

Energy Analysis of Crops Used for Producing Ethanol and CO₂ Emissions

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Abstract

A variety of biomass sources can be used for producing Ethanol. Among these are: sugar cane (Brazil), corn (USA), sweet sorghum (USA and Europe), sugar beets (Europe) and wheat (USA and Europe).

The production of fuel alcohol worldwide has been analyzed from various perspectives, with respect to productivity, the competition between food and energy crops, the social and economic aspects and, more recently, the environmental dimension.

However, another relevant study is aimed at calculating the energy input of the production and use of alcohol from sugar cane as compared to other primary sources for this fuel.

In view of the different systems for producing fuel alcohol in the various countries, an analysis of the energy balance may prove interesting for purposes of comparing the different processes of transforming biomass into fuel alcohol in terms of their energy efficiency and environmental impact.

The present study employs the methodology of energy balance for the analysis undertaken, highlighting the local conditions that influence the process of transformation of biomass into Ethanol and the respective carbon dioxide emissions to the environment.

Keywords - Energy crops; carbon dioxide; alcohol; energy balance.

1 - ENERGY BALANCE IN THE PRODUCTION OF ETHANOL ACCORDING TO THE DIFFERENT AGRICULTURAL CROPS USED

1.1 - The Sweet Sorghum

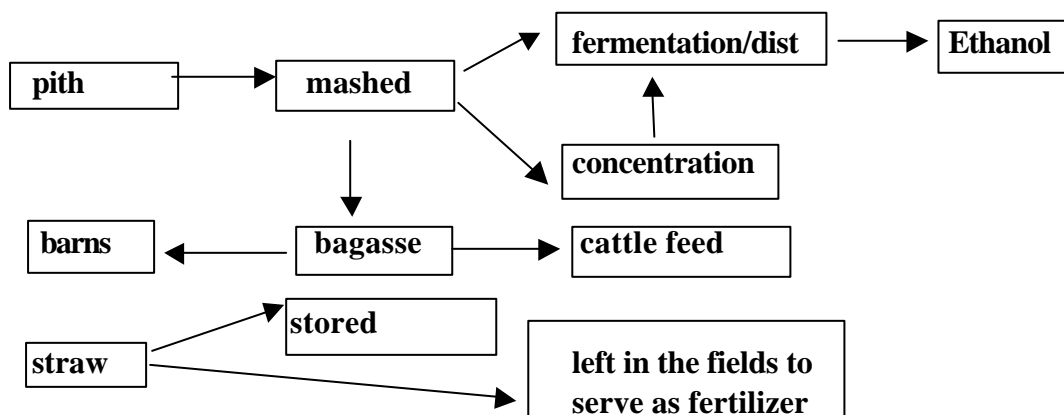
During the decade of the nineteen-eighties, sweet sorghum was first used as a source for producing Ethanol. In USA sweet sorghum grew well due to its adequate adaptation to soil conditions and the high agricultural productivity of the American Piedmont region.¹

However, today , 85% of the fuel Ethanol produced in the USA comes from corn.

In Europe, sweet sorghum has also been experimented with as a promising source for the production of Ethanol in the near future. According to the studies undertaken, sweet sorghum can yield, on the average, about 90 t/ha of vegetal biomass, of which dry matter accounts for 25 t.²

In view of the peculiarities of the USA sorghum culture, the stems are processed near the harvested areas and only the juice is transported to the factories for further transformation. In this production system, the raw material is separated into the pith, which contains the largest proportion of syrup and sugar and the bagasse, (containing the majority of the fibrous matter). The processing of the sorghum can be generally outlined as follows:¹

Figure 1 - The Simplified Shorgum processing



The average agricultural yield of sweet sorghum is as follows: 42.0 t/ha of stems; 11.35 t/ha of bagasse ; 11.35 t/ha of pith presscake ; 16.8 t/ha juice yielding 2.5 t/ha of sugar.

There are two basic types of Ethanol production from sweet sorghum. In the first type, the juice is transported by trucks from the harvested area to small factories where evaporation takes place and the juice is concentrated up to 60° Brix. These are located about 16 km away, on the average. Then, the output is transported for fermentation and distillation to distilleries, located about 48 km away, on the average. The second alternative system of processing ferments the juice at the harvested area proper. After this, the output is transported to a central factory, located about 48 km away from these areas on the average (in this case, the byproducts and other cellulose materials are used in the process).

With respect to the consumption of energy, the basic hypotheses are as follows:

- a) about 561 MJ/ha of diesel oil is used during the harvesting;
- b) the electricity used is generated through petroleum derivatives (liquid fuels);
- c) petroleum by-products are also used in the transportation;
- d) as to fertilizers, the values are roughly as follows: 67 kg/ha of N,P,K/year and 560 kg/ha of lime/year, which also require the use of fossil fuels for their production.

The average energy requisites for the agricultural production of sorghum are as follows (Table 1).

TABLE 1 - ENERGY DEMAND IN THE AGRICULTURAL PRODUCTION OF SORGHUM

Unit: MJ/ha

	LIQUID FUELS	TOTAL*
FERTILIZERS	4,761	5,411
PESTICIDES	587	1,398
SEEDS	99	197
EQUIPMENT		
GASOLINE	1,960	1,960
DIESEL OIL	1,482	1,482
MACHINES	83	555
TOTAL	8,972	11,003

* includes all forms of energy

Source ¹

There are other detailed and specific calculations for the consumption of energy in the production of sorghum which compute the consumption with the processing of sorghum on location, the transportation of

the sorghum and of the juice and the evaporation, fermentation and distillation stages. However, in this work, we shall use our own aggregated figures for the final energy consumption in the various stages of the production process. The data below (Table 2) shows the energy demand according to the two production alternatives.

TABLE 2 - SORGHUM PRODUCTION ENERGY BALANCE

	Sweet Sorghum	Option 1	Sweet Sorghum	Option 2
	Liquid Fuel	Total*	Liquid Fuel	Total*
Energy Input (MJ/ha)				
Agricultural Production	8,972	11,003	8,972	11,003
On site Processing	3,377	4,881	3,377	4,881
Evaporation	934	10,708	0	0
Ferm./Distill.	699	27,987	6,588	122,310
Total	13,982	54,579	18,937	138,194
Energy Output				
Ethanol Production (l/ha)	1,440	1,440	4,378	4,378
Total (MJ/ha)	49,450	49,450	150,341	150,341
Energy Ratio	3.54	0.91	7.94	1.09

* includes all forms of energy

Source ¹

1.2 - Corn

The use of corn for producing Ethanol in the USA shows significant regional variations with respect to the energy consumed. The major differences are to be found in the use of fertilizers and in the irrigation techniques employed. In most cases, the energy inputs are coal, natural gas and fuel oil, i.e., all of fossil origin.

Energy is consumed both in the corn production process (primarily in the form of energy used for the production of fertilizers and as fuel for the agricultural machines) and in the process of converting corn into Ethanol (grinding, fermentation and distillation).³

The average productivity in the US production of Ethanol from corn is 70.47 ton/ha of vegetal biomass.

For purposes of our study, we have adopted the figures of Marland et alii, calculated on the basis of some initial work hypotheses:

- All calculations are based on the upper heating values for the fuels;
- 75% of the electricity used in the process of converting corn into Ethanol is derived from fossil fuels;

The average energy yield of the fuels is as follows: Ethanol - 23.45 MJ/l, diesel oil- 39.6 MJ/l, gasoline - 34.78 MJ/l, gas - 26.43 MJ/l, natural gas - 38.02 MJ/m³

- The energy referent to the agricultural equipment (for instance, tractors) was not calculated specifically.

It is estimated as corresponding to 3% of the overall energy demand;

- The breakdown of energy for producing fertilizers is as follows: 72.27 MJ/kg - Nitrogen; 12.92 MJ/kg - Phosphorus; 9.95 MJ/kg - Potassium;
- On the average, 1 kg of corn produces 0.294 kg of Ethanol;

The data for 1974 indicated that 1 ha of corn required 19.91 GJ, the usual breakdown being:

- field operations (agricultural vehicles) using diesel oil, gasoline, LPG - 35.4% of the total;
- harvesting and drying using LPG and electricity - 5.8% of the total;
- fertilizers - 52% of the total;

- other uses (irrigation, pesticides, etc.) - 6.4 % of the total.

More recent data (1987) show a decrease in energy consumption down to 18.41 GJ/ha.

The breakdown of consumption according to fuel type should be as follows: Petroleum - 30%, Natural Gas - 57%, Electricity - 9%, Other Sources - 4%

The table below shows the consumption of energy in the course of corn production.

TABLE 3 - CONSUMPTION OF ENERGY FOR THE PRODUCTION OF CORN

Unit: GJ/ha

	Liquid Fuels	Natural Gas	Electricity	Other	Total
Liquid Fuels	5.48				5.48
Fertilizers		10.51	1.18		11.69
Other			0.52	0.73	1.25
Total	5.48	10.51	1.7	0.73	18.41

Source : ³

With respect to the process of conversion, the estimated averages for the consumption of energy range between 14,090 KJ/kg to 21,130 KJ/kg of Ethanol. Marland's work uses the range of 17,610 KJ/kg \pm 3,520.

The table below provides a summary of the values for energy consumption in corn production and conversion: (Table 4)

TABLE 4 - ENERGY CONSUMPTION IN THE PRODUCTION OF ETHANOL FROM CORN

Unit: GJ/kg of Ethanol

	Petroleum	Natural Gas	Coal	Other fossil	Non fossil	Total
PRODUCTION						
Direct Use	2.49					2.49
Fertilizers		4.79	0.41		0.13	5.33
Other			0.18	0.33	0.06	0.57
Sub-Total	2.49	4.79	0.58	0.33	0.19	8.38
CONVERSION						
Electricity			3.30		1.10	4.40
Heat for process.			13.22			13.22
Sub-Total			16.52		1.10	17.61 \pm 3.52
Total	2.49	4.79	17.10	0.33	1.29	26.00 \pm 3.52

Source: ³

1.3 - Wheat and Sugar beets

Wheat and sugar beets are commonly used for producing Ethanol in Europe. However, technological improvement is expected to turn the process more competitive relative to other fuels. The feasibility of wheat and sugar beets will be enhanced with the use of other technologies for the process of conversion, associated with energy cogeneration. The straw which is a byproduct of the process is not considered to have an important industrial value. However, if employed as an energy input, the utilization of this byproduct may help reduce significantly the energy input/output ratio in Ethanol production .⁴

The consumption of fossil fuels for the production of Ethanol from wheat is of the same order of magnitude as the energy contained in Ethanol and the other byproducts produced. Sugar beets, however, provide better results (roughly 30% of energy produced above that required for the production process). The data for the energy balance in the production of Ethanol and fossil fuels in Europe (The Netherlands) are presented in the table below:

TABLE 5 - ENERGY BALANCE OF FUEL PRODUCTION IN EUROPE

Unit: MJ/liter

	Input	Output	Ratio
Wheat	22.49	22.96	1.02
Sugar beets	17.37	22.51	1.30
Fossil Fuels			
Gasoline	5.31	32.91	6.20
Diesel oil	4.95	35.87	7.25

Source :⁵

If the agricultural byproducts were used for the production of electricity the ratio will be modified significantly, as can be verified below:

TABLE 6 - ENERGY INPUT AND OUTPUT PER HECTARE WITH CURRENT TECHNOLOGY
(Unit: GJ/ha/ year)

	INPUT	OUTPUT	RATIO
Ethanol from Wheat	66.75	68.14	1.02
Ethanol from S. beets	98.03	127.06	1.30
ELECTRICITY			
Straw	5.80	60.00	10.30
Poplar	18.30	277.00	15.10

Source: ⁴

The production of biomass in this case is around 6 to 10 times better than the production of biofuels. However, the use of this byproduct as animal feed provides substantially higher economic returns than its use for energy production. The largest share of the straw is used as a natural soil fertilizer in Europe and is commonly used for crops that require crop rotation. The main reason for not using the straw in electricity generation is the cost and the possible environmental problems such as emissions of pollutants.

Various European institutes have researched the energy balance of the production of Ethanol from wheat and sugar beets. Here below, we have provided some data referent to the various existing studies.^{8,9}

TABLE 7 - ENERGY BALANCE IN THE PRODUCTION OF ETHANOL FROM SUGAR BEETS AND WHEAT IN EUROPE
Unit: MJ/liter

WHEAT	INPUT	OUTPUT	RATIO
Novem (1992)The Netherlands	22.49	22.96	1.02
ERL (1990) UK	24.11	23.97	0.99
CEC (1988) European Comm.	25.10	29.50	1.18
Marro et allii(1980) UK	19.08	23.45	1.23
Ferruzi (1985) Italy	21.82	43.82	2.01
SUGAR BEETS			
Novem (1992)The Netherlands	17.37	22.51	1.30
ERL (1990) UK	23.05	24.74	1.07
CEC (1988) European Com.	23.60	42.60	1.81
Marro et all (1980) UK	21.98	23.45	1.07
ENEA (1988) Italy	12.95	29.24	2.26

Source: ⁵

Obs.: Ferruzi and ENEA's calculations include the energy content of the byproducts used as animal feed and fertilizers, while the other studies focus only on the energy directly used in Ethanol production.

Improvements in the energy balance of Ethanol production from wheat and sugar beets may occur in the near future especially as related to the energy content of fertilizers. Recent studies have shown that the energy content of Nitrogen ranging from about 65 to 74 MJ/kg of N may go down to about 40 MJ/Kg of N. Cogeneration may also bring additional and significant energy savings .⁴

The optimistic projections for increasing the efficiency of Ethanol production from wheat and sugar beets for the year 2000 assume a conversion of biomass into alcohol with the use of cogeneration and the employment of straw as an energy input in the production process (Table 8).

TABLE 8 - ESTIMATED PROJECTIONS FOR THE PRODUCTION OF ETHANOL AFTER 2000
Unit : MJ/liter

	INPUT	OUTPUT	RATIO
WHEAT	5.44	23.14	4.25
SUGAR BEETS	10.25	24.70	2.41

Source: ⁵

The study also provides information on consumption and production of energy according to agricultural crop and production phases. This data is important for future comparisons with alternative crops that may be used as primary energy sources for the production of Ethanol. De Boo's work corrects the data of Novem (1992) and uses the optimistic assumption of 40 MJ/kg of N for the energy content of fertilizers. The study further assumes that the byproducts are used as animal feed and as natural soil fertilizers. (Table 9)

TABLE 9 -ENERGY BALANCE FOR ETHANOL FROM WHEAT AND SUGAR BEETS BY PRODUCTION PHASES

WHEAT (2968 l/ha/year)			SUGAR BEETS (5645 l/ha/year)		
INPUT	MJ/liter	GJ/ha/year	INPUT	MJ/liter	GJ/ha/year
Agricultural	5.19	15.40	Agricultural	3.74	21.10
Transport	0.25	0.75	Transport	0.96	5.43
Production	17.05	50.60	Production	12.67	71.50
Total	22.49	66.75	Total	17.37	98.03
OUTPUT			OUTPUT		
Ethanol	21.23	63.00	Ethanol	21.26	120.00
Byproducts	1.73	5.14	Byproducts	1.25	7.06
Total	22.96	68.14	Total	22.51	127.06
Ratio	1.02	1.02	Ratio	1.30	1.30

Source: ^{4,5}

1.4 -Sugar Cane

With respect to the consumption of energy in the course of Ethanol production, the estimated results vary widely according to the available studies, the main reason being the great regional variability related to the production of fuel alcohol, the differences in the technologies and the methodologies used in the studies. We have taken Macedo's work ^{6,7} as our reference, since it contains a detailed description of the conditions of production and of the respective energy consumption in the production of Ethanol.

The work elaborates two scenarios aimed at comparing differences in technology. Scenario 1 uses data for the consumption of energy, inputs and investment in a factory which is considered representative, while scenario 2 incorporates the improved values obtained in optimized factories. Three levels of energy consumption are also considered:

- 1 - energy consumed directly as fuel and other forms of energy;
- 2 - energy used in the production inputs;
- 3 - energy in the production of equipment and in maintenance.

The data for the agricultural productivity of sugar cane is an average of the complete harvest cycle, around 78 t/ha:

- a) planted sugar cane - 100 t/ha
- b) First Cut - 80 t/ha
- c) Second Cut - 75 t/ha
- d) Third Cut 70 t/ha
- e) Fourth Cut 65 t/ha

For the industrial yield, the values for two types of factories were used (Autonomous factories and Distilleries annexed to the sugar mills).

Autonomous factories have an average of 70 l/t sugar cane and a maximum of 80 l/t. of sugar cane; Annexed with an average of 73 l/t. sugar cane and a maximum of 83 l/t

In this case, using the above limit values, the variation will range from 5,460 l/ha to 6,474 l/ha.

Taking in consideration Macedo's data ⁷, we obtained the following results.

TABLE 10 - ENERGY CONSUMPTION IN THE PRODUCTION OF ETHANOL FROM SUGAR CANE (90/91 HARVEST) Unit: MJ/ha

	AVERAGE VALUE		OPTIMIZED VALUE	
Agricultural Production (Total)	17 296.50		15 397	
Agricultural Operations	2 878		2 054	
Transportation	4 492		3 580	
Fertilizers	5 396		5 050	
Liming	528		528	
Herbicides/Insecticides	938		1 200	
Seeds	633		564	
Equipment	1 816		1 816	
Labor	613		613	
INDUSTRIAL PRODUCTION	5 467.80		3 166	
Electricity	978		0	
Chem. & Lubricants Prod.	511.66		511.66	
Buildings	1 105.26		737.10	
Heavy Equipment	1.343.16		897	
Light Equipment	1 528.80		1 020.24	
ENERGY TOTAL	22 764.30		18 563	
TOTAL FOSSIL ENERGY	21 138		17 345.62	
BALANCE	Input	Output	Input	Output
Agriculture	17 296.50		15 401.88	
Industry	5 467.80		3 166.02	
Ethanol		133 154.58		151 399.56
Bagasse		13 660.92		25 626.90
Total	22 764.30	146 815.50	18 567.90	177 026.46
Output/Input		6.45		9.53

Source: ⁷

Considering the increasing efficiency of alcohol producers the new energy balance is the follow:

TABLE 11 - NEW ENERGY BALANCE OF SUGAR CANE ETHANOL PRODUCTION

(A)Average Sugar Cane Production	189.87 MJ/ t cane
(B)Average Industry Alcohol Production	46.08 MJ/ t cane
(C)Ethanol Produced (Output)	1,996.37 MJ/t cane
(D)Bagasse Surplus (Output)	175.14 MJ/ t cane
(D+C) - (A+B)	9.2

Source : ⁸

The foregoing analysis of the results of the different energy balances according to the various forms of vegetal biomass used as sources for Ethanol production revealed the great comparative advantages of biofuel production from sugar cane. Being a plant which is well adapted to tropical conditions, the

productivity of sugar cane is high, yielding a significant positive result for the input and output relation in the production cycle. The table below compares the average energy input/output ratios (not considering the use of the byproducts and new technologies) for the different plant biosources and production systems.

1. **Sweet sorghum(Option 1) - 0.91**
2. **Sweet sorghum(Option 2) - 1.09**
3. **Corn - 0.9**
4. **Sugar Beets - 1.3**
5. **Sugar Cane (Average Value) - 5.85**
6. **Sugar Cane (Optimized Value) - 8.15**

On the basis of the present data, we develop a comparative carbon emissions of the different types of agricultural crops used for the production of ethanol and their overall impact on the environment. The first carbon emissions calculations are based on the above energy consumption data, IPCC's emission factor coefficient and proper approximations. The calculations are the following:

TABLE 12 - CARBON EMISSIONS OF ETHANOL PRODUCTION

Sweet sorghum	1.1024 t carbon/ha
Corn	135.18 t carbon/ha
Sugar beets	1.335 t carbon/ha
Wheat	1.96 t carbon/ha
Sugar Cane (Macedo's calculation)	0.377 t carbon/ha
Sugar Cane (our own calculation)	0.422 t carbon/ha

Source: Our own elaboration

2 - FINAL CONSIDERATIONS

According with these preliminary calculations Ethanol production from sugar cane may prove to be important alternative to produce energy from biomass emitting less carbon than others energy crops. The energy derived from sugar cane is a best clean source and has irrefutable environmental advantage through it's good energy balance. Including all aspects of the agricultural and industrial stages of ethanol production, the sugar cane is the smaller carbon emitter. In average terms, sugar cane emissions is 3.6 lesser than wheat, 3.19 than sugar beat, 1.6 times smaller than sweet sorghum and 320 times than corn. From this point of view, the ethanol from sugar cane may yet prove to be feasible in environmental terms, since international agreement in the field of climate change would bring a reduction in total carbon emissions of energy sector.

On the basis of the present work, we intend to develop a line of research that will allow a comparative analysis of the different types of agricultural crops used for the production of energy and their overall impact on the environment.

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