countries are the ones with highest yields (g/Ha) pushing them to the leadership on biodiesel production (see Figure 19) in the world. This fact makes Rapeseed the most important biodiesel among the world.

Figure 18 - Top 5 producers of Rapeseed (average values 2012 Source: FAOSTAT 30/11/2013)

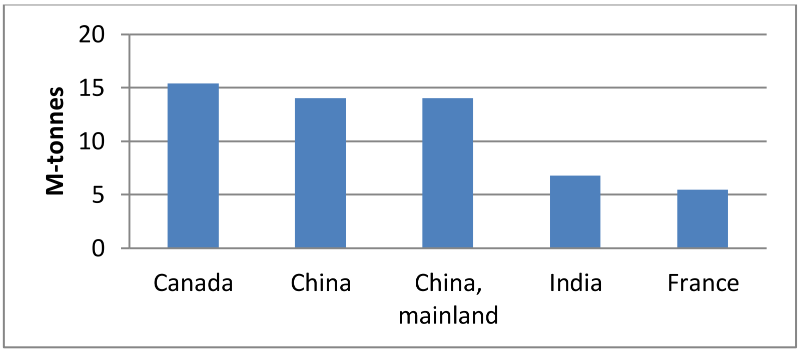
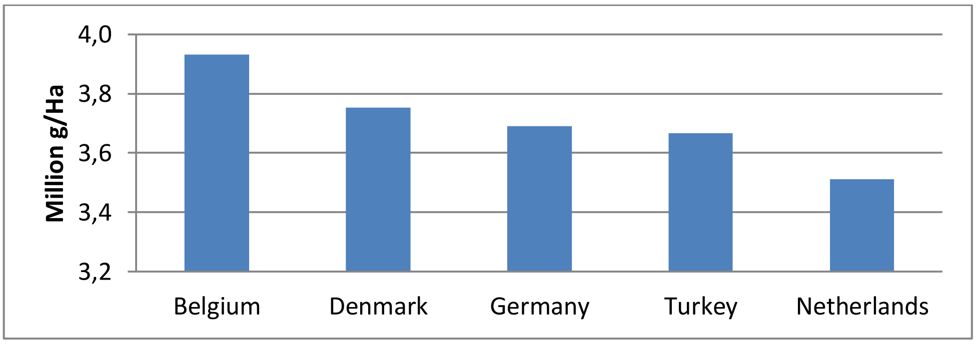


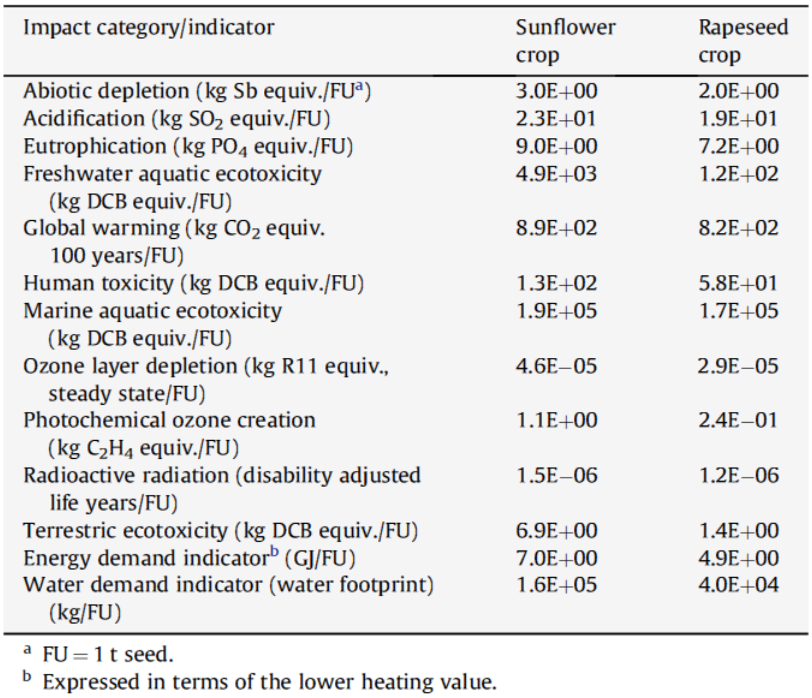
Figure 19 – Countries delivering the highest yields (average values 2012 Source: FAOSTAT 30/11/2013)



The main extraction process starts by decreasing the water content in the seeds to 9% followed by a seed cleaning and toasting process for then finally get squeezed. Rapeseed biodiesel is obtained by trans-esterification with glycerin as the main by-product. From the plant, straws are considered also as by-products as well as the seed cake and waste waters which serve as fertilizers and animal feed. As a first generation biodiesel, LUC issues need to be considered to avoid GHG emissions caused by possible deforestation and by-products help in the mitigation of them.

In a lifecycle assessment performed in Chile to compare energy crops, rapeseed showed a better environmental performance and lower water consumption [20]. Energy conversion efficiency in the production of rapeseed is reported to be the highest (5.0) measured as a ratio of energy output (biofuel) to the energy input of the entire process. Water footprint also shows to be considerably the lowest. It is concluded that the major driving force on the impacts and energy requirements are due to the fertilizers required. However, the general balance makes this energy crop an environmental sustainable alternative for Chile (see Table 8).

Table 8 – Potential environmental impacts and energy and water indicator of rapeseed and sunflower in Chile (Source: p.341 ref. [20])



Impact category/indicator	Sunflower crop	Rapeseed crop
Abiotic depletion (kg Sb equiv./FU[a])	3.0E+00	2.0E+00
Acidification (kg SO_2 equiv./FU)	2.3E+01	1.9E+01
Eutrophication (kg PO_4 equiv./FU)	9.0E+00	7.2E+00
Freshwater aquatic ecotoxicity (kg DCB equiv./FU)	4.9E+03	1.2E+02
Global warming (kg CO_2 equiv. 100 years/FU)	8.9E+02	8.2E+02
Human toxicity (kg DCB equiv./FU)	1.3E+02	5.8E+01
Marine aquatic ecotoxicity (kg DCB equiv./FU)	1.9E+05	1.7E+05
Ozone layer depletion (kg R11 equiv., steady state/FU)	4.6E−05	2.9E−05
Photochemical ozone creation (kg C_2H_4 equiv./FU)	1.1E+00	2.4E−01
Radioactive radiation (disability adjusted life years/FU)	1.5E−06	1.2E−06
Terrestric ecotoxicity (kg DCB equiv./FU)	6.9E+00	1.4E+00
Energy demand indicator[b] (GJ/FU)	7.0E+00	4.9E+00
Water demand indicator (water footprint) (kg/FU)	1.6E+05	4.0E+04

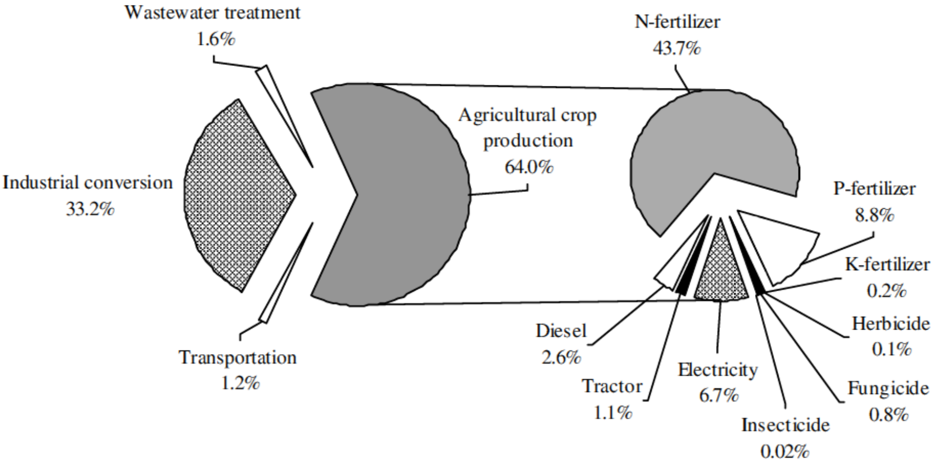
[a] FU = 1 t seed.

[b] Expressed in terms of the lower heating value.

Same conclusion arise in an environmental life cycle assessment of rapeseed in four different countries (Spain, Germany, France and Canada), from which although the variation of agricultural procedures and production processes affect the final results, the main result was that the use of fertilizers and associated soil emissions are the main contributions to the environmental impact [21].

Low yields and high fertilizers requirement appear in some countries in the rapeseed production. China is the second largest producer of rapeseed in the world (Figure 18) but its net energy balance is negative. In an energy cost study of the entire process, the low rapeseed yield and the intensive chemical fertilizer use pushed up the primary energy input, resulting in a cost of 1.1 times the energy embedded in the output fuel [22]. According to this fact, although China is a large rapeseed producer, it is not sustainable due to its poor energy conversion based on the low yields and high fertilizers use (see Figure 20).

Figure 20 – Energy cost fractions for rapeseed biodiesel in China (Source: p.1377 ref. [22])



2.4.2. Oil palm

Figure 21 – Oil Palm (Source: www.greenassembly.net)

Oil palm is a tree known as an important crop that yields important sources of food and animal feed. Basically these source are palm oil, palm kernel oil and palm kernel cake in which the first to are for human consumption and the latter for animal feed. There are two main varieties, namely the African palm and the American palm. The African has many tiny flowers crowded on short branches that develop into a large cluster of oval fruits. The American is like the African with respect to flowers and fruit but the trunk creeps along the trunk while the African has a straight trunk and the leaves are quite different so that in overall, they look relatively dissimilar. As such, they are tropical forest plants adapted to temperatures between 24°C and 30°C and 1780 to 2280 mm of rainfall per year [3].

The palm fruit is composed by a kernel surrounded by a mesocarp[9] and pulp (endocarp) and grows in bunches of up to 2000 fruits. Edible oil is extracted from the pulp while the kernel may be used in the soap industry. From the energetic point of view, both types of oil can be transformed to biodiesel while the stem is used as fuel for power generation combined with empty fruit bunches and oil palm fibers. Also, residues from the oil extraction process can be used to produce biogas, animal feed or as fertilizers to improve soil quality. In order to achieve high yields, a good water supply is essential which may put stress over this natural resource and negatively impact its availability, reason why it is preferable grown in high rainfall regions. Indonesia and Malaysia are the largest producers in the world (see Figure 22) but Guatemala and Colombia report the highest yields closely followed by Malaysia (see Figure 23).

Figure 22 - Top 5 producers of Oil Palm (average values 2012 Source: FAOSTAT 30/11/2013)

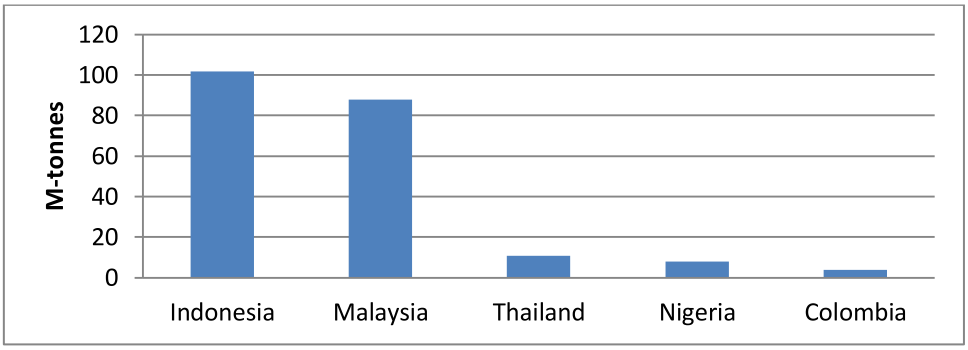
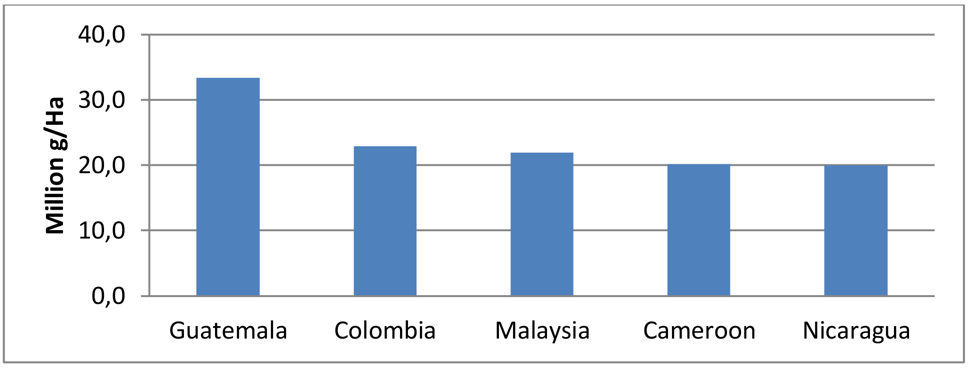


Figure 23 - Countries delivering the highest yields (average values 2012 Source: FAOSTAT 30/11/2013)



During the growth of the trees, large quantities of CO_2 capture occurs in the fields while the fertilizers used to the agricultural stage, throw to the environment GHG when they are produced and applied in the soils. In a GHG balance for crude palm oil in a northern region of Brazil, it was found that the major source of GHG emissions were in the stages of agriculture and oil extraction (see Figure 24) thus, in order to mitigate emissions, improvements should be done in their overall performance. In the same study, synthetic and residues fertilizers were compared resulting in a net

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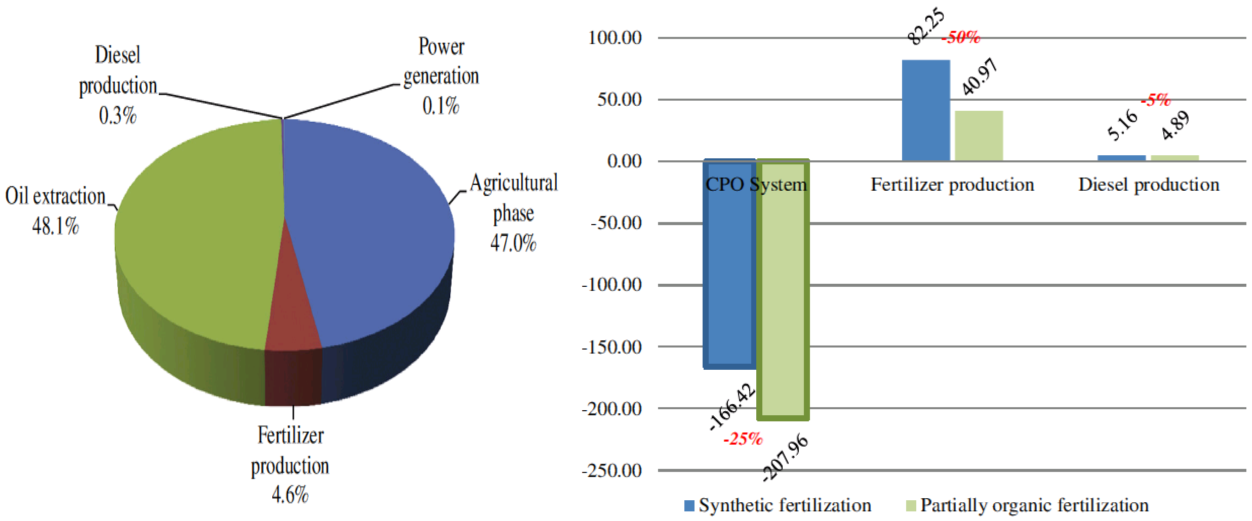
[9] Botanical term for the middle layer of the fruit between the endocarp and the exocarp. Fleshy layer of the fruit.

reduction of environmental impact. Nevertheless, the entire process was found sustainable with a GHG balance of approximately -208 kg CO_2eq per 1000 kg of crude oil palm per year [23]. From the same scope, Thailand has negative balance in GHG emissions due to LUC which means a reduction in emissions [24].

Figure 24 – GHG emission distribution from the palm oil production system (left) and GHG balance in the crude palm oil system using composting residues as substitutes for synthetic fertilizers in Brazil (Source: p.520 ref. [23])



Although palm oil brings a positive contribution in terms of energy security and environmental sustainability, firsts generation biodiesel brings up the discussion on the possibility of rising up food prices. In Thailand, as a matter of fact, the implementation of palm oil biodiesel has a minimal effect on palm oil price but it created a negative effect on the socio economic area [25]. In the mexican case, a cost-benefit analysis pointed out in 2009 that the substitution of diesel fuel with palm oil biodiesel is only affordable if subsidies or incentives from the government are present [26]. This fact in addition with the possible rise on food prices cause a negative socio economic impact which needs to be discuss.

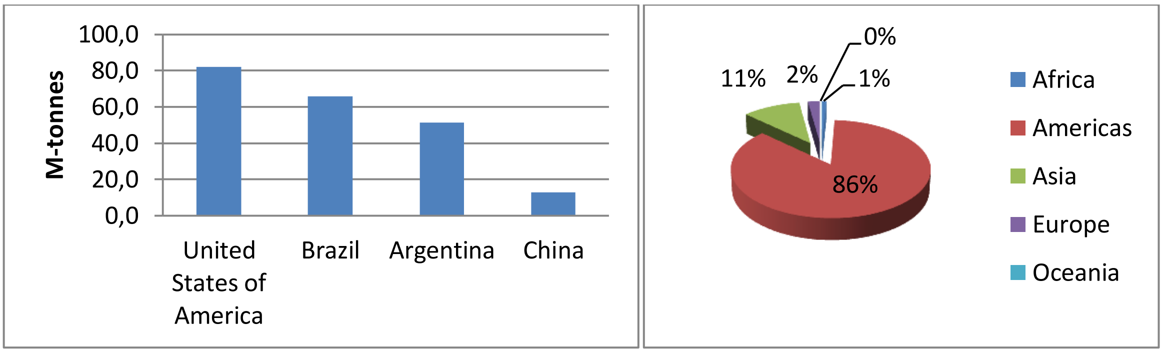
2.4.3. Soybean

Figure 25 – Soybean plant (Source: 1st-ecofriendlyplanet.com)

Soybean is specie of legume and as such, it is grown primarily for their food grain seed, for livestock forage and silage, soil enhancing green manure and biodiesel from seed oil. It is an annual legume which is grown in temperate regions and subtropics where it is usually rain fed, reducing to a minimum or even no irrigation requirements at all as it is drought resistant for short periods. It contains specific bacteria in its root system which is capable of fixing nitrogen from the atmosphere making them Nitrogen sources and increasing their plant proteins, thus providing big savings in Nitrogen fertilizers. It is by far the most important bean in the world providing vegetable protein for human consumption and as ingredients of chemical products, taking advantage of their relative low cost production. Soybean oil yield is relatively low compared to other oils like palm oil and it is the third most important after rapeseed and palm oil with approximately 19% of oil content [3].

Soybean oils are cracked and dried to optimum water content for oil production and then in a mechanical process oil is extracted and later refined. In 2008 biodiesel production from soybean accounted for about 25% of the global biodiesel production and it represented from 75% to 90% of the total biodiesel production in United States. By the year 2012, United States was the largest producer of soybean in the world (see Figure 26) followed by Brazil and Argentina, pushing the Americas to be the leaders of soybean production in the world and giving them the opportunity to develop a sustainable energy resource via soybean biodiesel.

Figure 26 - Top 5 producers of Soybean (left) and world production share (right) (average values 2012 Source: FAOSTAT 01/12/2013)



As in the previous scenarios of biofuels, in the soybean case the major primary energy consumption of the entire production process is based on the agricultural stage and in the conversion stage. A lifecycle assessment in Iran showed that, although there is a big share of the energy consumption and GHG emissions in those two production stages (see Figure 27 and Figure 28), the final energy and GHG balance show up with positive values looking forward a sustainable production [27].

Figure 27 – Energy cost contributions for biodiesel production in Iran (Source: p.7 ref. [27])

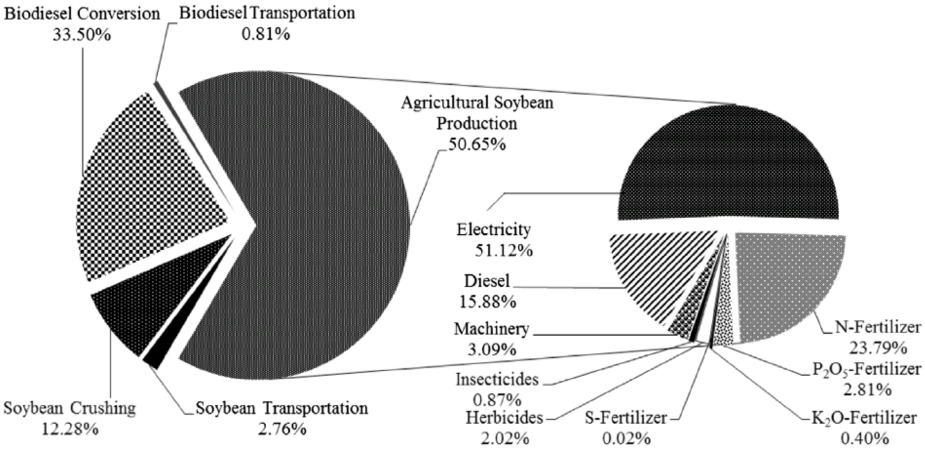
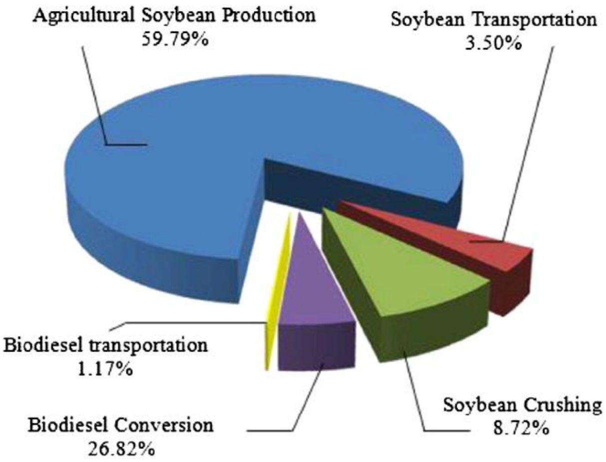


Figure 28 – The total GHG (kg CO_2 eq/ha) fractions in the five main stages of biodiesel production in Iran (Source: p.7 ref. [27])



From the land use point of view, soybean as a first generation biodiesel is in direct competition for soil and price markets of food. Clearly, as already discussed, food security may be affected thus, this fact is a disadvantage for sustainable biodiesel production. Also, dedicating land for an energy crop as soybean induces and indirect land use change on other activities like cattle or crops, rising like another constraint on its development.

According to a complete and detailed study on soybean biodiesel of the largest soybean producers (see Figure 26), in tropical areas, agriculture is characterized by high consumption of pesticides and heavy LUC from forest and as a consequence, loss of biodiversity and on the other hand, temperate regions experience high fertilizers consumption due to low crop yields [28]. Both scenarios impose negative impacts on the environment for which it is important to bind the potential expansion of this resource to sustainable policies emitted by their governments on the base of sustainable evaluations.

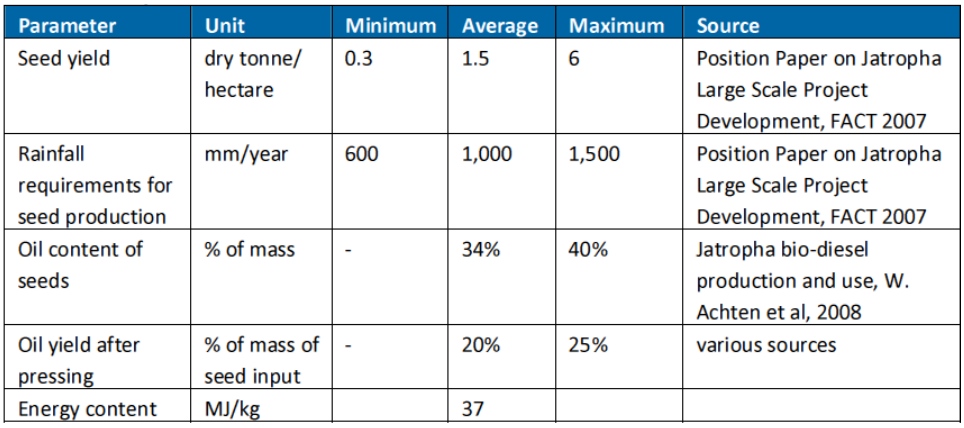
2.4.4. Jatropha Curcas

Figure 29 – Jatropha fruits (Source: http://www.cirad.fr/en/research-operations/research-results/2009/jatropha-curcas-a-fuel-of-the-future-for-the-south)

Jatropha is a perennial drought resistant shrub that can be grown on marginal land with low water and agrochemical supplies. As such, they are good for degraded farmland and little care is required. These abilities are attached to Jatropha thanks to its rooting nature which allows it to reach water from deep in the soil as well as to extract nutrients that are unreachable by other plants. Nutrients extracted from deep soil are returned to the surface via leaf and fruits fall, making of Jatropha a natural nutrients pump that helps to rehabilitate degraded land and mitigate soil erosion as well by means of its roots system.

Nevertheless, Jatropha is capable of producing fruit only if it receives sufficient light, nutrients and water, thus fertilizers and irrigation are required in order to assure good fruit yields. In that sense, optimum annual rainfall is between 1000 mm to 1500 mm in temperatures between 20°C and 28°C producing seeds with oil content that vary from 27% to 40% when tress are completely grown (3-4 meters tall) [3][29]. Yields vary noticeably as a function of the location and the growth conditions as well as due to the fact that it is still considered a wild plant with very low engineering and crop improvements (see Table 9).

Table 9 - Jatropha fact sheet (Source: p.6 ref. [30])



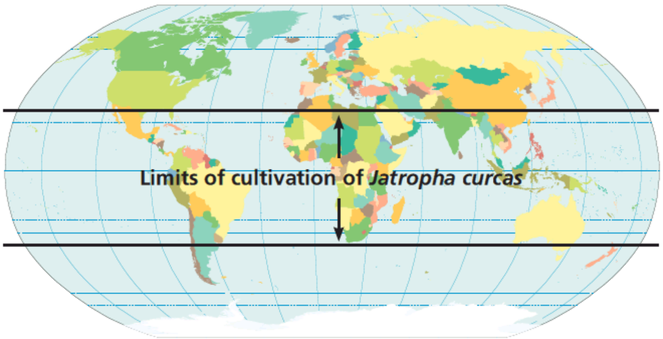
Parameter	Unit	Minimum	Average	Maximum	Source
Seed yield	dry tonne/ hectare	0.3	1.5	6	Position Paper on Jatropha Large Scale Project Development, FACT 2007
Rainfall requirements for seed production	mm/year	600	1,000	1,500	Position Paper on Jatropha Large Scale Project Development, FACT 2007
Oil content of seeds	% of mass	-	34%	40%	Jatropha bio-diesel production and use, W. Achten et al, 2008
Oil yield after pressing	% of mass of seed input	-	20%	25%	various sources
Energy content	MJ/kg		37		

The main applications and advantages of Jatropha are the following; Suitable for reduce erosion due to its large rooting system and lessening wind erosion as well as rainfall water infiltration improvement. Livestock barriers as they are poisonous. Natural manure thanks to its nutritional pump work as stated previously. Extracts from the plant have many uses in traditional medicine and veterinary. Finally fruits and seeds oil for the current interest of biodiesel.

From the biodiesel production point of view, Jatropha is a non-edible crop (second generation biodiesel) which does not compete directly with food, avoiding any discussion on direct impact of food prices and limiting the competition only to the land use and agricultural inputs scenario. Jatropha oil has physical and chemical properties which are highly suitable for biodiesel production. Oil extraction is relatively easy with low technological requirements but the subsequent conversion process requires higher degree of technical knowledge. After trans-esterification, useful by-products can be recovered; potassium fertilizer and glycerin basically. From the oil extraction, residues serve well as livestock feed, fertilizers, biogas feedstock and power generation.

An important advantage of this crop is the possibility to store fruits without losing its oil content or properties in time as may occur with other energy crops. This facilitates the small scale production of Jatropha in such a way that farmers can produce crude oil and store seeds far away from the biodiesel conversion plant. This model may help in rural developing improving small farmers' incomes at low cost.

Figure 30 – Cultivation limits of Jatropha Curcas (Source: p.28 ref. [29])

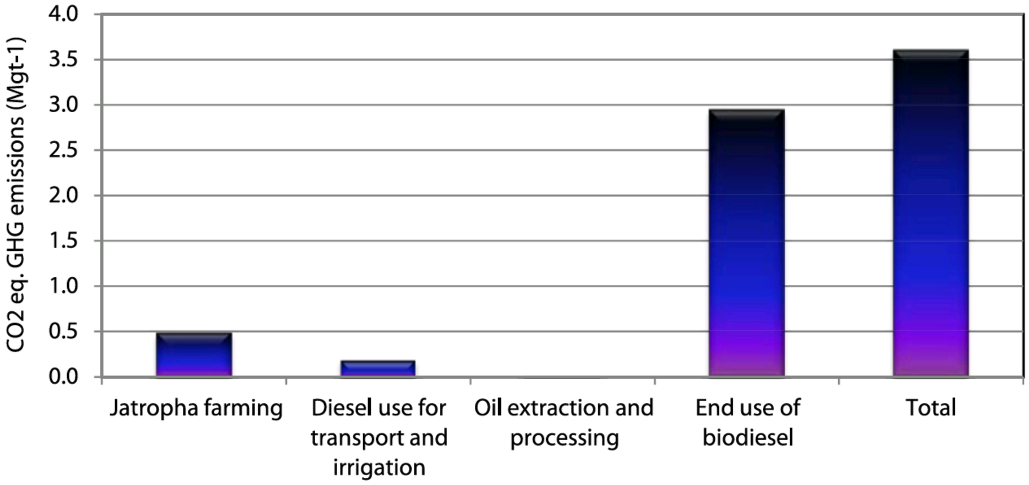


The origin of Jatropha is from Central America and the northern region of South America [30] but it spread around the world within the so called Jatropha belt (see Figure 30). It grows in tropical and subtropical regions between 30°N and 35°S at low altitudes (0-500 m.a.s.l) [29]. It is globally distributed in wild or semi cultivated fields in Latin America, Africa, India and South East Asia. It is widely grown in India, Nicaragua, North East Thailand, and now it has being promoted in Brazil, Mali and Nepal [31].

The trans-esterification process can be achieved through different routes bearing in mind factors that affect the process like alcohol to oil molar ratio, catalyst type, reaction temperature, rate of mixing and purity of reactants. One way is by using homogeneous alkali catalyzers, which is the conventional way, in which temperatures of 60-65°C are required at ambient pressure and short reaction time. A drawback is the pretreatment necessary when high contents of free fatty acids (FFA) are present in the crude oil for which other methods are studied. Such methods are intended to increase the conversion to FAME plus some other advantages regarding the conventional. These are the heterogeneous catalytic route, enzymatic method and supercritical methanol process as the most important in research. Nonetheless, the commercial production method today is the conventional with homogeneous catalyzers [32].

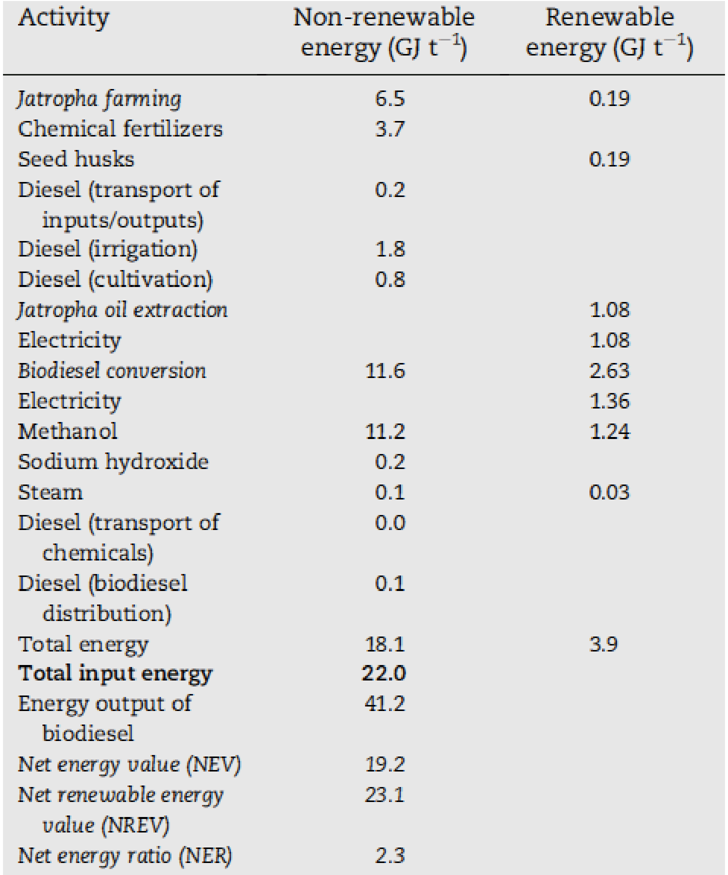
In a study performed for Tanzania on GHG emissions and energy balances of Jatropha biodiesel, it was found that the theory of carbon neutral is wrong in this case where a net GHG emission of 848 kg/ton was reported [33]. According to their conclusions, bearing in mind that the boundaries of the study included cultivation, oil extraction, trans-esterification and final combustion in diesel engines, the major source of GHG emissions is due to diesel engines (see Figure 31). However, this value should be compared to that one of engines powered by strictly fossil fuel and determine if there is a reduction or augmentation to conclude if it really works for the GHG reduction agenda.

Figure 31 – GHG emissions in the production and use of Jatropha in Tanzania (Source: p.100 ref. [33])



From the energetic point of view of the same example in Tanzania, Jatropha production showed a positive energy gain in a ratio of 2.3 (output energy embedded in the fuel to the non-renewable energy used in the entire process). As expected for a biodiesel production, large part of the energy demand is in the conversion stage mainly because of the use of methanol from non-renewable sources for trans-esterification, and in second place, cultivation stage due to the chemical fertilizers used, which required fossil fuels for their production, and irrigation machines run on conventional diesel fuel (see Table 10).

Table 10 – Energy balance results for life cycle of Jatropha biodiesel in Tanzania (Source: p.101 ref. [33])



Activity	Non-renewable energy (GJ t^{-1})	Renewable energy (GJ t^{-1})
Jatropha farming	6.5	0.19
Chemical fertilizers	3.7	
Seed husks		0.19
Diesel (transport of inputs/outputs)	0.2	
Diesel (irrigation)	1.8	
Diesel (cultivation)	0.8	
Jatropha oil extraction		1.08
Electricity		1.08
Biodiesel conversion	11.6	2.63
Electricity		1.36
Methanol	11.2	1.24
Sodium hydroxide	0.2	
Steam	0.1	0.03
Diesel (transport of chemicals)	0.0	
Diesel (biodiesel distribution)	0.1	
Total energy	18.1	3.9
Total input energy	**22.0**	
Energy output of biodiesel	41.2	
Net energy value (NEV)	19.2	
Net renewable energy value (NREV)	23.1	
Net energy ratio (NER)	2.3	

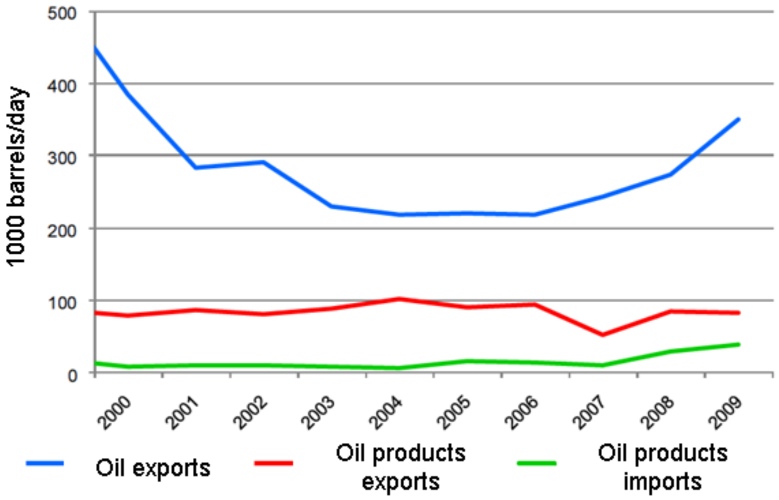
Similar situation occurred in an assessment done in Southwest China where they analyzed the energy potentials and the environmental benefits of Jatropha biodiesel. In general terms they found a potential of positive net energy result and GHG reductions if the development of the Jatropha industry followed their study [34]. In Malaysia, Jatropha was found to be the cheapest biodiesel feedstock with no impact on food price, GHG emissions reduction and an immense contribution in rural development [35]. On the area of LUC, an investigation on land clearing for Jatropha cultivation on Miombo Woodlands (Africa) confirmed the theory that, Jatropha can act as a carbon sink capturing atmospheric carbon when grown on complete wastelands and severely degraded conditions or, induce significant GHG emissions when introduced in tropical woodlands with substantial biomass and medium to high organic soil content [37].

Jatropha overall characteristics make of it a good prospect for sustainable biodiesel production bearing in mind the well-known advantages as a fossil fuel blender for compression ignition engines. Growing it on degraded wastelands with minimal fertilizers and irrigation will have as a result a positive environmental impact as well as replacing the fossil energy inputs with renewable energy and synthetic fertilizers with biomass based fertilizers. In addition, as the cultivation of biofuels like Jatropha induces the monocultures thus, negative impacts on biodiversity, special attention should be paid to areas of high biodiversity potentials in order to protect them from the latent LUC.

3. Biofuels in Colombia

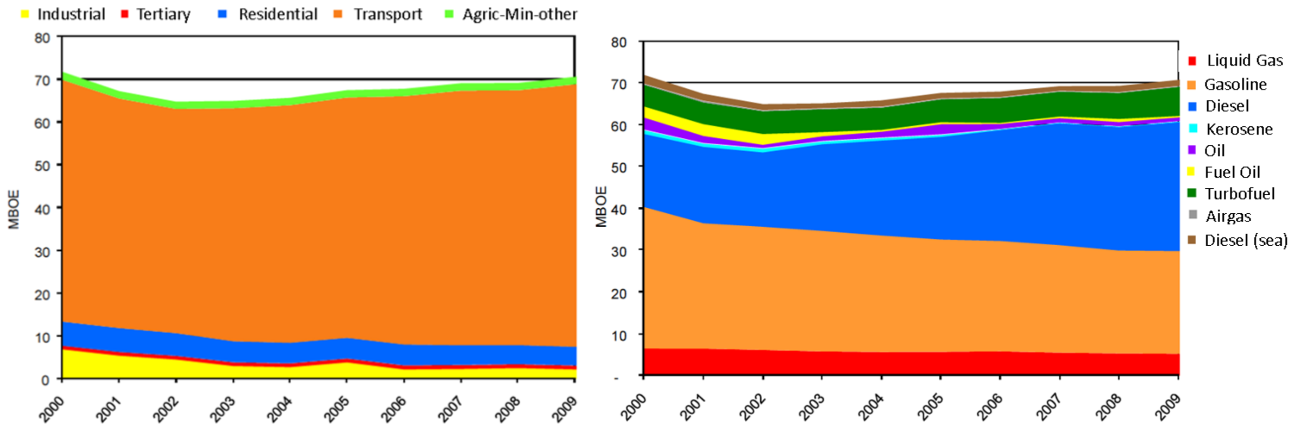
Colombia is the second largest biofuel producer of South America after Brazil and several expansions are planned to increase even more its production, not only to meet domestic policies on oxygenated fuels but also due to the opportunity presented by the recent free trade agreements with USA and EU. In 2001, the Law 693 opened the doors to bioethanol in Colombia and in 2004 Law 939 did the same to biodiesel due to different facts such as the Kyoto Protocol and the increasing international prices of oil, although Colombia is characterized for being a net crude oil exporter according to net balances performed by the International Energy Agency (IEA), and a highly independent country in terms of primary energy supply (PES) with a big surplus and exports potential (see Figure 32) [38].

Figure 32 – Commercial balance of crude oil and oil products in Colombia (Source: p.19 ref. [40])



As expected from the global energy demand by sectors, transport sector in Colombia has by far the largest oil products demand with and increasing trend (see Figure 33). This trend follows the economic growth of the last decade in the country driven by external investments and the intensification of natural resources exploitation, basically oil and mining. It should be pointed out that the main transportation system (passengers and goods) in Colombia is based on road transportation bearing the entire load on fossil fuel vehicles, primarily Diesel and Gasoline, and the few trains used for goods transportation are run also on fossil fuels (diesel). Other sectors like agriculture, mining and residential show a constant behavior in Colombia while industry has lowered its participation on the demand.

Figure 33 - Consumption by sectors of oil products (left) and by products (right) in Colombia (Source: p.22-23 ref.[40])



The highest share of oil products imports comes from Diesel with an 88% as reported in the year 2010 (see Figure 34), which, although in the commercial balance represents a low quantity as seen on Figure 32, it reports an increasing trend making the country to rise its dependability on external markets and reserves. In addition, in the year 2010 diesel signified 48% of the whole oil products demand in Colombia (see Figure 35) which meant that the internal production of Diesel is very low to match with the demand of this oil product thus offering a good market environment for biodiesel. The increasing demand of diesel obeys to the surge in big cities of massive transport systems based on diesel fuel, as well as the recent change of technology of vehicles from spark ignition to diesel (see Figure 33 and Figure 36) [41][42] and of course the economic growth of the country in terms of mining and oil.

Figure 34 – Oil products exports (left) and imports (right) of Colombia (Source: p.20 ref. [40])

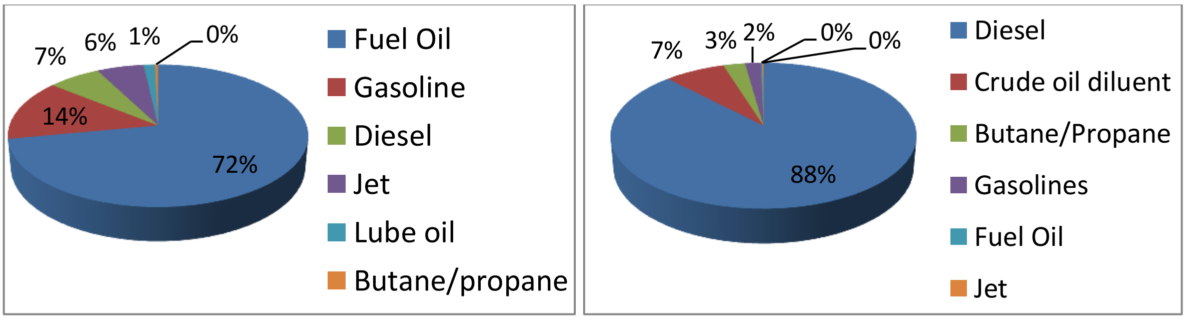


Figure 35 – Oil products demand of Colombia (Source: p.21 ref. [40])

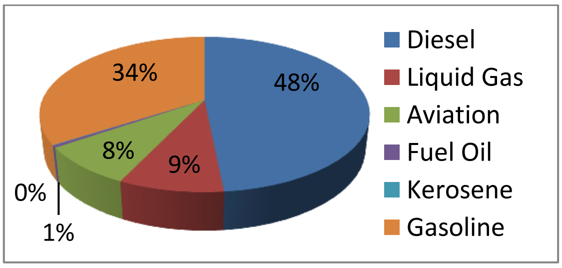
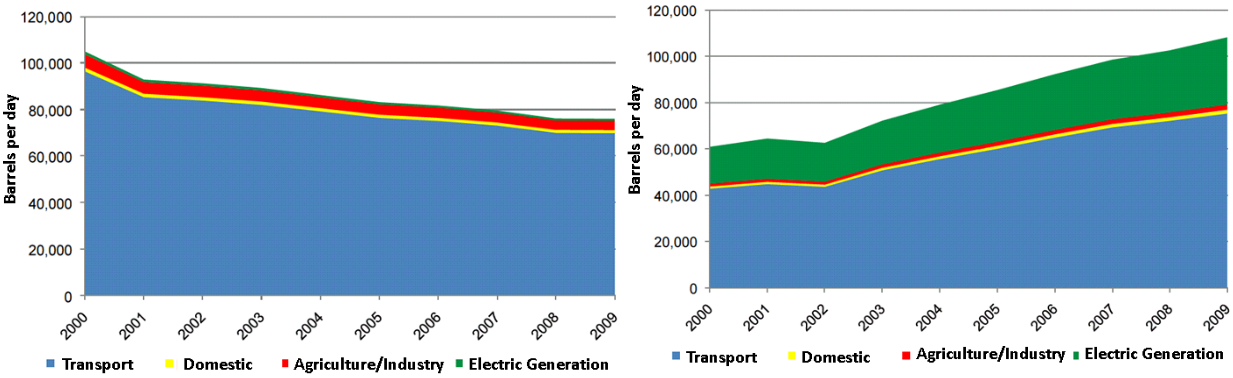


Figure 36 – Gasoline (left) and diesel (right) applications in Colombia (Source: p.24 ref. [40])

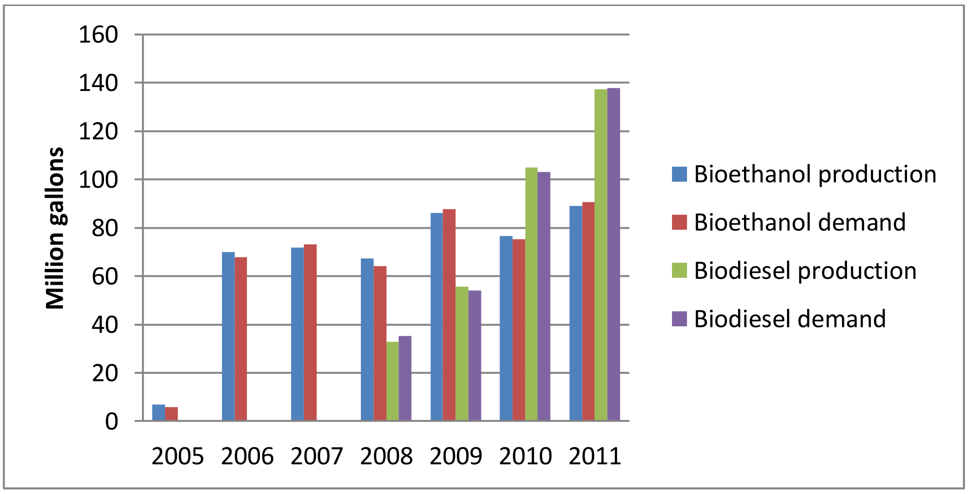


From the gasoline point of view, the Colombian domestic demand is the second highest with a 34% as seen in Figure 35, but it has a 2% on the total share of oil products imports and 14% on exports (see Figure 34). This shows the high domestic production of this oil product which not only matches with the national demand but also provides room for exports. In this sense, bioethanol production is useful not only to meet with the environmental issues but also but also contributes positively on the commercial balance.

Law 693 and 939 aimed to diversify the Colombian PES by means of alternative sources of energy which match with environmental, economic and social sustainable development. These acts of law permitted suitable policies to promote biofuels development including incentives for production, distribution and consumption, as well as reductions on taxations. In the past ten years, laws have been updated accordingly to the general environment inherent to biofuels, in terms of its evolution and domestic requirements and constraints. The laws tend to a diversification based on environmental sustainability, increase on fuels quality, rural and agro-industrial development, energy security and employment security.

Till 2009 the bioethanol produced in Colombia came from sugar cane exclusively, starting its industrial production in 2006 and grown in the south west region of the country, in the valley of river Cauca, while biodiesel started its industrial production in 2008 based on palm oil solely (see Figure 37) [39]. As a common denominator, it is observed that the biofuels feedstocks in Colombia were based on crops that own a well-developed status from the agricultural point of view. This assured high yields and thus, lower costs on an energy source that needs to be incentivized in order to be competitive facing blending policies. However, the food security discussion may arise in Colombia due to the direct competition between food and biofuels intrinsic to first generation biofuels, as well as the LUC, GHG emissions and primary energy conversion efficiency. The energetic diversification agenda is still open and other alternatives are in research stage.

Figure 37 – Biofuels production and demand in Colombia (Data retrieved from [41] December/2013)



According to UPME[10], in 2009 the share of gasoline consumption for transportation was 97% while diesel share reached 70% for transportation, which shows up the direct link between biofuels and the transportation sector. Bioethanol policies said that a blend of E10 is to be distributed in the entire country and, by January 2012, fuel-flex vehicles of E85 and less than 2000 cm^3 should be manufactured, sell and imported in the country. On the other hand, biodiesel was required in a mix of B5 for an initial stage, then, by the year 2010 a blend of B10 and finally from the year 2012 new diesel engines should work with a minimum B20. In a projection of 16 years it is shown a constant bioethanol demand of about 130000 barrels per day with E10 while biodiesel B5 has a constant increasing rate starting in 2009 with 5411 barrels per day and a final point in the year 2025 with 8400 barrels per day for a total increase of 55.1% [39].

3.1. Bioethanol – Sugarcane case

In Colombia, there are 5 distilleries with and installed capacity of 1.250.000 liters of ethanol per day concentrated in a region (Valle del Cauca) where sugarcane is highly cultivated at good performances and yields. Today, almost 75% of the area dedicated to sugarcane in the county is focused in this region [43]. It is a region characterized by very good conditions to grow up sugarcane due to the constant and bright sunlight throughout the whole year, adequate temperature balance between day and night, water availability and rainfall, and fertile soils [39]. To the year 2011, the mean yield reported by ASOCAÑA[11] was of 114 tonnes per hectare and the potential expansion is calculated from the actual 40.000 hectare to 1.518.000 hectares highly suitable for sugarcane harvesting [44].

The expertise and “know-how” in the agricultural and sugar extraction stages was achieved, not because of the recent demand of ethanol but thanks to sugar industry settled in this region for around 50 years. This industry pushed the country to be sugar self-sufficient and a net exporter of sugar, creating the perfect nest to produce sugarcane ethanol. According to life cycle analysis performed in 2012, the sugarcane ethanol is in compliance with human rights standards, social impacts and no negative impact on food security [43].

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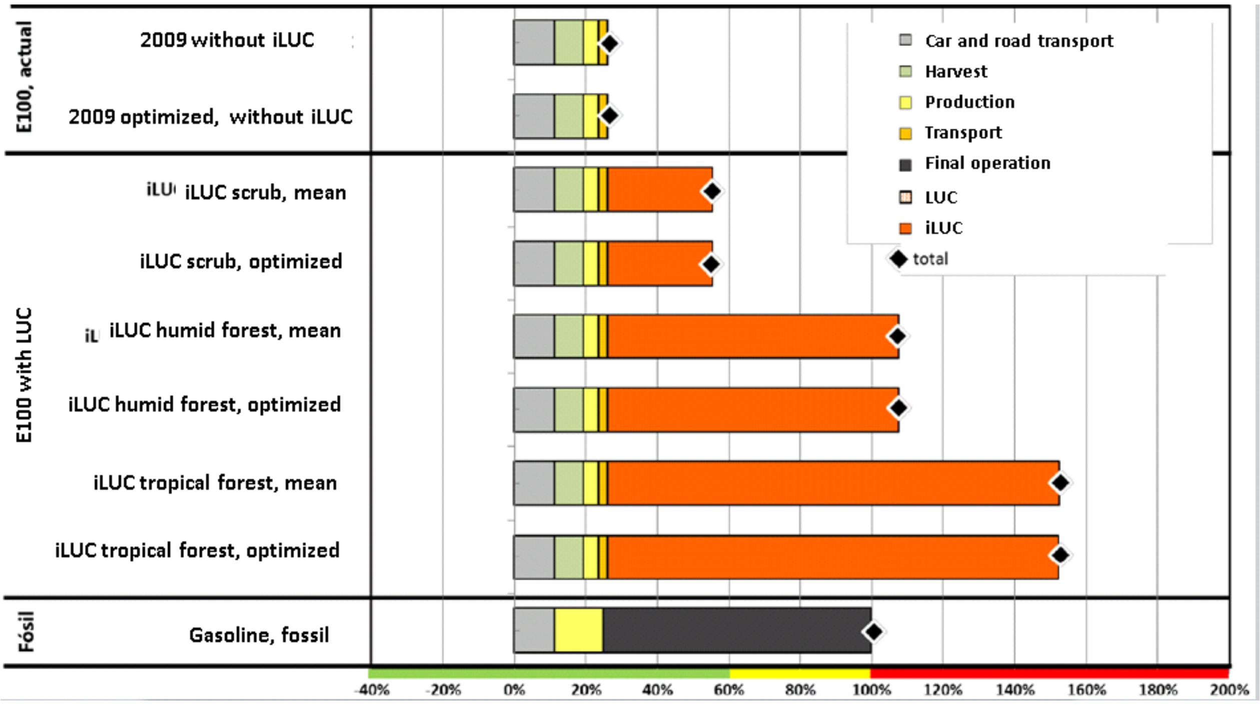
[10] Unidad de Planeacion Minero Energética. Colombian entity in charge of planning and management of information of the mining and energetic sector.

[11] Association of sugarcane producers in Colombia.

From the environmental point of view, a GHG emission study was performed in 4 different scenarios and compared to the actual scenario of gasoline (E0 vs. E100). The first one is the case where no iLUC[12] was performed (i.e. where sugarcane was already in place), the second is for indirect scrub felling, the third for humid forest felling and the forth one for tropical forest felling (see Figure 38). As a main result, it was found that whereas that there is no iLUC, the reduction of GHG is of 74% compared to that one of fossil fuel “E0” [44]. It is clear that special attention should be paid to iLUC otherwise GHG may be augmented instead of decreasing it as it is supposed to be. In that sense, only scrub felling could reduce GHG emissions if this iLUC is caused. As usual, also the harvesting stage increases GHG emissions.

Figure 38 - GHG emissions for the entire life cycle of ethanol per vehicle and km. in Colombia (Source: p.29 chapter 0, ref. [44])



The main advantages of sugarcane ethanol in Colombia, besides the environmental improvement, the reduction of dependence on fossil fuels and the economic and rural growth, are the surplus energy generated (heat and electricity) from residues of sugar extraction and the avoidance of food competition due to the fact that ethanol in Colombia is being produced also from the residues of sugar extraction.

3.2. Biodiesel - Oil palm case

In the year 2008 the production of Oil palm diesel begun in Colombia right after the acts of Law that established the biofuel’s policies in the county. As stated before, due to the high yields and “know-how” reached in its industry (more than 50 years of experience), Oil palm was chosen as the most suitable biodiesel feedstock in Colombia. In fact, as showed before, Colombia is the largest Oil palm producer in Latin America and the fifth in the world with the second largest yields on earth (see

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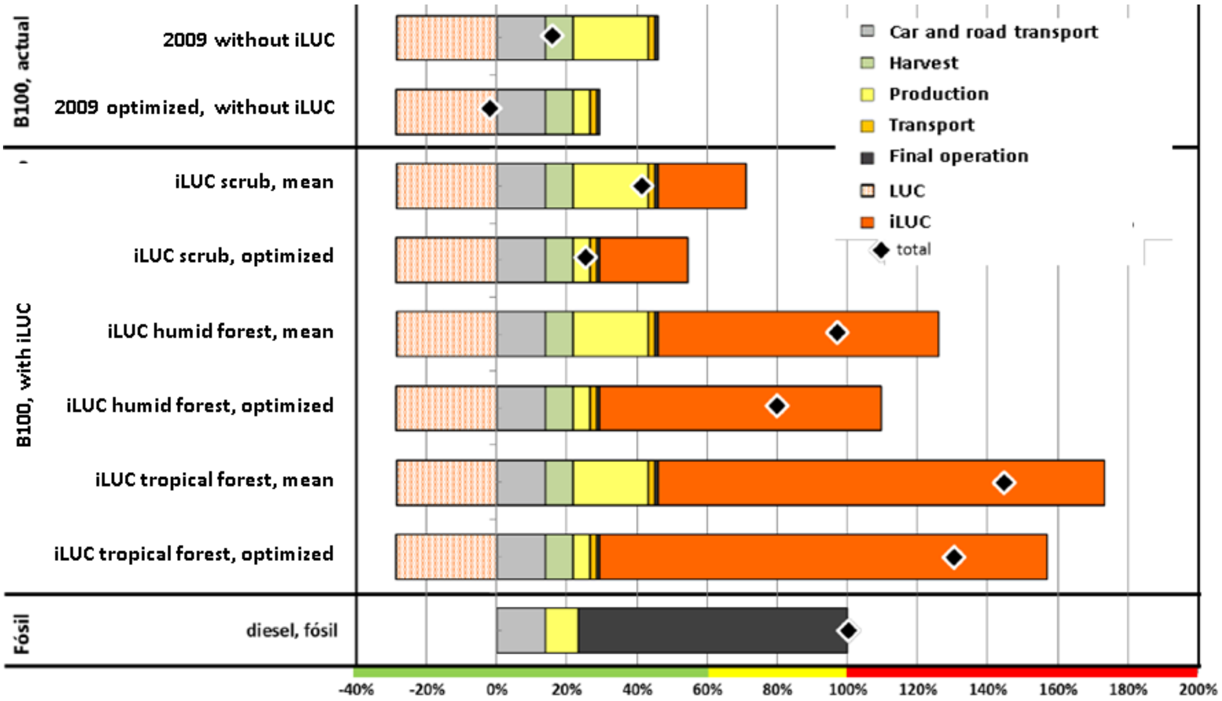
[12] iLUC: indirect Land Use Change. Displacement of land uses due to crops or cattle that were replaced with the new energy crop.

Figure 22 and Figure 23) very close to Malaysia which is a well-known oil palm diesel producer. In addition, Oil palm has the highest oil yields within the crops considered for biodiesel production.

The Oil palm production in the Colombian fields has reached a mean value of 19 tonnes of fresh fruit bunches (FFB) per hectare per year and the FFB milling installed capacity was of 1109 tonnes per hour in 2009 making a total of 486000 tonnes per year [44]. Till the year 2008 the area cultivated in the country was of 336.956 hectares and still, 1.053.000 hectares were identified as highly suitable for Oil palm plantations showing big room for expansion.

As reported for the ethanol case before, from the environmental point of view, a GHG emission study was performed in 4 different scenarios and compared to the actual scenario of diesel (B0 vs. B100). The first one is the case where no iLUC was performed (i.e. where Oil palm was already in place), the second is for indirect scrub felling, the third for humid forest felling and the forth one for tropical forest felling (see Figure 39). As a main result, it was found that whereas that there is no iLUC, the reduction of GHG is of 83% compared to that one of fossil fuel “B0” [44]. Compared to sugarcane, Oil palm has decrease contribution of about 30% on GHG emissions due to LUC in all scenarios which pushes leftwards the total GHG emission in Figure 39. However, it is clear that special attention should be paid to iLUC otherwise GHG may be augmented instead of decreasing it as it is supposed to be. In that sense, scrub felling and, in a relatively low proportion, humid forest felling could reduce GHG emissions if this iLUC is caused. As usual, also the harvesting stage increases GHG emissions.

Figure 39 - GHG emissions for the entire life cycle of biodiesel per vehicle and km. in Colombia (Source: p.19 chapter 0, ref. [44])



In 2011, FAO studied the Colombian Oil palm case and reported the approval by the United Nations of a FEDEPALMA project, which was considered to be the largest in the world and has the objective of capturing methane from residual wash water, reduction of fossil fuels consumption and cogeneration of renewable energy [45]. Also, it informed that there was no negative impact on food security due to the surplus used to exports and switched to biodiesel production as well as a big employment opportunity in this industry. However, in a model performed of Oil palm plantations expansion, the results reported that it is highly unlikely that the government can reach the goals proposed to 2020 [46]. It also reported the tendency of land expansion which showed a concentration on pastures lands and in a lesser proportion a mixture of agricultural and natural forests land thus, a low impact on LUC. In another study, LUC was discussed getting to a similar conclusion of the latter and, in addition, it concluded that field nitrous oxide emissions and biogas management options may influence heavily GHG emissions [47].

3.3. Biodiesel - Jatropha case

Consequently with its efforts to increase the biofuel production and consumption, Colombia is doing an effort to participate and establish a biofuel network in the region for research and development sponsored by FAO. The public entity in charge of agriculture and rural development[13] has given prominence to alternative projects of biofuels in Colombia, in which Jatropha shows up, in order to increase their productivity and find the best combination of parameters which result in an increased performance [45]. According to some memorials presented in Argentina in 2009, a consortium called Oil Source Holding Group Inc. made an agreement with different companies to invest in 100.000 hectares in different regions of Colombia to produce Jatropha diesel for electric generation in rural areas of the country [54].

In a test performed in a Colombian lab, extraction was executed by mechanical means evaluating pressure, temperature and preheating time of seeds grown in Colombia, concluding from the results in 2008 that the only parameter that affected the performance was pressure applied although preheating was recommended. Also, the oil extracted was refined to biodiesel in presence of catalyst so to study other variables of the process and find those important to increase its performance and to meet with the technical requirements of diesel in Colombia according to ICONTEC[14] [48]. In the same way, another test was accomplished to determine the optimal conditions for the trans esterification reaction of oil extracted from Jatropha grown in Colombia with a previous examination of the oil characteristics and its suitability for trans esterification. The main parameters of study were the molar relation between ethanol and Jatropha oil, reaction time, amount of catalyzer, reaction temperature and mixture agitation speed. It concluded that, first of all, Jatropha is appropriate for a trans esterification process and due to the optimal conditions founded and the high yields reported, Jatropha grown in Colombia is appropriate as a feedstock for biodiesel [53].

The space available in Colombia for agriculture is estimated in 20 million hectares located mainly in savannah and scrub forests bringing high opportunities for Jatropha cultivation [54]. In 2009, a thesis to identify the most suitable areas of Colombia to grow Jatropha from the biophysics and social economic point of view was done from a total of 77.084.656 hectares available in Colombia (67% of the national territory). From this offered area, it was found that 0.9% was highly suitable without any competition on land use, 2.7% was moderately suitable without land use competition

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[13] Ministerio de Agricultura y Desarrollo Rural, Republica de Colombia.

[14] ICONTEC (Instituto Colombiano de Normas Tecnicas) is the Colombian entity in charge of technical standardization. In this case the following were applied: refractive index (NTC289), acid number (NTC28), iodine value (NTC283) and saponification index (NTC335).

and, with conflict due to land competition use, 0.05% was found highly suitable and 0.5% discreetly suitable. In general terms, it was determined the positive viability for Jatropha in Colombia [49].

From the operative point of view, a study performed in 2010 focused on the potential use of Jatropha and palm oil diesel in Colombia according to the temperature of operation and cold start of the engine. It was found that both of them have good performances in cold cities like Bogotá even though Jatropha was better with and without additives [50]. In 2009, the increasing demand of diesel due to the rising massive transport system Transmilenio[15] in Bogotá incentivized another study that reported the logistic designed for a supply chain of biodiesel to Bogota. Based on the model implemented, a selection of countryside regions near to Bogota were chosen bearing in mind the soil recuperative characteristics of Jatropha, and the benefits to rural development [51].

Because of starting point of the development of Jatropha in Colombia, the agricultural methods are manual or not mechanized which leaves enough room for improvement. A design done in 2012 created a device to optimize the harvesting procedure regarding the manual procedure and the complexity on applying mechanized solutions to grab Jatropha fruits from the trees. This design made a detailed study on the entire agriculture process finding that harvesting stage could be optimized and so, creating the device for manual operation [52].

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[15] System based on articulated buses run on diésel with EURO 5 specifications.

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Politecnico di Milano

Sustainable evaluation of Jatropha oil as a biofuel in Colombia

The model – Calculation and description of the Jatropha biodiesel production process from mass and energy stand point.

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Master thesis – Energy Engineering for an Environmentally Sustainable World
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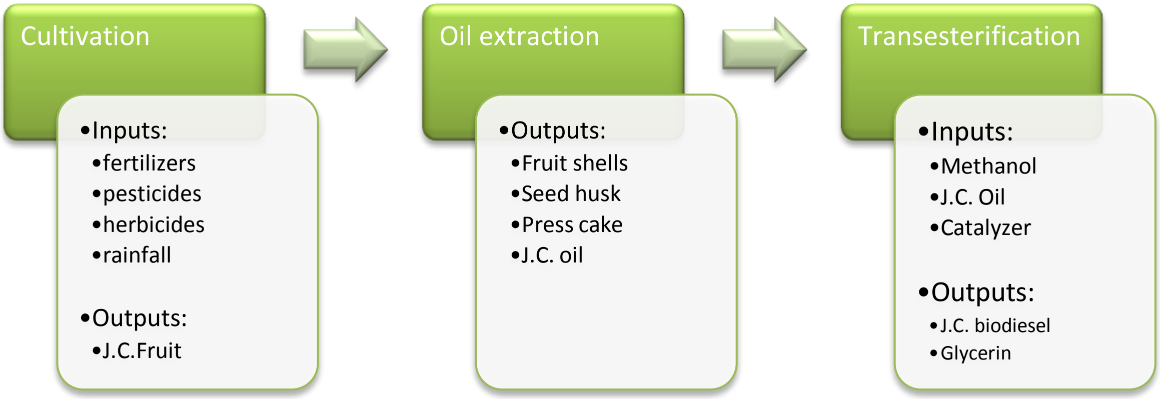
1. Introduction

In the aim of reducing the knowledge gap upon bioenergy technologies, detail studies are done worldwide in order to better understand the nature and evolution of these new energy options. Biomass energy has been proven to have as many advantages as disadvantages in terms of social, economic and environmental aspects depending on their actual management and in the way they are conceive. Decision makers require reliable information in these areas in order to guide a procedure towards a sustainable objective, giving high significance to develop tools which may help them decide for a suitable option. The model proposed in this work is clearly a tool which helps to understand in detail from both the energy and the mass flows point of view the production process of Jatropha Curcas Methyl Ester (JCME) or simply Jatropha biodiesel.

Colombia has the great advantage to have a territory full of agricultural options which certainly, with a proper management and policy making, represent a huge potential for rural and social development as well as a contribution to the food security of the country, bearing in mind the actual food preoccupation of the world. In addition, given that there is an increasing need to replace fossil energy and although Colombia is highly energy independent due to its fossil and natural reserves, biofuels represent a great opportunity to diversify its energy mix as well as to provide this resource to regions which are not interconnected a have been left behind in progress. Consequently, the main goal in developing this model is to do a sustainable analysis of biodiesel production in Colombia accordingly to the different agricultural environments present along the country and give decision makers appropriate tools to choose adequately.

Figure 1 – General overview of Jatropha biodiesel production chain included in the model.



The extents of the model were defined starting from the cultivation stage of Jatropha, passing through the oil extraction from the fruits till the production of the biodiesel (see Figure 1) under the national and international standards. In the following sections, the entire model will be explained in detail. All the mass and energy flows were calculated on a basis of a hectare per year and the recovery of by-products is considered as well, in order to increase the sustainability options of the process. Surveys were done in five farms in Colombia which are cultivating Jatropha, in order to gather as much information as possible of the main consumptions and yields. Due to the lack of information in this area for the Colombian case, a research on Jatropha biodiesel production around the world was performed to extract information and generalize the process, taking into consideration the environmental conditions of this country and performing proper assumptions.

2. Cultivation

This section exposes the aspects of the Jatropha trees requirements, density per unit of land and fruit yields. The base unit of analysis is one hectare per year and three main parameters were chosen as variables; water supply (rainfall intensity), soil fertility level and type of fertilizer.

2.1. Water supply

It is well established that irrigation can increase yields but the costs of irrigation are high in most cases and in regard of the Jatropha seed prices plus the advantage of low water requirement, water supply is led to annual rainfall of each region [1]. In that sense, three ranges of rainfall were studied; Optimal (1200 mm – 1500 mm), Normal (700 mm – 1200mm) and Suboptimal (500 mm – 700 mm or > 2500 mm). Jatropha plant is drought and flood resistant but its yield is heavily affected by these two conditions which are taken into account in the suboptimal range. According to the weather in the region to be studied, the range of rainfall will be chosen and consequently, the yields will vary as a function of this water supply (see Table 1).

Table 1 – Dry seeds yield (Source: Annex A [1])

Water supply	yield (kg/ha/y)	Soil fertility
Optimal (rainfall 1200 - 1500 mm)	6000	high
	2500	medium
	750	low
Normal (rainfall 700 - 1200 mm)	3500	high
	1500	medium
	500	low
Suboptimal (rainfall 500 - 700 mm or > 2500 mm)	1500	high
	750	medium
	250	low

2.2. Soil fertility, pesticides and herbicides

Identical as in the water supply parameter, the soil fertility level is another parameter to be varied between three ranks; High, Medium and Low. A study of the region in which is intended to be cultivated with Jatropha should focus in an analysis of the soil fertility in order to determine the fertilizer requirements to grow Jatropha. This plant is known for its ability to survive in very poor soils but as well as its drought resistance, its productivity is heavily affected by these type of conditions (see Table 1) [2].

Adequate quantities of fertilizers should be applied in order to achieve the maximum yield. Low nutrition would produce low yields while excessive fertilizer may induce the production of higher amounts of biomass with little fruit yields. Jatropha is still considered a wild plant which has lack of genetic studies and improvements, but trials have been done to approach from an experimental point of view to the optimal yields under determined fertilization schemes [6].

Different types of fertilizers are included in the model but basically there are two types: chemical and organic. Chemical are more efficient but far more expensive in terms of energy embedded in their fabrication (fossil mostly), while organic may come from the same Jatropha production process creating some energy savings and higher energy recovery from the same plant as well as creating a sustainable cycle. Fertilizers used in the model are listed in the table below (see Table 2). Other types of organic fertilizers are the ones of animal manure which may match with the Jatropha requirements but with a higher bulk mass than those chemicals taking advantage of their low energy embedded. The amount required (kg/ha/year) for each of the listed items depends basically on the soil fertility level and this variance is also included in the model based on data from different papers and studies [1][3][4].

Table 2 – Fertilizers used in the model

Chemical and Organic Fertilizers
NPK 15-15-15[1]
Dry cow manure
Dry chicken manure
Vermicompost
Chemical fertilizer (15-5-10)
Chemical fertilizer (12-2-10)
Digestate from biogas (NPK 15-15-15)
Urea (46%Nitrogen)

Pesticides are almost not required in the sense that Jatropha itself is toxic and serves as pesticide. Also the studies in this area are still poor but, it is known that once a specie is grown intensively, given that this creates abundant offer, insects and pests are attracted to this abundance. In the meantime, the wastes of oil extraction such as seedcake and fruit shells serve well as pesticides making the demand for this material negligible. In the case of herbicides, although it has been highly questioned worldwide, glyphosate and paraquat [3] are used to prevent weeds which steel nutrients from the Jatropha tree surroundings. An alternative is to fight weed with man labor but in case of big production sites, this might get costly and hard labor.

2.3. Plantation

The plantation scheme should obey to different aspects such as competition between trees for water, nutrients and light [2]. If an area is too dense in trees per unit of area, the risk of shadow from other trees is high and in case of an intensive agricultural area with machinery usage, the space for proper working is an important thing to bear in mind. In the model this consideration was not taken into account because the calculations were based on seed yields per hectare rather than by tree. Anyhow, for the Colombian case, a plantation configuration of 3x2 meters in between trees was assumed with a final density of 1666 trees per hectare and a seed yield variation according to the water supply and the soil fertility level (see Table 1) [8].

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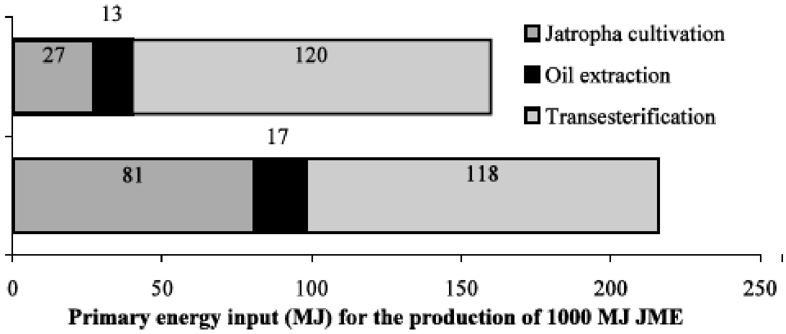
[1] NPK 15-15-15 stands for a fertilizer of Nitrogen, Phosphorous and Potassium in which their respective content on a weight basis is 15% for Nitrogen, 15% for Phosphorous and 15% for Potassium. Same procedure applies for the other NPK fertilizers.

2.4. Energy requirements

Fundamentally, the energy requirements in the cultivation stage are due to irrigation, fertilizers, agricultural machinery, pesticides and herbicides. Irrigation and fertilizers are the most intensive energy demanders in cultivation, where it is reported that irrigation may count for almost 46% of the energy input while fertilizers may represent 45% of the general requirement with their embedded energy [5].

Figure 2 – Energy requirements for two different agricultural intensities, high and low. (Source: p.1077 ref. [5])



In the model, as irrigation is not going to be analyzed, it represents an enormous energy saver but definitely, chemical fertilizers are the cause of high energy demand for cultivation (see Figure 2). Generally cultivation activities are high intensive primary energy demanders [7]. This is due to the energy required for the fabrication of the fertilizers used. On the other hand and as it will be discussed further, organic fertilizers reduce the amount of input energy. Values for energy in fertilizers and herbicides are given accordingly to the amount required of each of them (see Table 3). Those energy factors were included in the model and clearly determine the energy balance of the whole chain. Although the share of the input energy of machinery and other cultivation activities is low compared to that one of fertilizers and herbicides, they were also included in the model.

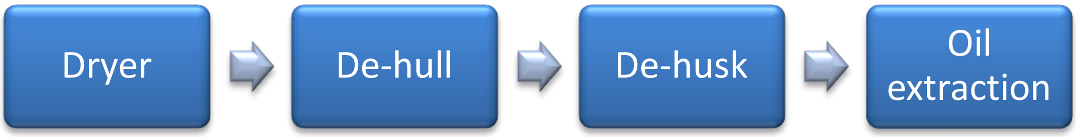
Table 3 – Energy factors for Jatropha biodiesel cultivation (Source: ref.[3])

Product	**Unit [MJ/kg]**
Fertilizer production	
Nitrogen	87.9
Phosphorous	26.4
Potassium	10.5
Herbicides production	
Glyphosate	452.5
Paraquat	458.4

3. Oil extraction

Oil extraction can be made manually, mechanically or using solvents (chemical) [5]. In this case, the model was focused on mechanical extraction of oil from seeds by means of a de-huller, de-husker and finally a screw press machine. The complete process is conceived under the assumption of a previous drying process of the fruit at ambient conditions till a 7% of moisture content in the seed is achieved [1]. A reduced moisture content increases oil yields and rise the heating value of the wasted biomass after oil extraction but it also enlarges the energy required for extraction process due to the higher frictional forces in the seed and fruit shell [9]. Three stages were considered in the process; de-hulling, de-husk and final oil extraction (see Figure 3).

Figure 3 – Oil extraction production block



3.1. De-hulling, de-husk and press

The Jatropha fruit is composed by an external fruit shell and the seed. On a dry basis, the fruit shell has the 37.5% of weight while the seed is the rest 62.5%. Independently, the seed composition is 42% of husk which is the thin layer that covers the kernel whose 58% is the huge oil bearer in the entire fruit [10]. In that sense, besides the primary product (Jatropha oil), by-products of this chain are the Jatropha shells, seed husks and seed cake (see Figure 4).

Figure 4 – Compositions of Jatropha fruit. (Source: ref.10)

De-hulling is procedure that may be done manually but in small scale productions. A de-hulling machine may be used in which case is better to introduce the fresh fruit rather than dried due to higher diameter of the fruit in fresh conditions [9]. This helps to separate better the fruit shell from the seed but still, the fruit shell is required to be dried in order to reduce transportation weights and to increase heating value of fruit shell if energy is planned to be recovered from it taking advantage of such as a by-product. In the model, this procedure is considered after the entire fruit is dried and to better quantify the mass and energy flows.

After de-hulling, a de-husk process is considered where the husk is removed from the seed leaving only the kernel which is the most important oil carrier (to be extracted by a screw press) and the husk as a by-product. According to a study performed on the forces applied during the oil extraction, it is established that avoiding the de-husk process creates some extra internal forces which help reducing the power required to extract the oil from seeds and also, the husk pieces inside the press contribute to a better flow inside the screw [9]. If no husk pieces are let into the screw press, the smashed kernel starts to accumulate inside the screw press making the process more difficult. In this case, modifications need to be done on the machine regarding the pressure, temperature and reduction are through the screw press. Nevertheless, for simplicity of the model as well, the de-husk stage is performed separately to better quantify the mass and energy flows.

As expected from the seed yields variability according to soil fertility and water supply, in the model the oil, seed cake and husk yields were included given the seed performance (see Table 4). The by-products till this point discussed (i.e. fruit shells, seed cake and husks) were included in an anaerobic digester modelled for biogas production and to increase the energy gains as well as to contribute to the sustainability of biodiesel production. The anaerobic digester of the model will be discussed in detail in the next sections.

Table 4 – Oil yield, seed cake and husk yields as a function of water supply and soil fertility. (Source: ref. [1])

Water supply	Oil yield (kg/ha/y)	Seed cake and husk (kg/ha/y)	Soil fertility
Optimal (rainfall 1200 - 1500 mm)	1200	4800	high
	500	200	medium
	150	600	low
Normal (rainfall 700 - 1200 mm)	700	2800	high
	300	1200	medium
	100	400	low
Suboptimal (rainfall 500 - 700 mm or > 2500 mm)	300	1200	high
	150	600	medium
	50	200	low

Nowadays, screw presses are very commercial and are designed to work with a vast variety of seeds in the vegetable oil extraction industry. Several studies have been performed in order to determine the capacity of those machines in extracting the oil from Jatropha seeds [9]. It is said from experimentation that, in general terms, the machines available in the market can work at 70% of their capacity for Jatropha seeds [9][11]. The Sayari expeller, manufactured in Tanzania, has a work rate of 15 to 33 liters per hour with a 4 to 5 kW engine and is capable of extracting 15 liters of oil from 75 kg of seed [2] [9]. Different oil expellers were consulted and used in the model (see Table 5).

3.2. Energy requirements

Although oil extraction may be performed manually it is clear that for the sake of productivity it is much better to use tools like the screw presses which, at relatively low energy consumption (see

Figure 2), may increase not only productivity but also the amount of oil recoverable from the seed by mechanical means as it was shown in an application in the Philippines [12]. The model adopted this type of oil extraction and the energy required was calculated over the entire production block of de-hulling, de-husk and screw press based on commercial information (see Table 5) and some other studies [9][11][12].

Table 5 – Oil expellers in commercial use around the world and their energy demand per feed mass. (Source: Annex J and L of ref.[9] and ref.[11])

Oil extraction machines		
BT50 press	170	kJ/kg_seed
	205	kJ/kg_seed
AP03	270	kJ/kg_seed
Komet S120F .	450	kJ/kg_seed
BT biopress type 100	305	kJ/kg_seed
Tiny Tech Tiny Oil Mill	381	kJ/kg_seed
Hybren 60	100	kJ/kg_seed
Mini 100	386	kJ/kg_seed
Mini 200	386	kJ/kg_seed
Mini 500	377	kJ/kg_seed
type 90	206	kJ/kg_seed
Goyum 60	315	kJ/kg_seed
Goyum 100	204	kJ/kg_seed
KEK-p0101	386	kJ/kg_seed
KEK-p0500	226	kJ/kg_seed
AP 10/06	386	kJ/kg_seed
Ap 12	386	kJ/kg_seed
AP 14/30	309	kJ/kg_seed
6YL-120	283	kJ/kg_seed
ZX-105A	248	kJ/kg_seed
Sayari expeller	386	kJ/kg_seed
Sundhara expeller	386	kJ/kg_seed
average =	306.7	kJ/kg_seed

As it was stated before, to increase the oil extraction efficiency, a reduction of the moisture content is essential [1]. This can be done either by heating up the seeds previously or simply by letting them dry at ambient conditions for a defined period of time. Considering the last case, the energy necessary for this ambient drying is negligible for the model calculations. The energy outputs of this block of production are included in the mass flows of the main product and the by-products namely fruit shells, seed cake and seed husks which are introduced in an energy recovery process (anaerobic digester).

4. Trans-esterification

Jatropha oil as extracted is considered crude oil and before the trans-esterification process, crude oil needs to be de-gummed and de-waxed in order to match with the international standards of diesel fuels. The impurities present in the Jatropha oil consist of both dissolved and suspended particles that are not part of the oil. The oil that leaves the expeller contains significant amounts of solid material (5% to 15% solids by weight) that need to be removed [1].

Figure 5 – Trans esterification production block.

4.1. De-waxing and de-gumming

The first step applied was the de-waxing stage where the crude Jatropha oil is left for a period of 15 hours in an ambient with temperature of 10°C. During this time precipitation of wax takes place and then it is centrifuged so to separate this wax phase from the oil. Then, the oil is heated up to a temperature of 65°C and mixed with phosphoric acid and hot distilled water during a period of 45 minutes, time in which gums precipitate and are separable from the oil. For both procedures, sedimentation and/or filtration are cheap techniques and almost negligible energy consumers which may replace centrifuged steps.

4.2. Trans-esterification

Once the oil is purified the trans-esterification process takes place. An alcohol is required in order to perform the separation of the oil triglycerides into mono esters. Commercially, methanol is used to do such work in order to obtain the so called methyl esters but ethanol has a higher efficiency in this area (creating ethyl esters) and it may contribute to a sustainable production due to the fact that ethanol may be produced also from biomass contributing to a stable cycle. Nonetheless, ethanol trans-esterification requires several other steps after trans-esterification and also requires higher activation energy for the reaction (i.e. higher pressures and temperatures) which makes the process more complicated. This is why the model is based on a methanol trans-esterification process in presence of a catalyzer (KOH) which reduces the activation energy of the reaction.

A solution of catalyzer and methanol is prepared and then mixed up with the oil which is heated up to 75°C during a period of 6 hours. The amounts of each reactant depend on the quantity of oil produced in the previous steps. Methanol counts for the 20% on a weight basis of the oil to be processed while the catalyst KOH is a 1% [13]. In general terms and theoretically, 100 units of Jatropha oil mixed up with 20 units of methanol and 1 unit of catalyzer produces 100 units of Jatropha Methyl Ester, 20 units of glycerin and the amount of catalyzer is not consumed [2]. To guarantee a complete disruption of the triglycerides in the Jatropha crude oil an excess of methanol of 6 to 1 (molar ratio alcohol to oil) is included [5]. The latter constitutes the basic calculation of the model in this particular stage.

Finally, a separation of phases is done so to clean up the biodiesel produced, to reutilize the methanol not consumed during the reaction due to the excess included and the catalyst. Biodiesel in this point may be suitable for combustion purposes and glycerin, as a by-product is ready to be used in other applications.

4.3. Energy requirements

Besides the energy that is loaded to the production block of trans-esterification by means of the Jatropha crude oil, other mass flows introduce energy to the process like the catalyzer and reactants required for purification of the crude oil. Although all those mass flows contribute to the energy balance, the most important energy bearer is methanol not only due to the energy embedded in it through its own production process but because of the consumption of this material in the reaction. This situation can be visualized in the Figure 2 where trans-esterification process has a big weight on the entire biodiesel production. In the model, the energy requirements of the different devices is calculated for the entire block while the methanol consumption is introduced separately for the sake of simplicity and visualization in the model.

5. By-products

From the previous production blocks discussed, a series of by-products are obtained which may be recoverable or reused by means of alternative processes. In the particular case of the present model the by-products considered are the wastes from oil extraction, namely the fruit shell, seed husks and seed cake, and glycerin from the trans-esterification process. Methanol from the excess provided to trans-esterification is also reused as well as the catalyst. The first ones are used in alternative processes which increase the energy gain and contribute to the sustainability of the entire chain while the second ones are just reused in the already described processes. In the model an alternative process was calculated; an anaerobic digester.

The anaerobic digester of the model was fed with the mass flows of fruit shells from dehulling, seed husks from de-husk and seed cake from oil extraction. In addition, according to the feed mass, a determined amount of water was introduced into the digester in order to achieve the optimal amount of biogas. The waste material of this process (digestate) may be returned to the fields because its high nitrogen phosphorous and potassium content is suitable as a fertilizer [14]. The Jatropha wastes have high contents of nutrients which are usually returned to the fields but, applying an anaerobic digestion stage before, increases the energy recovery from the fruit while preserving the nutrients. Biogas is counted as energy output of the entire system while the sludge wasted from the digested is considered as an energy saving due to its applicability as fertilizer and pesticide[2] in the Jatropha field or in other agricultural activities.

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[2] Jatropha fruit wastes are used as pesticides mainly because of their toxins contents.

6. Energy balance

Taking into consideration the complete production process of Jatropha biodiesel (i.e. the three main production blocks discussed and implemented in the model), an energy balance was included into the model in order to analyze the feasibility of Jatropha biodiesel for the different regions of Colombia, from both the energy and environmental stand point of view. Different energy factors were included for the various mass flows on a weight consumption basis as well as the energy consumptions from machines and production blocks.

Basically, two parameters were established; the Net Energy Balance (NEB) or Net Energy Gain (NEG) and the Net Energy Ratio (NER). These parameters are well known in life cycle energy analysis and provide an enormous tool to decision makers of this type of projects. NEG or NEB which is difference between the total energy outputs and the total energy inputs of the system, is one of the accepted indices for analyzing the energy efficiency of biofuels, as well as the NER which is the ratio of the total output energy to the total input energy [15][16].

A NEB greater than zero is a good indicator for Jatropha biodiesel which means that there is an effective gain of energy with good qualities on environmental issues, where normally fossil fuels receive a NEB smaller than zero. In the same way, a NER greater than the unit is typical of a process where a good energy gain is obtained while a NER equal or smaller than the unit shows a system of energy consumption with no gain or savings.

At the end, the model shows the energy balance of the complete process based on input parameters of the cultivation stage, namely the water supply, soil fertility level and fertilization schemes. With this model set up, the next step is to introduce this data from all the regions of Colombia and find out in which ones Jatropha biodiesel really shows up as a sustainable energy solution to be applied.

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Politecnico di Milano

Sustainable evaluation of Jatropha oil as a biofuel in Colombia

Colombia – Results and analysis of the model applied

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1. Introduction

Once the model proposed in the previous chapter has been tested, it is ready to work on the Colombian case of Jatropha biodiesel production chain from cultivation till the final product; Jatropha Curcas Methyl Ester or simply Jatropha biodiesel. As stated before, the model has three main input parameters which are the water supply to the cultivation stage, the soil fertility level and the fertilizer applied. Calculations of the model are based on a hectare per year so as the main input and output flows and the output of the model is an energy balance of the complete production chain. The main parameters for describing the energy performance of the process are the Net Energy Ratio (NER), which is the ratio of the net output energy to the net input energy of the system, and the Net Energy Balance (NEB) which defines the energy gain by the difference between the net input energy and the net output energy of the entire system.

To better evaluate the feasibility from the energy point of view of the Jatropha production process in Colombia, the model was applied in a by region scale. From a political and geographic stand point, Colombia is divided into 32 departments but the model is loaded with 23 regions. This was made for the sake of simplicity because there are some regions which have almost the same environment, rainfall and soil fertility level. Such is the case of the Amazonas region where departments were grouped due to their similarity in terms of forest, as well as the Orinoquia region due to its plains characteristics (see Table 2). So, an analysis by region is going to be done in order to determine the sustainability from the energy point of view.

2. Inputs

2.1. Water supply

Table 1 - Dry seeds yield (Source: Annex A [3])

Water supply	yield (kg/ha/y)	Soil fertility
Optimal (rainfall 1200 - 1500 mm)	6000	high
	2500	medium
	750	low
Normal (rainfall 700 - 1200 mm)	3500	high
	1500	medium
	500	low
Suboptimal (rainfall 500 - 700 mm or > 2500 mm)	1500	high
	750	medium
	250	low

As stated before, Jatropha trees are known for their resistance to drought situations as well as floods. The real problem of these two extreme situations is that the seed yield of the tree is heavily affected. Dry situations will result in low biomass and almost none fruit yields while a flood or too much rain will cause a big increase on the tree’s biomass (i.e. leaves, roots, etc.) but a low fruit yield as well [3]. Water supply for the Colombian case is specified in the model to be based only in annual rainfall (no irrigation applied at all), taking into consideration that the average rainfall of the country is high with respect to the requirements of Jatropha trees and also based on the actual Jatropha fields spread in Colombia [4]. This is why no irrigation is taken into the model but just the rainfall ranges of the different regions in Colombia (see Table 2 and Table 2).

Based on information from IDEAM[1] who is in charge in Colombia to study this particular issue of rainfall, a characterization by regions was performed in order to load such data to the model. Analyzing the rainfall of these regions, mean range values were extracted and assigned to the three categories of the water supply input; suboptimal, normal and optimal. Doing an observation of the data extracted it can be seen that the majority of the Colombian territory falls into the suboptimal level, a minority into the optimal and none into the normal range (see Table 2).

Table 2 – Rainfall and fertility level of Colombia by regions (Source: ref. [1][2])

Region	Rainfall [mm]			Fertility level
Amazonia	2500	3000	Suboptimal	low
Antioquia	3000	3500	Suboptimal	medium
Atlantico	1000	1500	Optimal	high
Bolivar	2000	2500	Suboptimal	high
Boyaca	1500	2000	Suboptimal	medium
Cauca	4000	4500	Suboptimal	medium
Cesar	2000	2500	Suboptimal	medium
Choco	5000	7000	Suboptimal	medium
Cordoba	1500	2000	Suboptimal	high
Cundinamarca	1000	1500	Optimal	medium
Eje cafetero	2000	2500	Suboptimal	medium
Huila	1500	2000	Suboptimal	medium
La guajira	500	1000	Suboptimal	low
Magdalena	1000	1500	Optimal	high
Nariño	2500	3000	Suboptimal	medium
Norte de Santander	2000	2500	Suboptimal	medium
Orinoquia	3000	3500	Suboptimal	low
San Andres y Providencia	1500	2000	Suboptimal	high
Santander	2500	3000	Suboptimal	medium
Sucre	1500	2000	Suboptimal	high
Tolima	1500	2000	Suboptimal	high
Valle del Cauca	2000	2500	Suboptimal	medium

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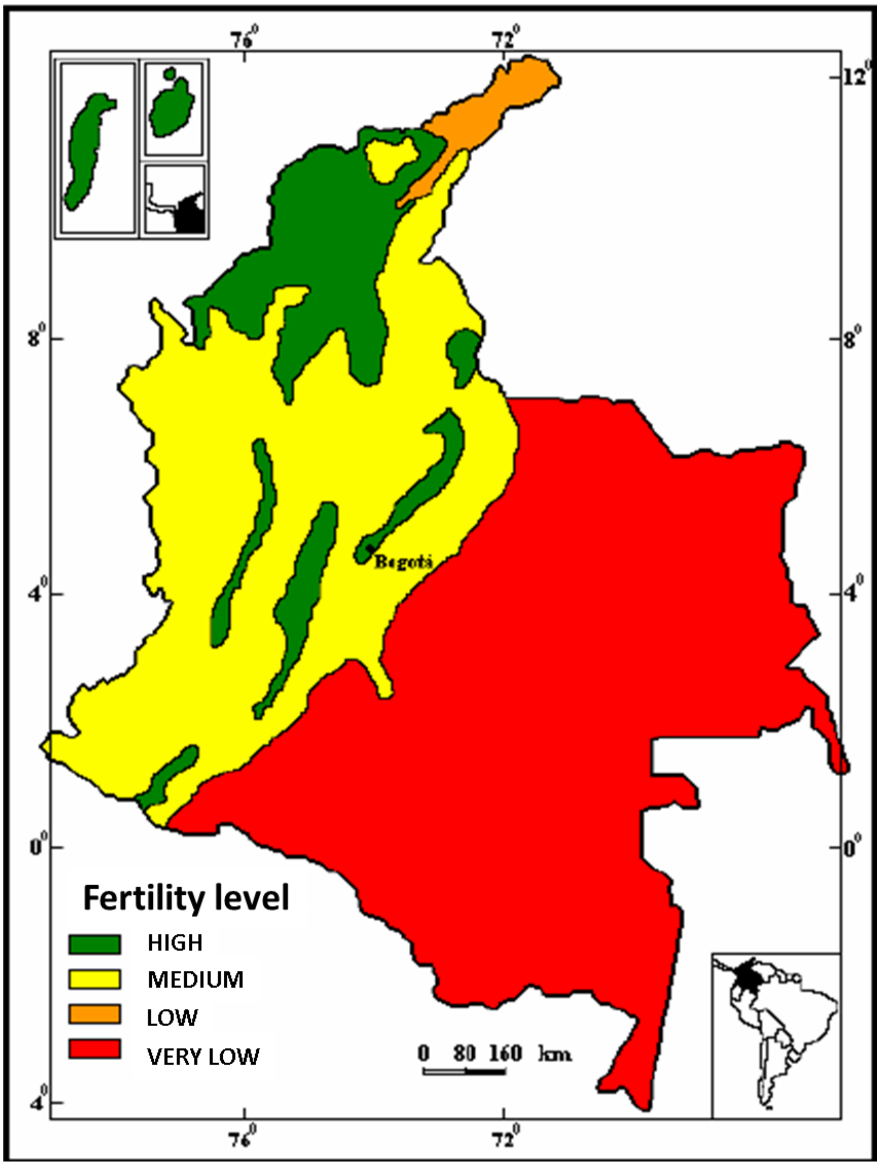
[1] IDEAM: Colombian institution of Hydrology, Meteorology and environmental studies.

From the data obtained it may be inferred that, in terms of water supply, Colombia is not quite suitable for an optimal performance of Jatropha trees due to the high rainfall along the country. Nonetheless, good results were thrown by the model and will be seen later, basically because there are some other factors affecting Jatropha trees yields.

2.2. Soil fertility level

Although Jatropha is a very low nutrient consumer, in order to achieve optimal performances and yields, it is required to apply fertilization schemes on Jatropha fields based on the soil fertility level (see Table 1). In that sense, a characterization of the soil is required to load this information to the model. A study on Colombia's soil was performed and reported the fertility of the entire territory into four levels; high, medium, low and very low (see Figure 1). These levels were used and applied to each region in the model in three levels (high, medium and low) taking low and very low into an only level.

Figure 1 – Natural fertility of Colombian soils. (Source: ref.[2])



It can be seen from the map that almost have of the territory has very low conditions of fertility (see Figure 1). These red areas are regions of vast forest where very low agricultural and industrial activities are performed (most likely in the southern region or Amazonia), or huge plains where the main activities are mineral and oil extraction as well as cattle activities (most likely to the eastern plains or Orinoquia region). In the Amazonia, the only places where there are human activities are in head cities or capital of the departments (see Figure 2 in Annex A). These human settlements are not connected to the electric grid for obvious reasons so they need to be auto sufficient in terms of energy and other resources. So, although it seems that Jatropha biodiesel production in these areas is not very feasible from the soil fertility point of view, still the model need to be run in order to assure this vague assumption because the idea of producing their own energy source is clearly a necessity. For the rest of the country it is observed that most of it has a medium level of soil fertility and even high in some regions from the center and north of the country.

2.3. Fertilization

The model was done to run under eight different fertilizers between organic and chemical. According to the production of Jatropha fruits of a certain hectare per year, a determined amount of fertilizer is required. Each fertilizer provides nutrients to the tree (separately) in such way that the amount of total fertilizer required for a determined field changes according to the type of fertilizer used. Generally, the amount of chemical fertilizer required is usually lower than the amount of organic fertilizer required, for instance dry cow manure, in a certain Jatropha field. Those equivalences are performed by the model and for each region of Colombia were applied separately to analyze the field performance from the energy point of view. It should be noticed that the model considers chemical fertilizers input flows as energy carriers due to the production process required to obtain those fertilizers.

Table 3 - Fertilizers used in the model

Chemical and Organic Fertilizers
NPK 15-15-15[2]
Dry cow manure
Dry chicken manure
Vermicompost
Chemical fertilizer (15-5-10)
Chemical fertilizer (12-2-10)
Digestate from biogas (NPK 15-15-15)
Urea (46%Nitrogen)

The fertilizers chosen for the model are listed in the Table 3 and the amounts used vary according to the soil fertility level. Thus, a high fertility level soil induces low fertilizer appliance and high yields while low fertility level soils work the opposite.

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[2] NPK 15-15-15 stands for a fertilizer of Nitrogen, Phosphorous and Potassium in which their respective content on a weight basis is 15% for Nitrogen, 15% for Phosphorous and 15% for Potassium. Same procedure applies for the other NPK fertilizers.

3. Outputs

3.1. Net Energy Ratio (NER)

One of the outputs of the model is the NER which is a suitable parameter for analyzing the energy flow of a determined system. It is the ratio of the net output energy to the net input energy of the system. A value higher than one is a common value achieved by biofuels due to the relatively low energy required to obtain them, while fossil fuels usually obtain a value minor than the unity. It should be said that the desired values are NER > 1 for Jatropha biodiesel, which means that the energy required to produce Jatropha biodiesel is much lower than the one fixed to the Jatropha biodiesel produced. It should be pointed out that, it is completely possible a NER<1 for Jatropha biodiesel production if the performance conditions of the system applied are poor enough to get this value. In the Table 4 the results of the model applied to each region of Colombia are reported accordingly to the fertilizer used.

Table 4 – Net Energy Ratio (NER) of the Jatropha biodiesel production according to different fertilizers per region of Colombia.

Region	Fertilizers applied							
	Vermicompost	Dry chicken manure	Dry cow manure	Chemical NPK15-15-15	Chemical NPK15-5-10	Chemical NPK12-2-10	Organic NPK15-15-15	Urea 46%N
Amazonia	3.0	3.0	3.0	0.2	0.7	0.7	0.2	0.8
Antioquia	5.7	5.7	5.7	0.8	2.5	2.6	0.8	2.7
Atlantico	9.2	9.2	9.2	6.3	6.9	7.0	6.8	7.2
Bolivar	7.3	7.3	7.3	3.0	5.5	5.6	5.4	5.7
Boyaca	5.7	5.7	5.7	0.8	2.5	2.6	0.8	2.7
Cauca	5.7	5.7	5.7	0.8	2.5	2.6	0.8	2.7
Cesar	5.7	5.7	5.7	0.8	2.5	2.6	0.8	2.7
Choco	5.7	5.7	5.7	0.8	2.5	2.6	0.8	2.7
Cordoba	7.3	7.3	7.3	3.0	5.5	5.6	5.4	5.7
Cundinamarca	8.2	8.2	8.2	2.4	2.9	3.0	4.5	3.2
Eje cafetero	5.7	5.7	5.7	0.8	2.5	2.6	0.8	2.7
Huila	5.7	5.7	5.7	0.8	2.5	2.6	0.8	5.7
La guajira	3.0	3.0	3.0	0.2	0.7	0.7	0.2	0.8
Magdalena	9.2	9.2	9.2	6.3	6.9	7.0	6.8	7.2
Nariño	5.7	5.7	5.7	0.8	2.5	2.6	0.8	2.7
Norte de Santander	5.7	5.7	5.7	0.8	2.5	2.6	0.8	2.7
Orinoquia	3.0	3.0	3.0	0.2	0.7	0.7	0.2	0.8
San Andres y Providencia	7.3	7.3	7.3	3.0	5.5	5.6	5.4	5.7
Santander	5.7	5.7	5.7	0.8	2.5	2.6	0.8	2.7
Sucre	7.3	7.3	7.3	3.0	5.5	5.6	5.4	5.7
Tolima	7.3	7.3	7.3	3.0	5.5	5.6	5.4	5.7
Valle del Cauca	5.7	5.7	5.7	0.8	2.5	2.6	0.8	2.7

First of all, it should be pointed out the relation between chemical and organic fertilizers with the NER. Organic fertilizers like manures develop the highest NER in all regions while chemical fertilizers like NPK 15-15-15 show values even below the unity. A reason for this situation may be the high energy content induced by chemical fertilizers. As it was said before, the energy used to elaborate chemical fertilizers is also counted in the model. As such, the energy added to the input is higher than that one when using organic fertilizers, increasing the overall input energy, thus, decreasing the NER.

In the Annex B, charts were included showing the overall input energy per production blocks for each kind of fertilizer. For instance, in the case of vermicompost fertilizer (organic), the energy demand share shows how the energy used in cultivation is high for those regions where the soil fertility level is low while in high fertility level soil occurs the opposite (see Figure 3). Instead, when the fertility level is high, the Jatropha seeds yield should be increased so the energy required to process those seeds should increase as well (i.e. oil extraction and trans esterification), which is the case of Atlantico and Magdalena in Figure 3.

Another example of this situation is shown in Figure 9 for NPK 15-15-15 (chemical). In low fertility level regions such as Orinoquia, the amount of energy demanded for cultivation is above 95% of the total input energy share. As this region requires high amounts of fertilizers and a chemical one is used, the energy consumption rises heavily. This results in a NER below the unit and an undesirable situation for Jatropha biodiesel production. Also, as the fertility level is so low, the seed yield is very poor so the energy required to process them is very low due to the low mass flow. Something similar occurs in regions like Cauca, Cesar and Choco, where the share for the cultivation block is almost the same, near to 95%. In general terms, the performance of the system in the entire territory is very poor while using NPK 15-15-15. Only Atlantico and Magadalena show good results and this is due to their optimal rainfall range and high fertility soil.

In the Annex B, a chart for each fertilizer's energy demand share was included for all Colombian regions (see Figure 5, Figure 7, Figure 11, Figure 13, Figure 15, Figure 17) to extrapolate the same analysis in all types of fertilizers. Using chemical fertilizers appears to be a disadvantage in certain regions. Taking a look to NPK 15-15-15 in Boyaca for instance, a NER < 1 shows that from the energy point of view is not sustainable to produce Jatropha biodiesel. It is required a higher amount of energy than that one that will be produced. The worst scenarios are those ones where NPK 15-15-15 is applied and in addition, the soil fertility level is low. A low fertility level forced a higher consumption of fertilizer, thus, a higher consumption of input energy and an even lower NER.

A particular case is that one of the organic fertilizer NPK 15-15-15 which basically is the digestate produced by the anaerobic digester after producing biogas from the residual wastes of the oil extraction process. It was included in the model with an equivalence ratio where 1 kg of digestate corresponded to 0.154 kg of fertilizer NPK 15-15-15. The result of the analysis and comparing both the organic and the chemical version of this NPK 15-15-15 show and increment on the NER for the organic case, proving what has been discussed till this point about the energy required to produce the fertilizer. The organic NPK 15-15-15 is recycled and in this way, some energy savings appear increasing the final NER. Looking region by region for both fertilizers it may be seen that in general terms the NER is higher for the organic although is the same type of fertilizer. The difference is based on the energy required or saved by producing them.

3.2. Net Energy Balance (NEB)

The other output of the model is the NEB which is an appropriate parameter for studying the energy flow in a defined system. It corresponds to the difference between the net energy output of the system and the net energy input of the same system. A NEB>0 means that the system has a gain of energy and for producing a certain amount of energy in the output, a lesser amount of primary energy is required. This is the common case of biofuels due to their low input energy requirements. On the other hand, a NEB<0 shows a system where the energy required at the input of the process is higher than that one at the output, in which case is a consumer system. Fossil fuels production is characterized to set in this kind of situation. Jatropha biodiesel production system is desirable to have a NEB>0 in order to be sustainable from the energy point of view. Nonetheless, it might happen that in the present study, some regions show up with a negative NEB indicating their poor performance due to factors such as the ones studied in the present model. In the Table 5 the results of the model applied to each region of Colombia are reported accordingly to the fertilizer used. Green values are positive NEB while red ones are negative NEB.

Table 5 - Net Energy Balance (NEB) of the Jatropha biodiesel production according to different fertilizers per region of Colombia. Values in MJ.

Region	Fertilizers applied							
	Vermicompost	Dry chicken manure	Dry cow manure	Chemical NPK15-15-15	Chemical NPK15-5-10	Chemical NPK12-2-10	Organic NPK15-15-15	Urea 46%N
Amazonia	2598.1	2598.1	2598.1	-16246.7	-1535.8	-1356.9	-16246.7	-918.7
Antioquia	9574.3	9574.3	9574.3	-2125.7	7007.7	7118.8	-2125.7	7390.8
Atlantico	82823.9	82823.9	82823.9	78268.7	79493.1	79637.2	58765.0	79990.3
Bolivar	20038.5	20038.5	20038.5	15483.3	19039.3	19082.5	14023.8	19188.4
Boyaca	9574.3	9574.3	9574.3	-2125.7	7007.7	7118.8	-2125.7	7390.8
Cauca	9574.3	9574.3	9574.3	-2125.7	7007.7	7118.8	-2125.7	7390.8
Cesar	9574.3	9574.3	9574.3	-2125.7	7007.7	7118.8	-2125.7	7390.8
Choco	9574.3	9574.3	9574.3	-2125.7	7007.7	7118.8	-2125.7	7390.8
Cordoba	20038.5	20038.5	20038.5	15483.3	19039.3	19082.5	14023.8	19188.4
Cundinamarca	33990.8	33990.8	33990.8	22290.8	25435.6	25805.8	22290.8	26712.7
Eje cafetero	9574.3	9574.3	9574.3	-2125.7	7007.7	7118.8	-2125.7	7390.8
Huila	9574.3	9574.3	9574.3	-2125.7	7007.7	7118.8	-2125.7	19188.4
La guajira	2598.1	2598.1	2598.1	-16246.7	-1535.8	-1356.9	-16246.7	-918.7
Magdalena	82823.9	82823.9	82823.9	78268.7	79493.1	79637.2	58765.0	79990.3
Nariño	9574.3	9574.3	9574.3	-2125.7	7007.7	7118.8	-2125.7	7390.8
Norte de Santander	9574.3	9574.3	9574.3	-2125.7	7007.7	7118.8	-2125.7	7390.8
Orinoquia	2598.1	2598.1	2598.1	-16246.7	-1535.8	-1356.9	-16246.7	-918.7
San Andres y Providencia	20038.5	20038.5	20038.5	15483.3	19039.3	19082.5	14023.8	19188.4
Santander	9574.3	9574.3	9574.3	-2125.7	7007.7	7118.8	-2125.7	7390.8
Sucre	20038.5	20038.5	20038.5	15483.3	19039.3	19082.5	14023.8	19188.4
Tolima	20038.5	20038.5	20038.5	15483.3	19039.3	19082.5	14023.8	19188.4
Valle del Cauca	9574.3	9574.3	9574.3	-2125.7	7007.7	7118.8	-2125.7	7390.8

Again, as in the previous case analyzed, chemical fertilizers drove up the net energy input of the system. In Table 5 it can be seen for example that, for regions of low fertility level soils like Amazonia or Orinoquia (see Table 2), the energy input is surely pushed by the fertilizer consumption in those cases which needs to be very high given the poor conditions of the soil. In fact, generally those regions are far apart of the big production and commercial centers of the country so, the energy required for transportation of chemicals will increase even harder the negative NEB. For the same regions, if organic fertilizer is used, it appears to be an energy gain which is achievable thanks to the savings on energy to produce fertilizers. We may say that in those regions is an imposition to work Jatropha biodiesel production based solely on organic fertilizers produced locally in order to accomplish a slightly sustainable production process from the energy point of view.

In the Annex B, a series of charts were attached for each type of fertilizer showing the net output, net input and the NEB for each region (see Figure 4, Figure 6, Figure 8, Figure 10, Figure 12, Figure 14, Figure 16, Figure 18). From all of them it may be infer what was discussed before of energy consumption due to chemical fertilizers. Only negative NEB are found for chemical fertilizers and specifically for those regions where either the fertility soil level is low or for those with suboptimal rainfall ranges.

On Table 5 it can be seen that the regions that have the best performance are Atlantico and Magdalena. Those two have the advantage to possess an optimal rainfall which combined with its medium fertility soil level, produces the best practice of the country. NEB of those two regions show to be higher than, in a significant proportion, the rest of regions of Colombia. In a lesser proportion, regions like Bolivar or Santander still show a positive NEB which may be exploded. From those two it can be also extracted that not only the fertilizers play an important roll in yields but also the rainfall ranges where suboptimal conditions impose low yields and thus, low output energy.

A particular case rises up and is the case of San Andres y Providencia. This region is a set of islands in the northern Caribbean sea which, due to its geographic situation, are completely not connected to the national grid. Their energy supply is based on what they can buy or produce in the island. Jatropha biodiesel production in this island shows a positive NEB and in a relatively high scale. Although the rainfall range is suboptimal, the fertility soil level is high which increases the Jatropha seed yields at a low fertilizer cost in terms of energy input. This suggests that the application of this energy supply in the islands may work efficiently towards sustainability and energy security.

Also another important fact to be pointed out is that, Bogota is located in the region of Cundinamarca which, according to Table 5, has an important and positive NEB. Cities like Bogota in Colombia are starting to demand diesel in a big proportion and their demand increase is very noticeable. So, assuring a good supply of biodiesel energy in the region will contribute positively to the cities energy demand and as we can see, Cundinamarca shows up as a good provider of biodiesel from the energy point of view.

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Annex A – Map of Colombia

Figure 2 – Geographic and political regions of Colombia (Source: IGAC[3]).

Fuente: IGAC, Atlas de Colombia, 1999

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[3] IGAC: National Geographic Institute Agustin Codazzi.

Annex B – Results of model applied to Colombia

Figure 3 - Shares of energy demand by production block of Jatropha biodiesel per region in Colombia (Fertilizer: Vermicompost)

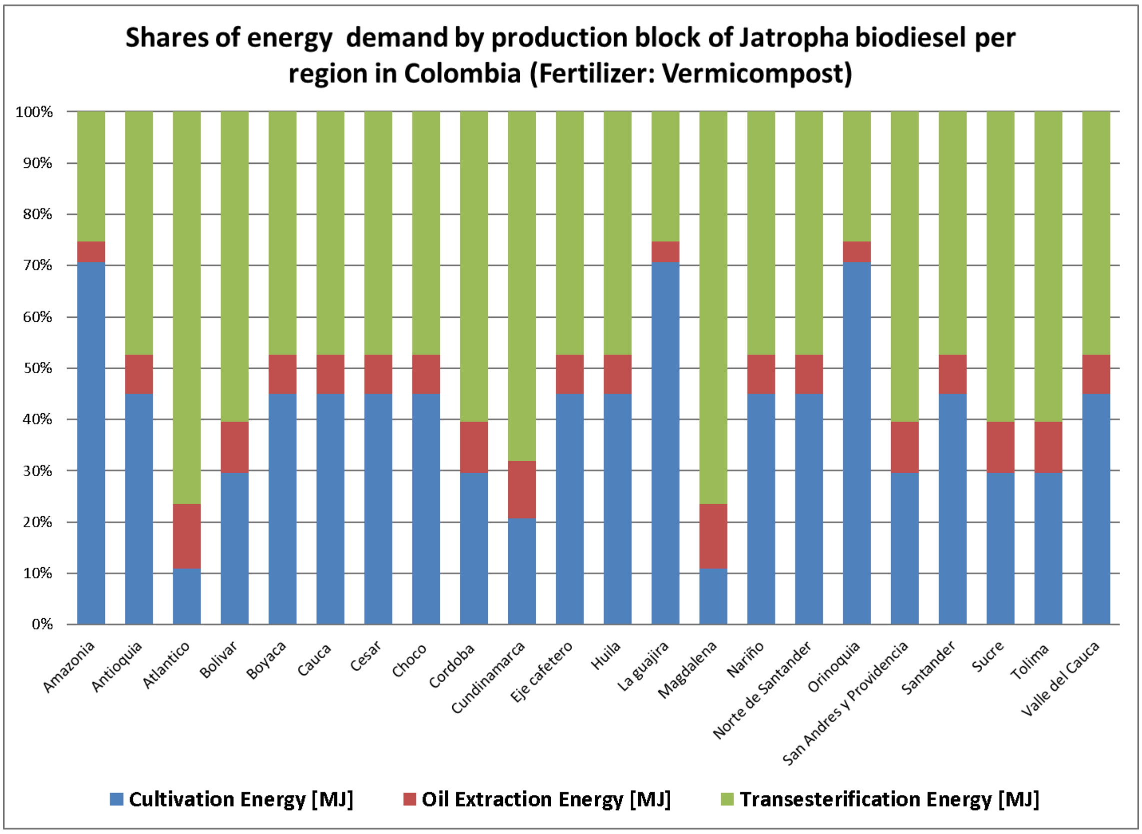


Figure 4 - Net Energy Balance (NEB) of Jatropha biodiesel production per region of Colombia (Fertilizer: Vermicompost)

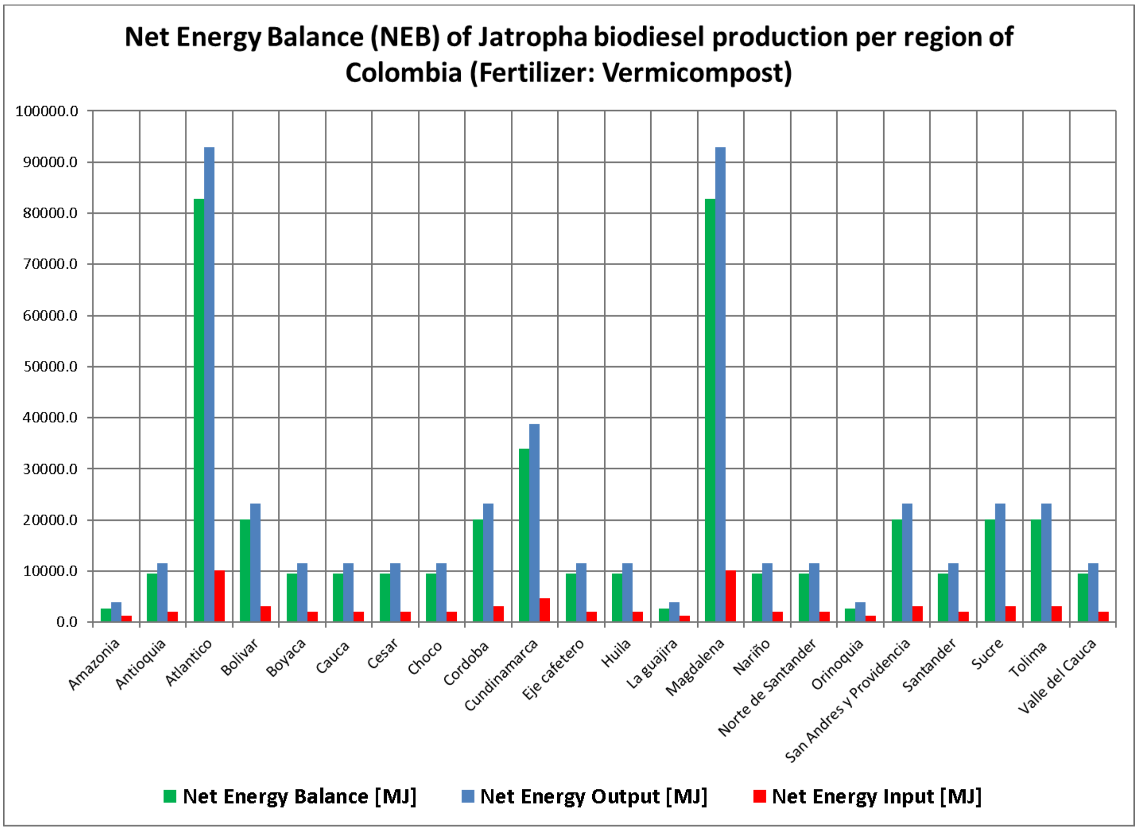


Figure 5 - Shares of energy demand by production block of Jatropha biodiesel per region in Colombia (Fertilizer: Dry chicken manure)

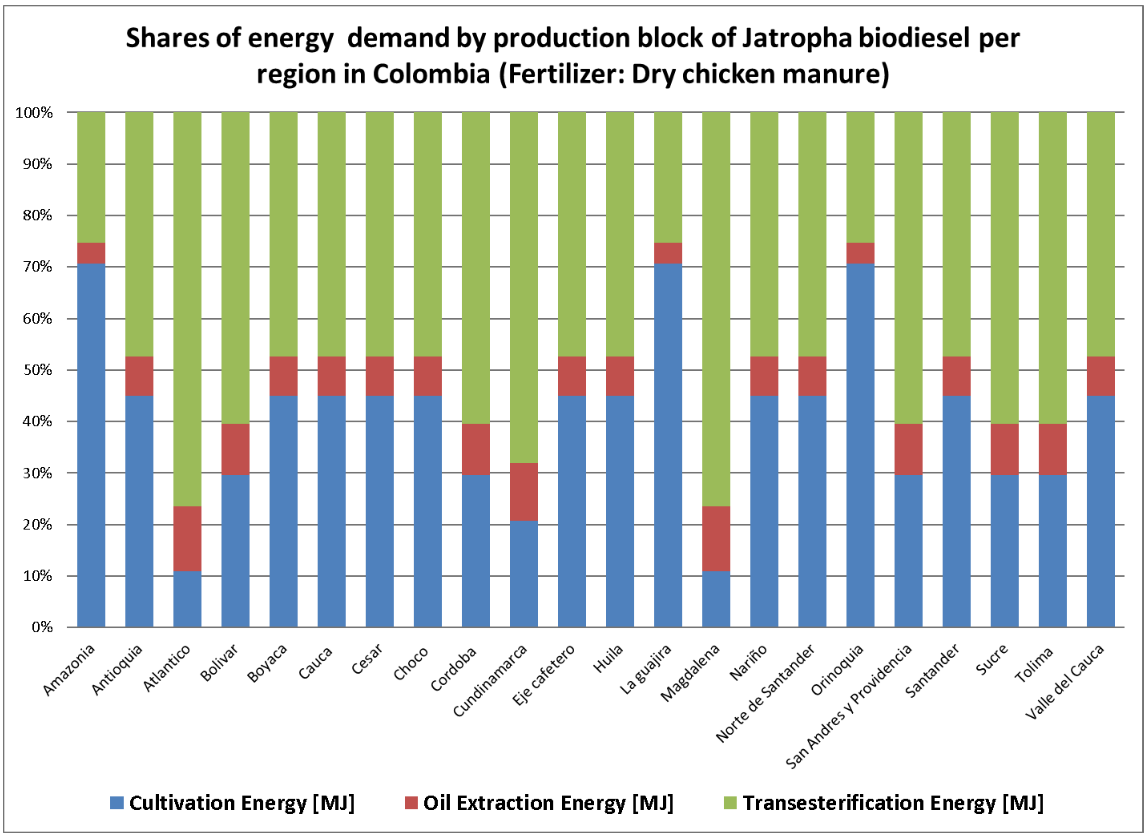


Figure 6 - Net Energy Balance (NEB) of Jatropha biodiesel production per region of Colombia (Fertilizer: Dry chicken manure)

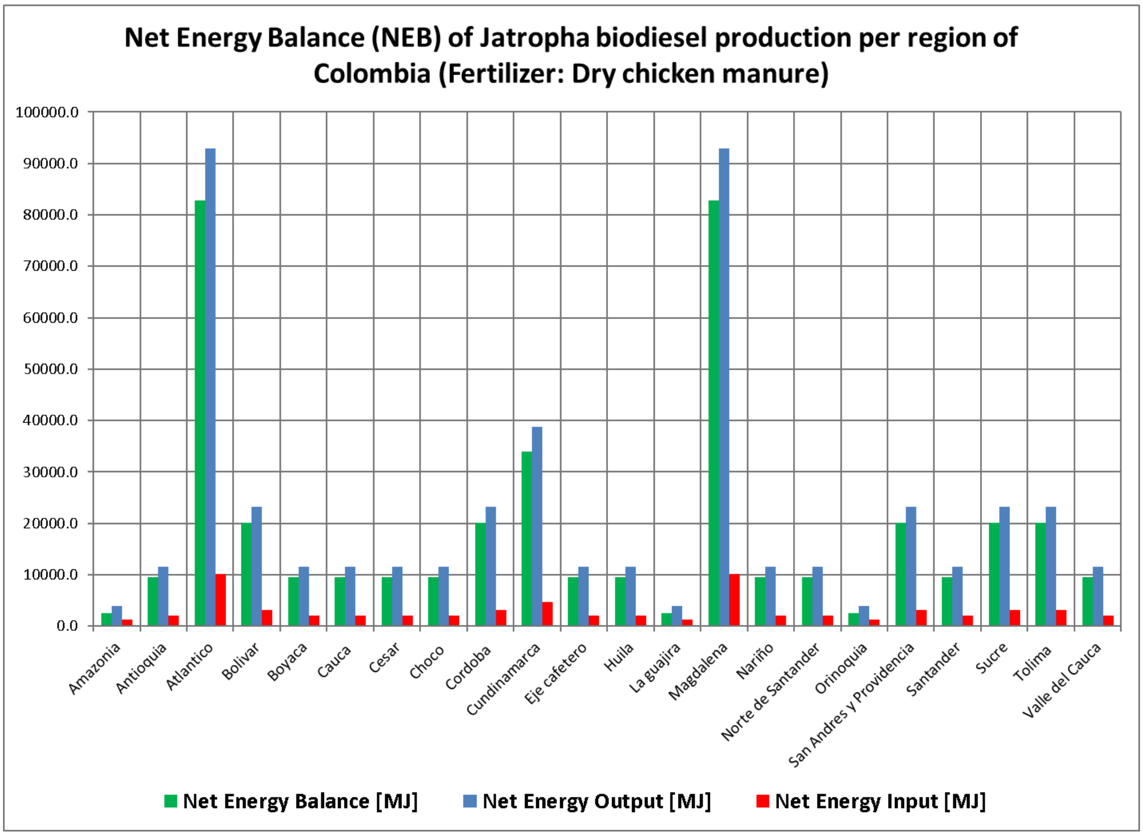


Figure 7 - Shares of energy demand by production block of Jatropha biodiesel per region in Colombia (Fertilizer: Dry cow manure)

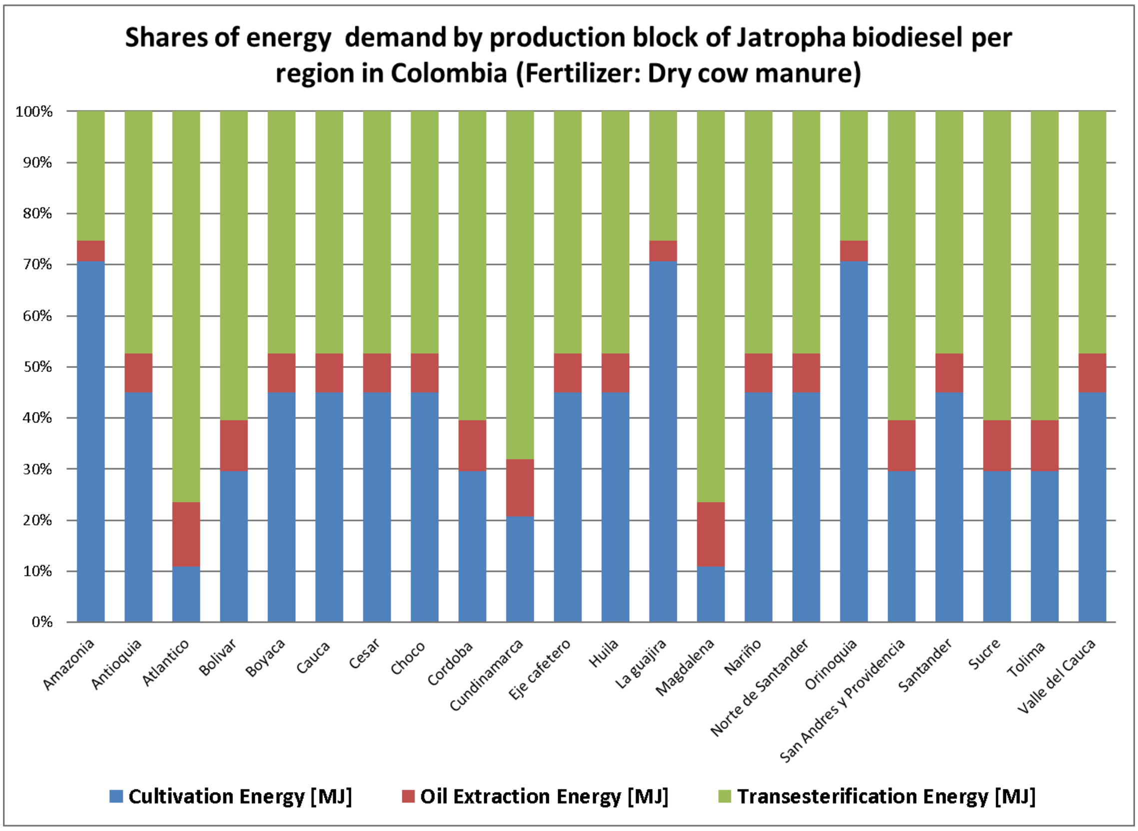


Figure 8 - Net Energy Balance (NEB) of Jatropha biodiesel production per region of Colombia (Fertilizer: Dry cow manure)

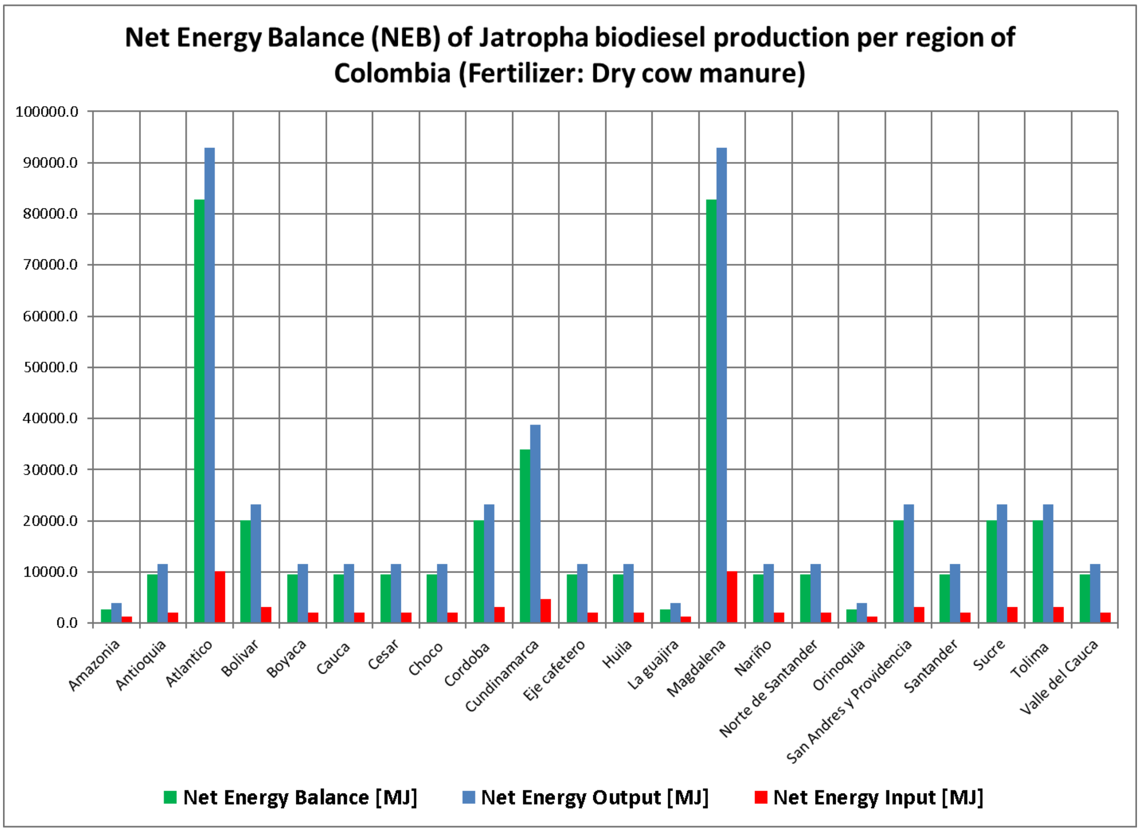


Figure 9 - Shares of energy demand by production block of Jatropha biodiesel per region in Colombia (Fertilizer: Chemical NPK 15-15-15)

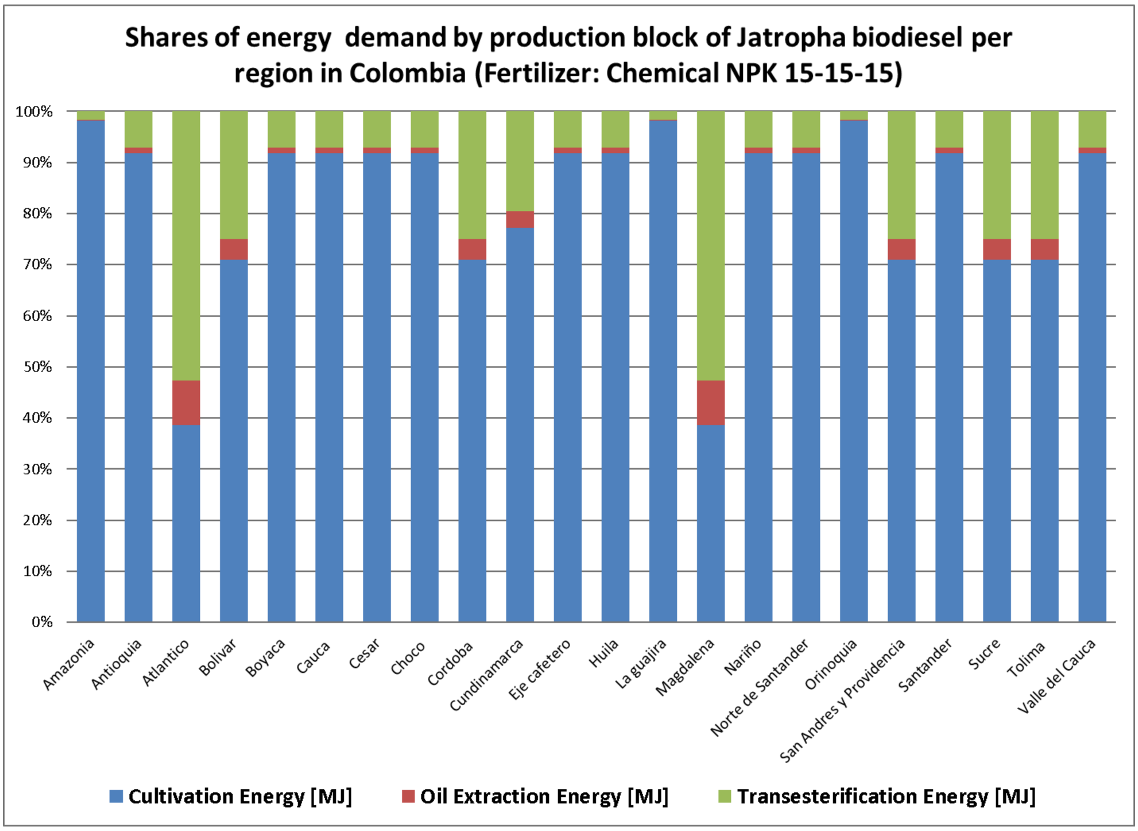


Figure 10 - Net Energy Balance (NEB) of Jatropha biodiesel production per region of Colombia (Fertilizer: Chemical NPK 15-15-15)

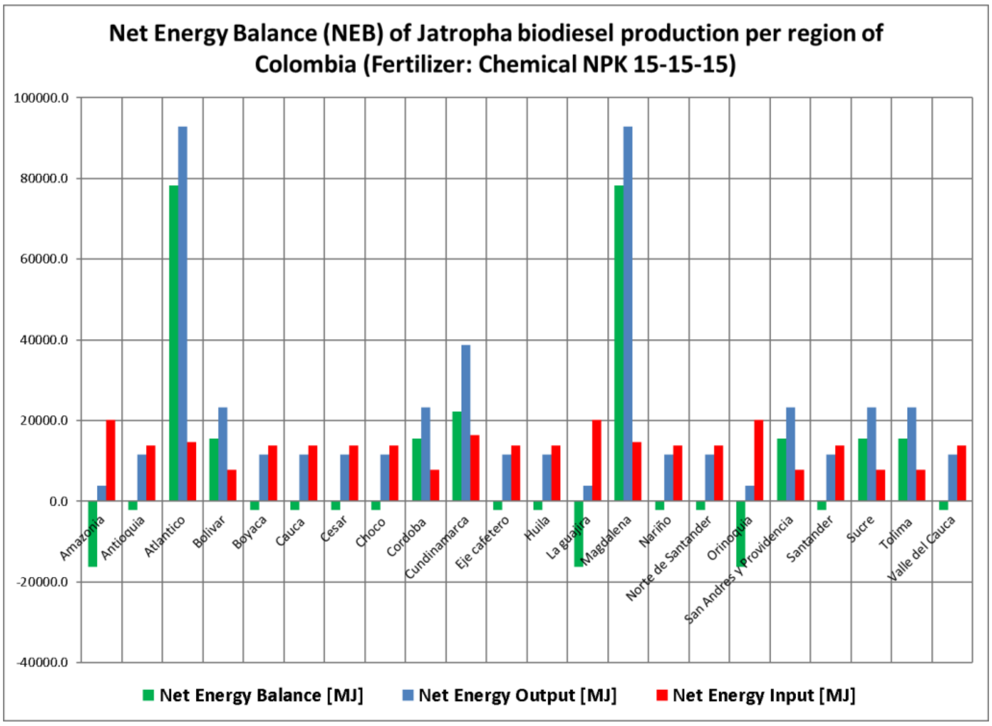


Figure 11 - Shares of energy demand by production block of Jatropha biodiesel per region in Colombia (Fertilizer: Chemical NPK 15-5-10)

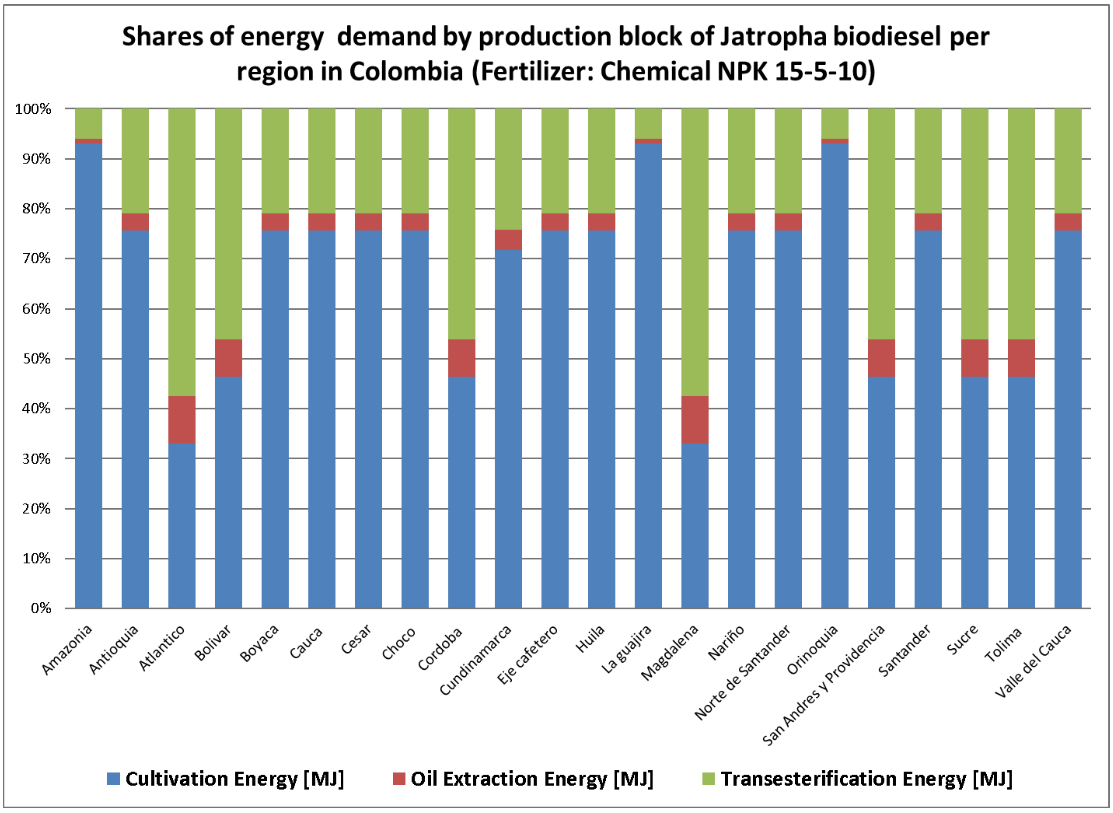


Figure 12 - Net Energy Balance (NEB) of Jatropha biodiesel production per region of Colombia (Fertilizer: Chemical NPK 15-5-10)

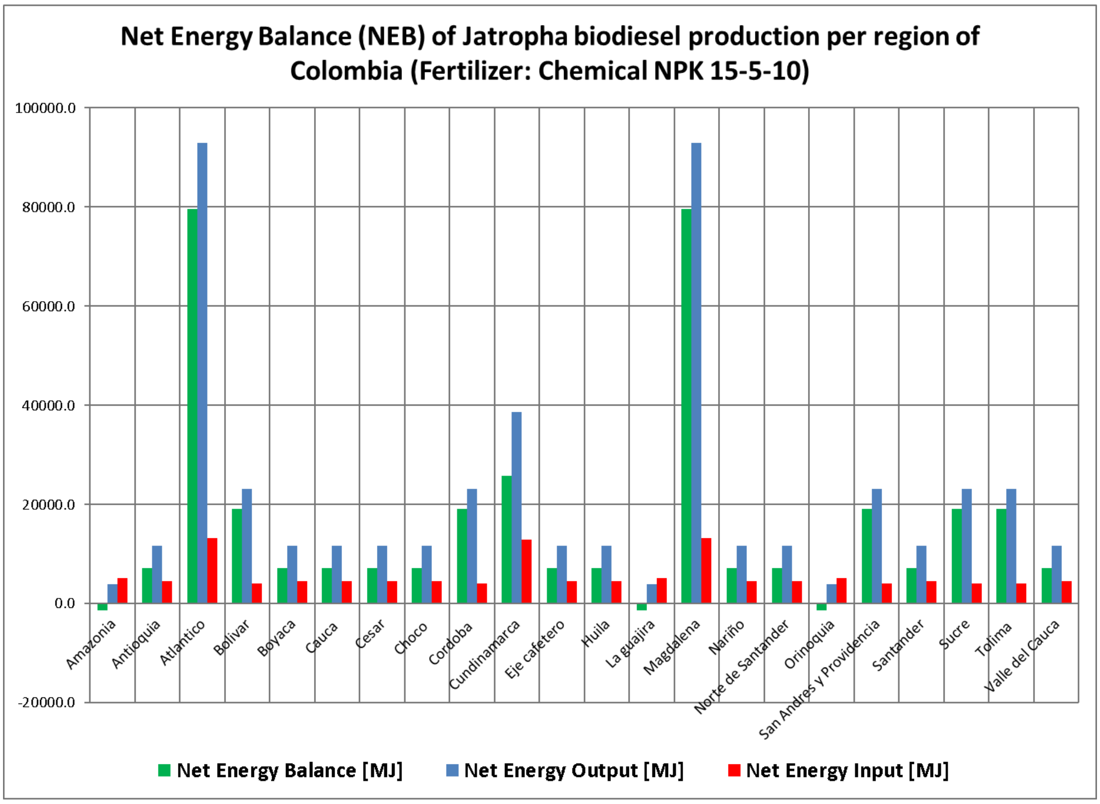


Figure 13 - Shares of energy demand by production block of Jatropha biodiesel per region in Colombia (Fertilizer: Chemical NPK 12-2-10)

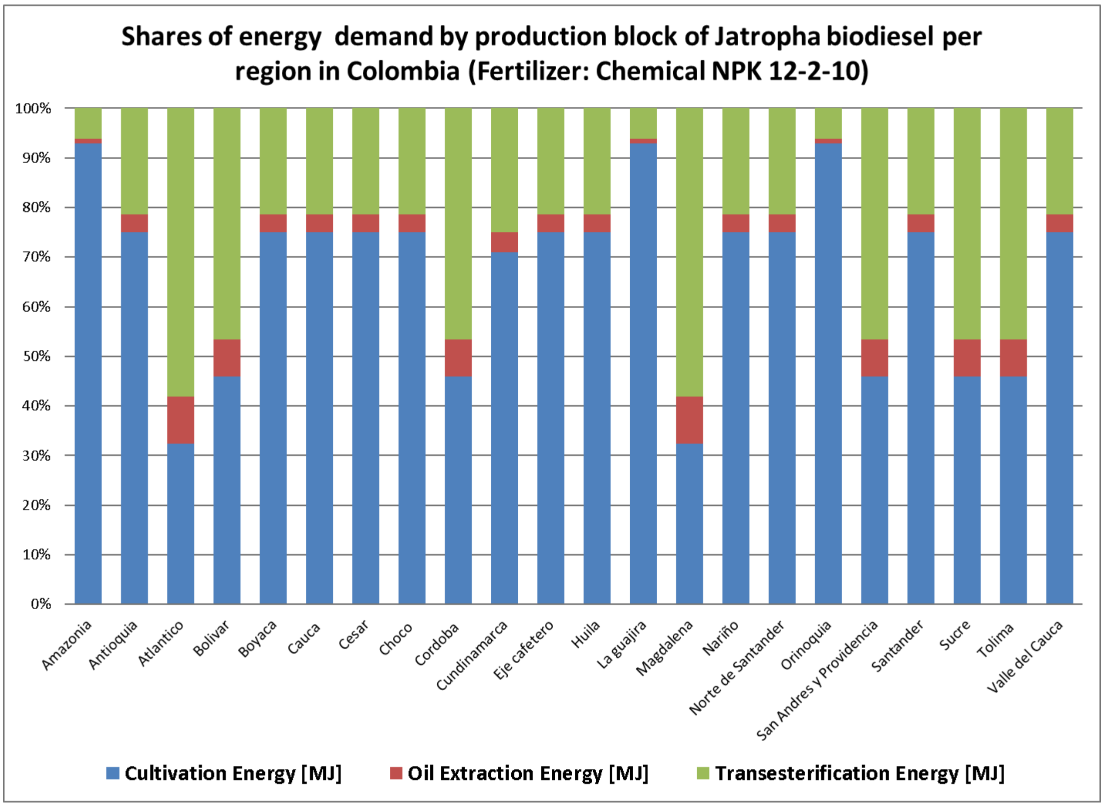


Figure 14 - Net Energy Balance (NEB) of Jatropha biodiesel production per region of Colombia (Fertilizer: Chemical NPK 12-2-10)

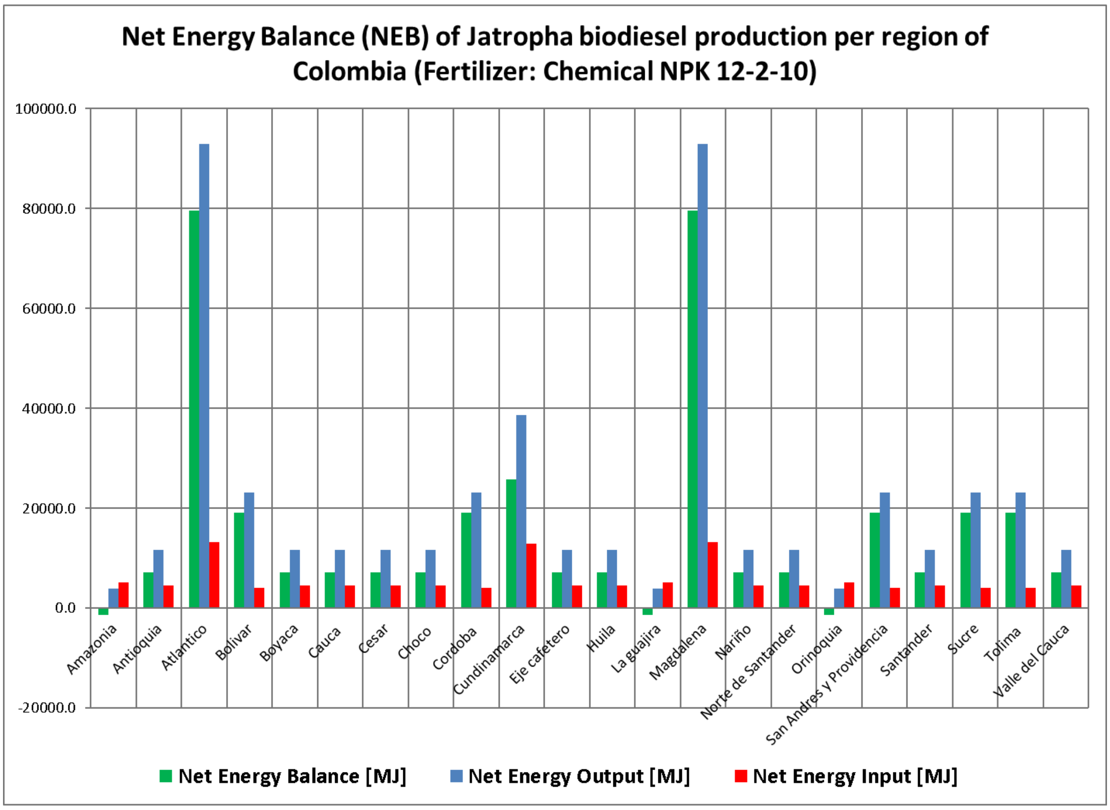


Figure 15 - Shares of energy demand by production block of Jatropha biodiesel per region in Colombia (Fertilizer: Organic NPK 15-15-15)

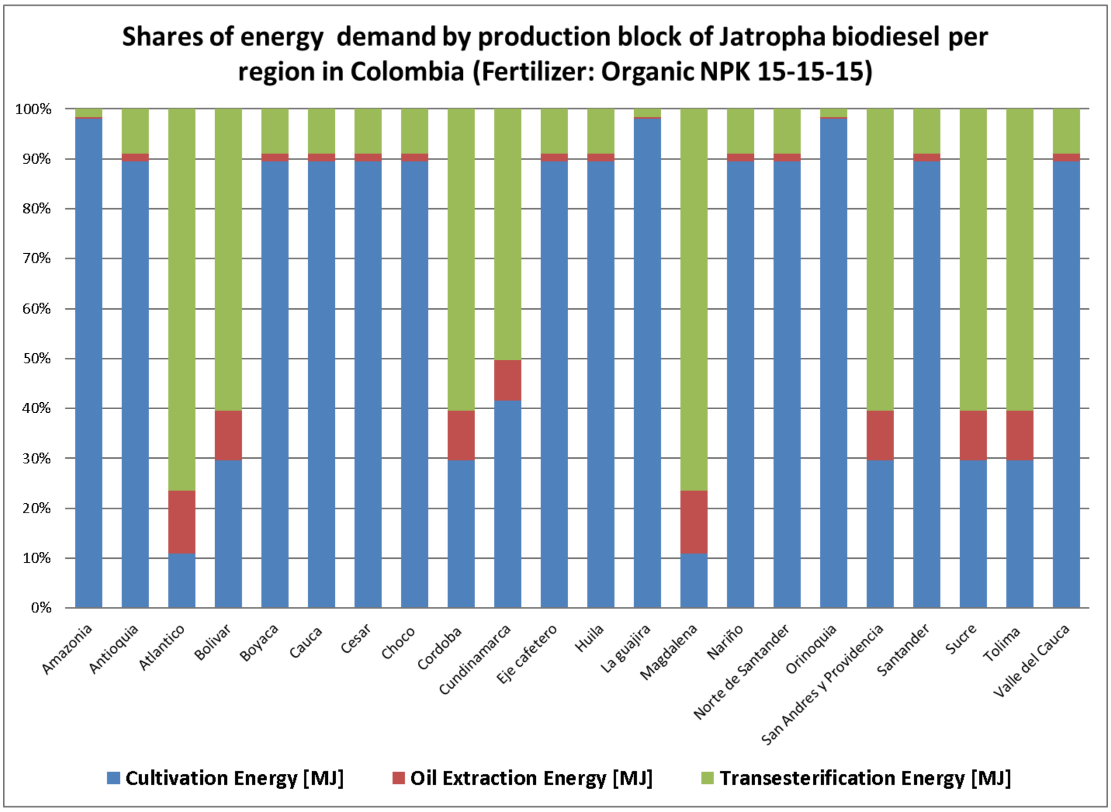
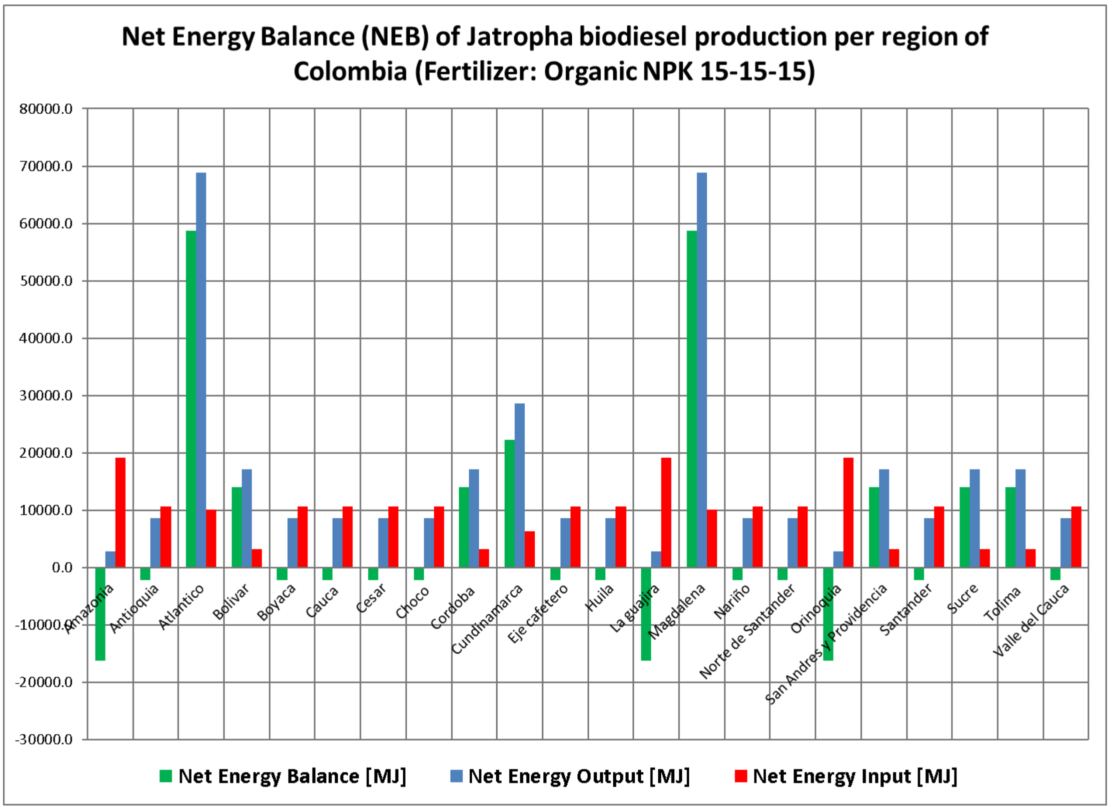


Figure 16 - Net Energy Balance (NEB) of Jatropha biodiesel production per region of Colombia (Fertilizer: Organic NPK 15-15-15)



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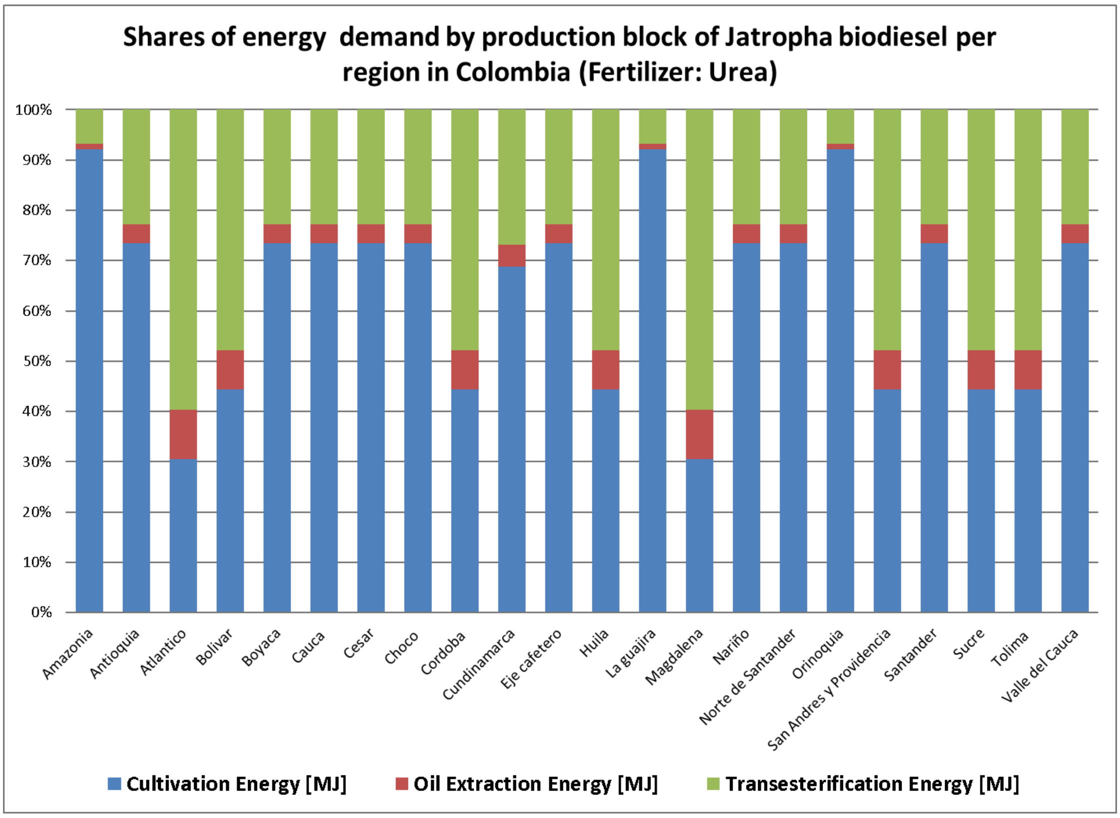
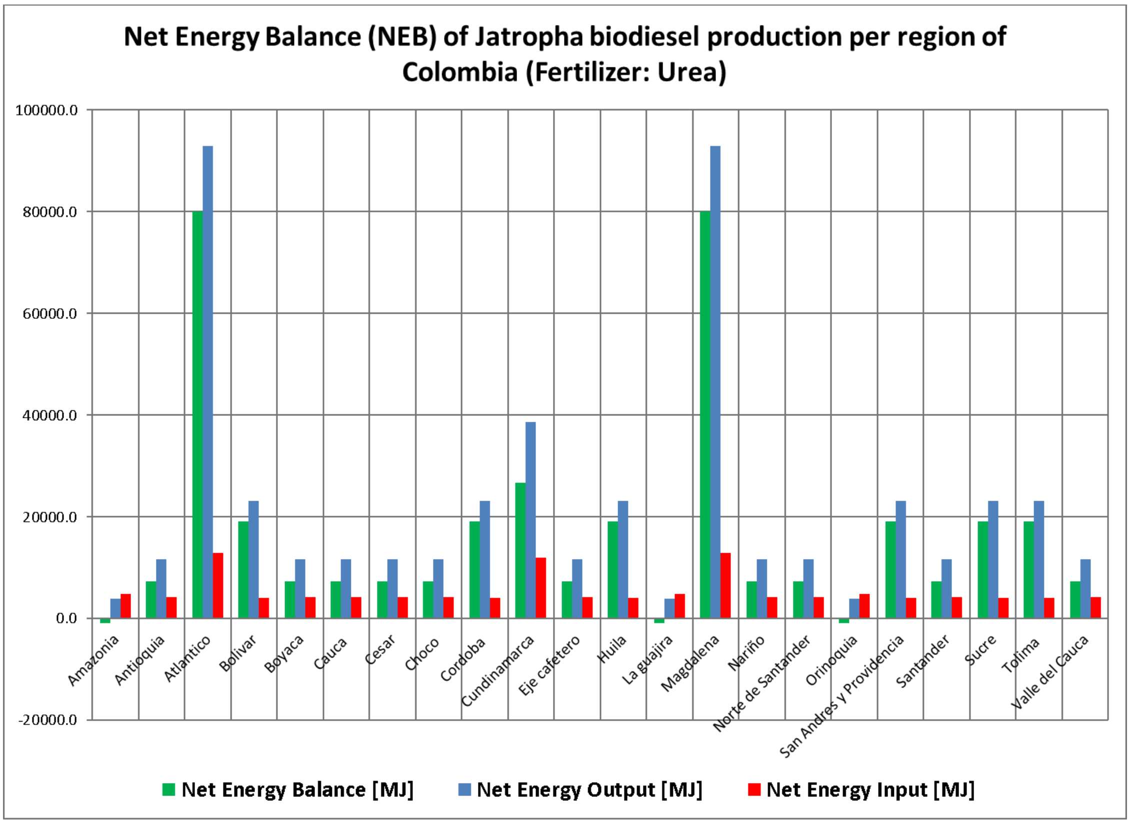


Figure 18 - Net Energy Balance (NEB) of Jatropha biodiesel production per region of Colombia (Fertilizer: Urea)



Politecnico di Milano

Sustainable evaluation of Jatropha oil as a biofuel in Colombia

Sustainable evaluation and conclusions – key issues for Colombia

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Master thesis – Energy Engineering for an Environmentally Sustainable World
Politecnico di Milano – Piacenza, 2014

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1. Introduction

The actual worldwide interest on biofuels is increasing greatly to the point that special attention should be paid to its sustainability. The biodiesel production should meet a set of requirements in that sense that still are in study period. In developing countries, the biodiesel shows up as an opportunity to diversify its energy mix, generating rural growth and increasing energy security. Today, Colombia's economy rhythm is rising prominently pulling up key production sectors such as the energy one; it is said that the economy of a country is directly linked to its energy demand. Hence, this country which is already in route of producing biofuels on a well-established policy basis and on a "full gas" attitude of growing its actual production, sustainable evaluations should be responsible done.

It is said that sustainability has a three dimension perspective based on the economic, social and environmental points of view which, in the case of biodiesel production, should be analyzed together along. The economic aspect investigates the feasibility of a project, if the business makes sense, if there are enough stable competitive conditions to be exploited, what kind of impacts it may have (for instance food prices in our case), etc. Then again, the environmental stand point explores criteria such as GHG[1] emissions, energy balances, land use change (LUC), carbon stocks, productive capacities, pressure upon resources like water and soil, and its impacts over the environment such as water, air pollution and biodiversity. Last but not least, the social sustainability embraces issues of rural development, community participation, and labor-land policies [1]. The aim of this document is to analyze in detail the environmental issues and in addition some general things from both economic and social sustainability.

2. GHG emissions in Colombia

An inventory was performed in Colombia in the year 2004 and published in 2009, anthropogenic emissions were calculated, basically carbon dioxide (CO_2), methane (CH_4) and nitrogen oxides (NO_x) and some others contained in international agreements of climate change. The calculations were done based on the Global Warming Potential (GWP) of each gas emitted according to the IPCC[2] factors. The report of the general results is found in the Annex A (see Table 3) divided into the main productive sectors of Colombia that emit GHG (i.e. Energy, industry, agriculture, land use and land use change (LUC), residual wastes management).

Taking into consideration the impacts of Jatropha biodiesel production and use, the following are the sectors that may be directly impacted. The Energy sector contributes with 36.65% of the total emissions where 85% is due to the combustion of fossil fuels (mainly energy generation and transportation). The agriculture sector adds to the share with 38.09% of the total emissions in the country, where the utilization of Nitrogen fertilizers is responsible for a 47.54% and finally, LUC is responsible for 14.45% of the total national share (see Figure 1).

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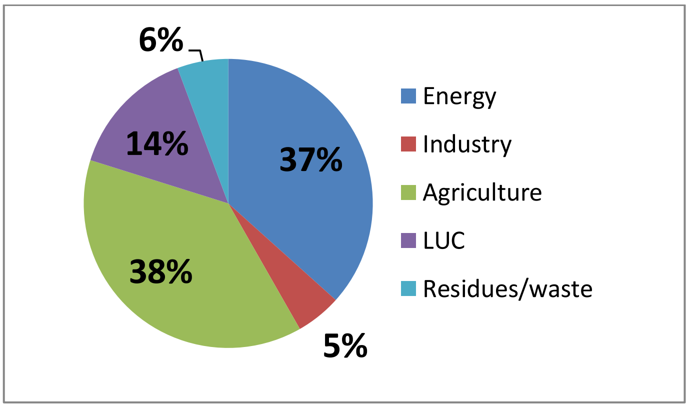
[1] GHG: Greenhouse gasses.

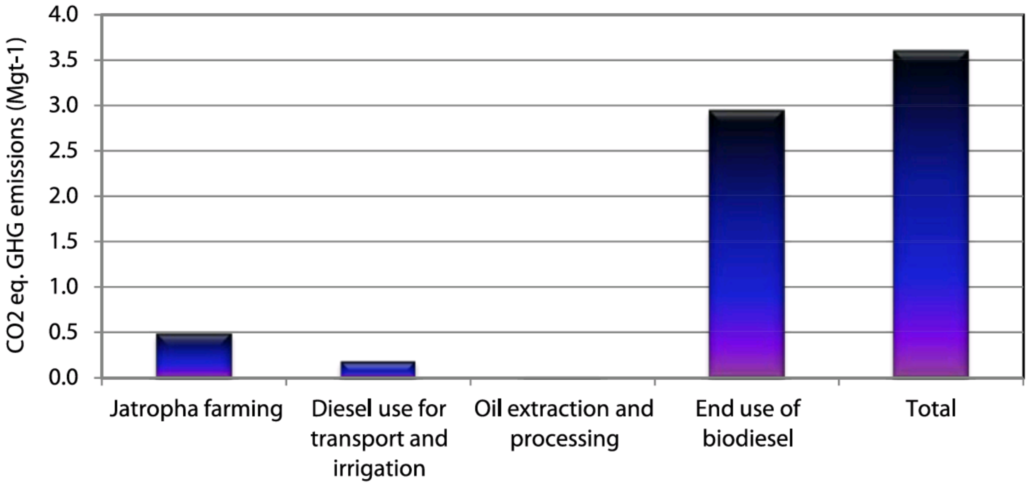
[2] IPCC: Intergovernmental Panel on Climate Change.

Figure 1 – GHG emissions in Colombia by sectors (Source: ref. [2] and Annex A)



The share of energy can be mitigated with the gradual implementation and usage of biodiesel in generation and transportation. Jatropha biodiesel, just as other biofuels, reduce GHG basically by decreasing the net addition of CO_2 to the atmosphere. Moreover, it produces less particulate matter, hydrocarbons, nitrogen oxides and sulphur oxides than fossil diesel [3] In terms of transportation it is clear that the big contribution to GHG comes from this item and not from the production of the biodiesel itself as it may be extrapolated from the Tanzanian case [4]. So, all in all, the combustion of Jatropha biodiesel contributes to the mitigation of GHG in Colombia.

Figure 2 - GHG emissions in the production and use of Jatropha in Tanzania (Source: ref. [4])



Nonetheless, as we saw from the model proposed, the fertilization has high amounts of Nitrogen which not only boosts the energy input of the production system but it also contributes to GHG emissions due to the NO_x emissions from Jatropha fields. Even though this is a negative parameter for agriculture in Colombia, taking into consideration a study performed on biofuels in Colombia which did an assessment of GHG emissions in the country for oil palm and sugar cane (biofuels feedstocks in Colombia) which concluded that Colombian biofuels fulfill the international standards of GHG mitigation, and also considering the fact that Jatropha consumes less nutrients than the both of them, it may be inferred that Jatropha cultivation also meets the actual GHG mitigation programs.

From the LUC point of view, the space available in Colombia for agriculture is estimated in 20 million hectares located mainly in savannah and scrub forests bringing high opportunities for

Jatropha cultivation [5]. In 2009, a thesis to identify the most suitable areas of Colombia to grow Jatropha from the biophysics and social economic[3] point of view was done from a total of 77.084.656 hectares available in Colombia (67% of the national territory). From this offered area (see Table 1), it was found that 0.9% was highly suitable without any competition on land use, 2.7% was moderately suitable without land use competition and, with conflict due to land competition use, 0.05% was found highly suitable and 0.5% discreetly suitable. Both, highly and Moderate suitable options consider almost no direct land use change causing a depletion of carbon stocks and thus, an increase in the net GHG emissions.

Table 1 – Area per region and per level of aptitude to cultivate Jatropha (Source: ref. [6])

Region	Aptitude level for cultivation of Jatropha			
	Highly suitable [ha]		Moderate suitable [ha]	
Amazonia	0	0.0%	0	0.0%
Antioquia	21931	3.3%	7356	0.3%
Atlantico	13919	2.1%	0	0.0%
Bolivar	35994	5.3%	430800	18.5%
Boyaca	0	0.0%	0	0.0%
Cauca	0	0.0%	781	0.0%
Cesar	154119	22.9%	355200	15.3%
Choco	0	0.0%	2513	0.1%
Cordoba	287944	42.7%	361781	15.6%
Cundinamarca	738	0.1%	53256	2.3%
Eje cafetero	0	0.0%	7969	0.3%
Huila	238	0.0%	75175	3.2%
La guajira	0	0.0%	187031	8.0%
Magdalena	51063	7.6%	393681	16.9%
Nariño	0	0.0%	38469	1.7%
Norte de Santander	0	0.0%	10375	0.4%
Orinoquia	0	0.0%	0	0.0%
San Andres y Providencia	0	0.0%	0	0.0%
Santander	0	0.0%	1256	0.1%
Sucre	72875	10.8%	223381	9.6%
Tolima	35531	5.3%	155988	6.7%
Valle del Cauca	0	0.0%	20481	0.9%

In general terms, it was determined the positive viability for Jatropha in Colombia from this point of view [6]. In an assessment perform with Jatropha it was reported a GHG emission of 29.16 gCO_2e/MJ which according to a study performed in the same work, corresponds to more than twice the emission of oil palm. The key issue here was that it was performed without taking into consideration any recovery of energy like the anaerobic digester in the present model or the recycle of oil extraction residues as fertilizers. They conclude that regardless this value, Jatropha is

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[3] It also considered regions where indigenous tribes were settled, or other social issues in which case, the land is protected by law and cannot be used for any commercial, agricultural or industrial activity.

considered as a potential oil palm compliment and for sure proved to be environmental sustainable [7].

3. Energy balance and land use

A proper exercise would be to analyze both, the aptitude of the land to cultivate Jatropha from the biophysics and social economic point of view and the performance of the land to produce Jatropha fruits, in order to better understand the whole panorama of energy and environment (see Table 1 and Table 2).

For example, taking a look to Atlantico and Magdalena which proved to have the best energy performances for producing Jatropha biodiesel, it can be seen that 2.1% of the land in Atlantico corresponds to a highly suitable situation while Magdalena has a 7.6% of the total amount of the country's highly suitable lands for Jatropha which in total correspond to nearly 65000 ha to produce Jatropha biodiesel at optimal conditions. Using the model, this is equivalent to say that between the two regions they would be able to produce nearly 86 million liters of Jatropha biodiesel per year once the trees are producing (@1335 lts/ha/year). This corresponds to almost 25 % of the biodiesel production of the country in 2011 (see State of the art chapter, section Biofuels in Colombia). In addition, if we count the moderate land from Magdalena, the total amount of land would increase to nearly 550000, thus an ideally total production of more or less 734 million litters which means around 194 million gallons which is higher than the 140 million gallons of biodiesel produced in 2011, doubling the Colombian production just from those two region's lands under an environmental sustainable scheme.

Table 2 – Net Energy Ratio (NER) of the Jatropha biodiesel production according to different fertilizers per region of Colombia (Source: results of the model proposed)

Region	Fertilizers applied							
	Vermicompost	Dry chicken manure	Dry cow manure	Chemical NPK15-15-15	Chemical NPK15-5-10	Chemical NPK12-2-10	Organic NPK15-15-15	Urea 46%N
Amazonia	3.0	3.0	3.0	0.2	0.7	0.7	0.2	0.8
Antioquia	5.7	5.7	5.7	0.8	2.5	2.6	0.8	2.7
Atlantico	9.2	9.2	9.2	6.3	6.9	7.0	6.8	7.2
Bolivar	7.3	7.3	7.3	3.0	5.5	5.6	5.4	5.7
Boyaca	5.7	5.7	5.7	0.8	2.5	2.6	0.8	2.7
Cauca	5.7	5.7	5.7	0.8	2.5	2.6	0.8	2.7
Cesar	5.7	5.7	5.7	0.8	2.5	2.6	0.8	2.7
Choco	5.7	5.7	5.7	0.8	2.5	2.6	0.8	2.7
Cordoba	7.3	7.3	7.3	3.0	5.5	5.6	5.4	5.7
Cundinamarca	8.2	8.2	8.2	2.4	2.9	3.0	4.5	3.2
Eje cafetero	5.7	5.7	5.7	0.8	2.5	2.6	0.8	2.7
Huila	5.7	5.7	5.7	0.8	2.5	2.6	0.8	5.7
La guajira	3.0	3.0	3.0	0.2	0.7	0.7	0.2	0.8
Magdalena	9.2	9.2	9.2	6.3	6.9	7.0	6.8	7.2
Nariño	5.7	5.7	5.7	0.8	2.5	2.6	0.8	2.7
Norte de Santander	5.7	5.7	5.7	0.8	2.5	2.6	0.8	2.7
Orinoquia	3.0	3.0	3.0	0.2	0.7	0.7	0.2	0.8
San Andres y Providencia	7.3	7.3	7.3	3.0	5.5	5.6	5.4	5.7
Santander	5.7	5.7	5.7	0.8	2.5	2.6	0.8	2.7
Sucre	7.3	7.3	7.3	3.0	5.5	5.6	5.4	5.7
Tolima	7.3	7.3	7.3	3.0	5.5	5.6	5.4	5.7
Valle del Cauca	5.7	5.7	5.7	0.8	2.5	2.6	0.8	2.7

Another example is the one performed with Cesar and Cordoba which have the highest amounts of land between highly suitable and moderate suitable land (see Table 1). In total for highly suitable land between both regions there are 442000 ha. Using the model, an average value of production for both region is 250 lts/ha/year which produces a total of 110 million liters or 29 million gallons which is even more than the production of the optimal regions stated before (i.e. Atlantico and Magdalena). Now taking into account the moderate suitable lands from the same regions, a total of 1.160 million of ha is available to produce 290 million lts or 76.5 million gallons of Jatropha biodiesel which is 50% of the production in 2011 of biodiesel in Colombia. Both cases have excellent energy performances and may help to attend the national demand of biodiesel in and environmentally sustainable way.

Similar analysis can be performed to different regions of the country, where in terms of environment sustainability, the NER brings a good tool to infer good performances and decline whether there are poor performances like the extreme cases of Amazonia, Orinoquia and La guajira. In general terms, Colombia shows good performances in at least 50% of its territory to produce Jatropha biodiesel but due to some biophysics and socio economic issues it is not applicable in all the regions. Nevertheless, it is shown that Colombia has a good scenario facing towards a possible expansion of its biodiesel production based not only in oil palm but in Jatropha Curcas as well.

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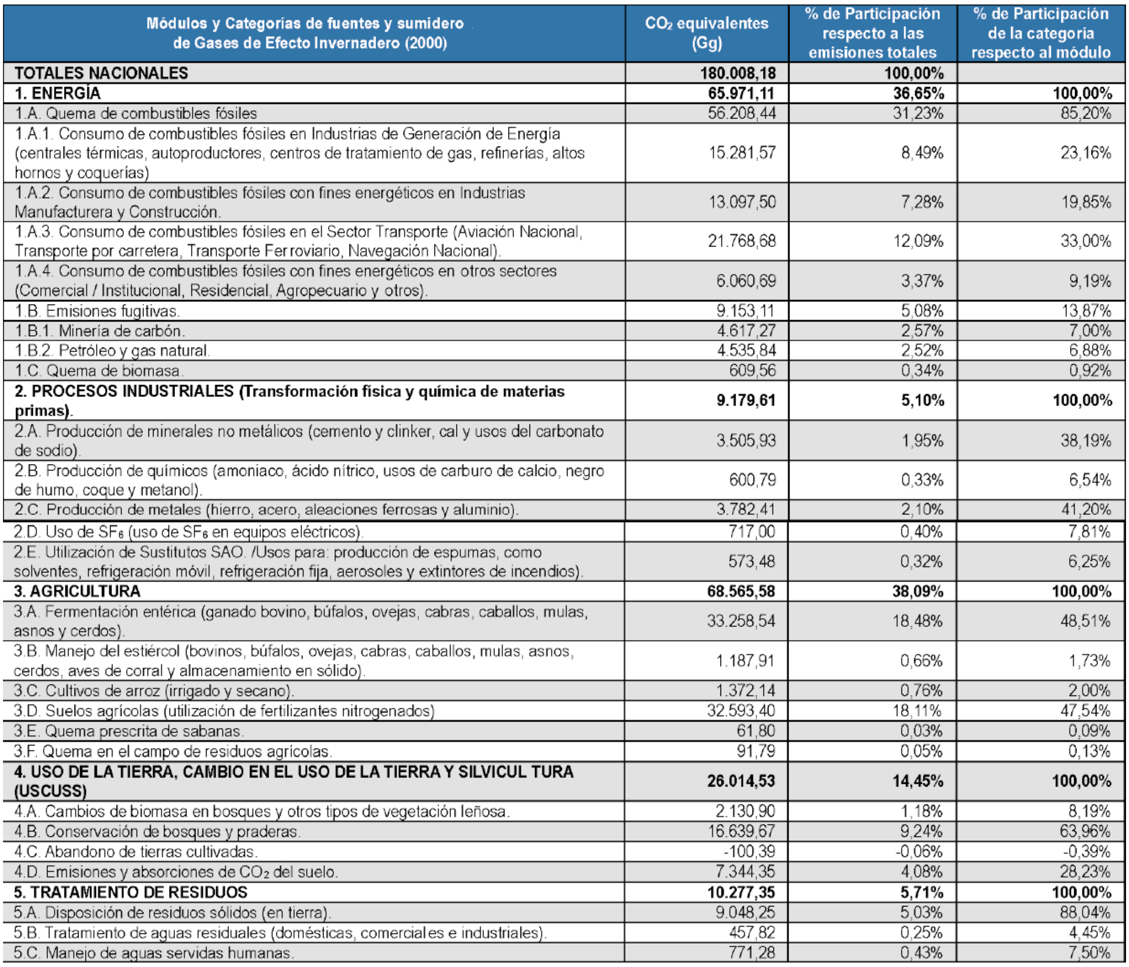
Annex A – GHG of Colombia by sectors in 2004

Table 3 – GHG of Colombia by productive sectors in 2004 (Source: ref. [2])



Módulos y Categorías de fuentes y sumidero de Gases de Efecto Invernadero (2000)	CO_2 equivalentes (Gg)	% de Participación respecto a las emisiones totales	% de Participación de la categoria respecto al módulo
TOTALES NACIONALES	**180.008,18**	**100,00%**	
1. ENERGÍA	**65.971,11**	**36,65%**	**100,00%**
1.A. Quema de combustibles fósiles	56.208,44	31,23%	85,20%
1.A.1. Consumo de combustibles fósiles en Industrias de Generación de Energía (centrales térmicas, autoproductores, centros de tratamiento de gas, refinerías, altos hornos y coquerías)	15.281,57	8,49%	23,16%
1.A.2. Consumo de combustibles fósiles con fines energéticos en Industrias Manufacturera y Construcción.	13.097,50	7,28%	19,85%
1.A.3. Consumo de combustibles fósiles en el Sector Transporte (Aviación Nacional, Transporte por carretera, Transporte Ferroviario, Navegación Nacional).	21.768,68	12,09%	33,00%
1.A.4. Consumo de combustibles fósiles con fines energéticos en otros sectores (Comercial / Institucional, Residencial, Agropecuario y otros).	6.060,69	3,37%	9,19%
1.B. Emisiones fugitivas.	9.153,11	5,08%	13,87%
1.B.1. Minería de carbón.	4.617,27	2,57%	7,00%
1.B.2. Petróleo y gas natural.	4.535,84	2,52%	6,88%
1.C. Quema de biomasa.	609,56	0,34%	0,92%
2. PROCESOS INDUSTRIALES (Transformación física y química de materias primas).	**9.179,61**	**5,10%**	**100,00%**
2.A. Producción de minerales no metálicos (cemento y clinker, cal y usos del carbonato de sodio).	3.505,93	1,95%	38,19%
2.B. Producción de químicos (amoniaco, ácido nítrico, usos de carburo de calcio, negro de humo, coque y metanol).	600,79	0,33%	6,54%
2.C. Producción de metales (hierro, acero, aleaciones ferrosas y aluminio).	3.782,41	2,10%	41,20%
2.D. Uso de SF_6 (uso de SF_6 en equipos eléctricos).	717,00	0,40%	7,81%
2.E. Utilización de Sustitutos SAO. /Usos para: producción de espumas, como solventes, refrigeración móvil, refrigeración fija, aerosoles y extintores de incendios).	573,48	0,32%	6,25%
3. AGRICULTURA	**68.565,58**	**38,09%**	**100,00%**
3.A. Fermentación entérica (ganado bovino, búfalos, ovejas, cabras, caballos, mulas, asnos y cerdos).	33.258,54	18,48%	48,51%
3.B. Manejo del estiércol (bovinos, búfalos, ovejas, cabras, caballos, mulas, asnos, cerdos, aves de corral y almacenamiento en sólido).	1.187,91	0,66%	1,73%
3.C. Cultivos de arroz (irrigado y secano).	1.372,14	0,76%	2,00%
3.D. Suelos agrícolas (utilización de fertilizantes nitrogenados)	32.593,40	18,11%	47,54%
3.E. Quema prescrita de sabanas.	61,80	0,03%	0,09%
3.F. Quema en el campo de residuos agrícolas.	91,79	0,05%	0,13%
4. USO DE LA TIERRA, CAMBIO EN EL USO DE LA TIERRA Y SILVICULTURA (USCUSS)	**26.014,53**	**14,45%**	**100,00%**
4.A. Cambios de biomasa en bosques y otros tipos de vegetación leñosa.	2.130,90	1,18%	8,19%
4.B. Conservación de bosques y praderas.	16.639,67	9,24%	63,96%
4.C. Abandono de tierras cultivadas.	-100,39	-0,06%	-0,39%
4.D. Emisiones y absorciones de CO_2 del suelo.	7.344,35	4,08%	28,23%
5. TRATAMIENTO DE RESIDUOS	**10.277,35**	**5,71%**	**100,00%**
5.A. Disposición de residuos sólidos (en tierra).	9.048,25	5,03%	88,04%
5.B. Tratamiento de aguas residuales (domésticas, comerciales e industriales).	457,82	0,25%	4,45%
5.C. Manejo de aguas servidas humanas.	771,28	0,43%	7,50%