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INTEGRATED ENERGY BALANCE OF THE PRODUCTION OF QUALITY "CACHAÇA" AND BIOFUEL

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Abstract

The production of small-scale farm fuel alcohol is a viable economic activity, but in Brazil, there are few studies on the energy balance of its production. In the present work, the energy balance of the integrated production of quality "cachaça" and fuel alcohol at the farm level was carried out, as well as the determination of technical coefficients in a microdistillery in Minas Gerais (Zona da Mata), Brazil, for the production of sugar cane, cachaça and farm fuel alcohol. The productive capacity of this microdistillery in the analyzed period was 5,271.63 liters of cachaça and 658.95 liters of farm alcohol per day. Energy expenditure in the production of sugar cane (agricultural phase) was 245.14 MJ per ton of cane (MJ TC^{-1}), with 80% of the total of this energy going to the production of cachaça and 20% for the production of sugarcane fuel alcohol. The energy expenditure for the production of cachaça and fuel alcohol from sugar cane was 30.44 MJ TC^{-1} (industrial phase), of which 80% went to obtain cachaça and 20% for the farm fuel alcohol. The energy output / input ratio was 4.61 (fuel alcohol + excess bagasse). Much of the energy demand is due to the use of nitrogen fertilizers and diesel oil. The farm alcohol produced had a renewability index of 0.27, showing it to be a renewable fuel.

Keywords: *agroenergy, brandy, cachaça, farm ethanol, sugar cane.*

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Introduction

"Cachaça", also known as pinga, aguardente, is a beverage obtained by simple distillation of fermented sugarcane, with an alcohol content of 38 to 54% (Bortoletto et al, 2015). Cachaça ranks fourth among the most consumed distilled spirits in the world, and first in Brazil (Bortoletto; Alcarde, 2015); its production is expanding in all Brazilian states. São Paulo is the largest producer on an industrial scale, while Minas Gerais is the largest producer of farm-made cachaça. A total of 9.8 million litres were exported to Europe and America, which is a market in expansion (Riachi et al, 2014).

The "cachaça" called of quality is produced only from the heart fraction of the distillation of fermented sugarcane broth, a fraction equal to 75% of the total distillate. Some producers take advantage of the other distillation fractions, head and tail, respectively 15% and 10% from the beginning and the end of the distillate volume, and turn them into farm fuel ethanol (Silva, 2007).

The production of sugarcane, cachaça and farm ethanol requires the use of energy in the forms (i) direct, which is the one spent in the agricultural operations of tillage, in cultivation tracts, irrigation, harvesting and internal transportation of the production, which is obtained mainly from fossil fuels and electricity, and (ii) indirect, which is involved in the manufacture of agricultural inputs used, as fertilizers and pesticides, and durable goods such as agricultural machinery, equipment and buildings (Kallivroussis et al, 2002).

The balance of the direct and indirect energies in the agricultural and industrial stages of the production, processing and industrialization of the sugarcane is of great importance; it permits to know which link in the production chain is the most energy expensive, thus allowing decision-making concerning the rational use of inputs.

As with any bio-energetic product, the farm production of fuel ethanol requires the use of inputs of fossil origin, thus requiring an analysis to determine the yield with respect to the energy input (Triana, 2011).

The fuel ethanol production on a small scale is presented by Nogueira (2008), Santos (2011), Silva (2012), Maroun (2013) and Bonato Filho (2013). So, Santos (2011) studied the energy and economic viability of the fuel ethanol production in a micro-distillery, concluding that the energy balance of its production obtained from sugarcane broth is favorable with an output / input ratio of 5.01, that is, an energy gain of 4.01.

Silva (2012), studying the production of farm fuel ethanol in the context of family farming from the experience of the Cooperbio cooperative, Caiçara- RS, found an unfavorable balance because the power input was obtained from wood instead of sugarcane bagasse, which was returned to the producer.

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The present study was motivated by the few studies concerning the energy balance of the integrated production of quality cachaça and farm fuel ethanol on a small scale, combined with their importance for the domestic (farm fuel ethanol) and external (quality cachaça) markets.

Thus, this research proposes to determine the energy costs of the integrated production of quality cachaça and fuel ethanol, by using data collected in a microdistillery located in the Zona da Mata of Minas Gerais, Brazil, as well as from bibliographic references.

Methodology

An inventory of the supplies and equipment used in the agricultural and the industrial phases of the integrated production of quality cachaça" and farm fuel ethanol of a farm producer that uses the head and tail wastes from the production of the cachaça to obtain fuel ethanol for self-utilization is made as shown by Roque (2015). The farm is located in the Zona da Mata of the state of Minas Gerais, Brazil.

Due to the need for detailed data necessary for this study, parts of them were obtained both from the published literature and catalogs of the equipment manufacturers, and through consultations with sugarcane producers. However, most of the information was obtained at the microdistillery under study, using data from its operations control and accounting, as well as interviews with the owner and the manager of the production unit.

The borders to determine the energy balance included the agricultural and industrial phases of the processing of the sugarcane, thus comprising the steps ranging from the planting to the production of the quality cachaça and the fuel ethanol (Figure 1).

The quality cachaça" and farm fuel ethanol production data obtained from the owner of the micro-distillery are presented in Table 1, where and thereafter TC means tons of sugarcane.

The productivity achieved in the 2013/2014 harvest was 73.6 ton ha-1 of sugarcane, which is close to the national average of 75 ton ha-1 for the 2013/2014 season according to Conab (2014).

The sugar cane used in the micro-distillery was produced in the farm, which also owned all equipment utilized. The equipment, tools and vehicles used in the field operations were inventoried for each agricultural operation shown in Table 2. Due to the small-scale production the same equipment is used in different operations. Some field operations do not use specific machinery such as, e. g., for the application of fertilizer. For the field operations and for the agribusiness an eight-hour working day was considered.

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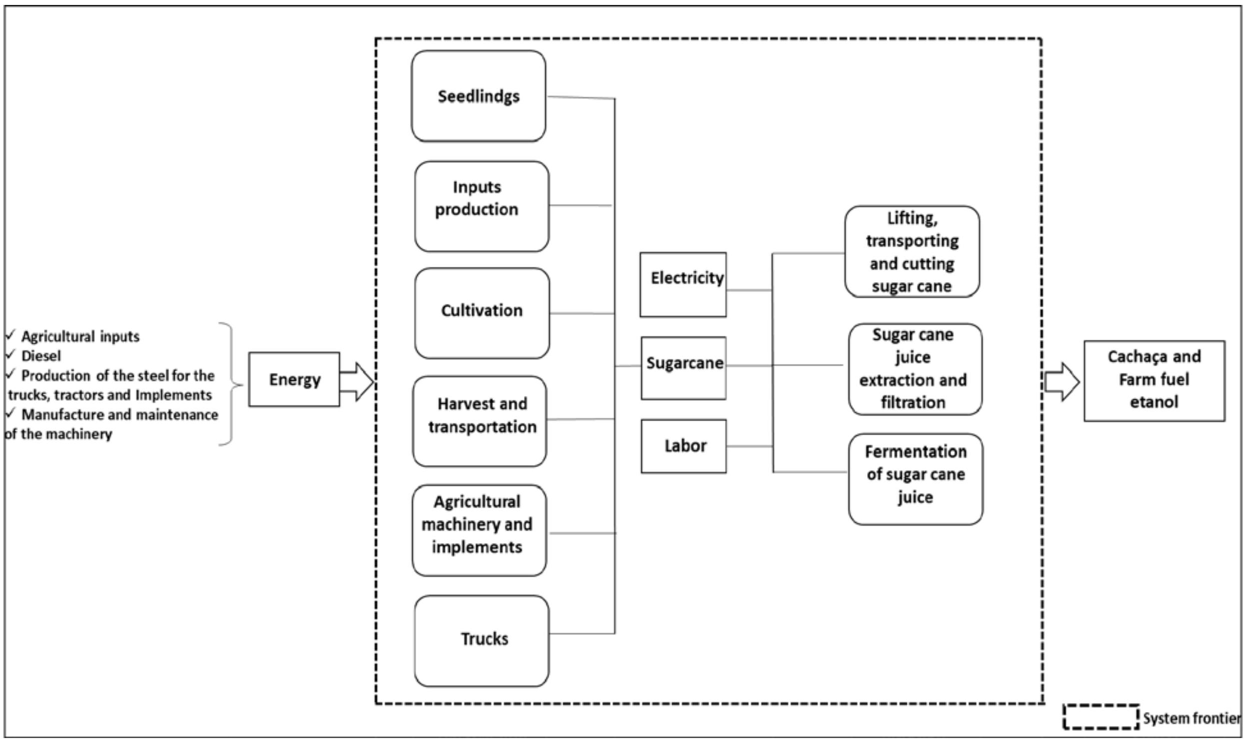

Figure 1. Agricultural and industrial steps considered in the energy balance.
Source: Adapted from Souza (2010).

Table 1. "Cachaça" and farm fuel ethanol production data of the micro-distillery in the 2013/2014 season.

Parameters	Unit	Quantity
Production of *cachaça*	L day^{-1}	5,271.63
Production of fuel ethanol	L day^{-1}	658.95
Average productivity of the cane production	t ha^{-1}	73.60
Production area (non-contiguous)	ha year^{-1}	50
Yield of *"cachaça"*	L TC^{-1}	123.19
Yield of head and tail fuel ethanol	L TC^{-1}	15.39
Industrial processing period	Days	86
Average time of distillation	hours day^{-1}	8
Annual production of *"cachaça"*	L year^{-1}	453.360
Annual production of fuel ethanol	L year^{-1}	56.670

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Table 2. Agricultural operations and machinery used in the production of sugarcane.

Agricultural operation	Implement type, tractor and truck
Sugar cane plant	
Mechanical eradication of soqueira (plowing)	Tractor 105 CV, Plow 3 discs
Harrowing (2x)	Tractor 105 CV, Harrow 18 discs
Internal transportation of inputs	Truck with 12 tons capacity
Soil corrective application	Tractor 105 CV, Spreader with capacity of 500 kg
Grooving	Tractor 105 CV, 2 lines groover
Fertilizer application *	-
Seedling cut*	-
Seedling transportation	Truck with 12 tons capacity
Unloading, distribution and rive *	-
Covering*	-
Crop without burning *	-
Cane charging with loader	Tractor 88 CV, loader
Sugar cane soca	
Chemical Weeding *	-
Fertilizer transportation	Truck with 10 tons capacity
Fertilizer application *	-

*Note: * Manual operation.*

Recently the owner changed the type of soil corrective for the sugarcane plant from limestone in the dosage of 2000 kg ha^{-1} to agrisilicon with 1,500 kg ha^{-1}. Due to lack of information about the energy consumption in the production of agrisilicon, in this study the available values for limestone were used.

The data provided by the manufacturer regarding the time spent in the field operations and the fuel consumption are presented in Table 3. The fuel consumption of 10 L $hour^{-1}$ by the Santal loader was obtained by Souza (2010), and the average time of 20 minutes for loading a truck with an average capacity of 10 tons was supplied by the the farmer.

In the manual harvesting a man was considered to reap 3 tons (ha day) $^{-1}$. In the 2014 crop 3,680 tons of sugar cane were harvested, which were grown in plots with an average area of 5 hectares and at an average distance of 13 kilometers from the micro-distillery. The transportation of the sugarcane crop to the distillery was performed by three trucks with an average capacity of 10 tons each. The total distance traveled by the trucks was obtained by adding the number of trips from the plots to the plant, resulting 9970 km. The fuel consumption was computed using the average of 3.5 km L^{-1} of Diesel oil for the empty truck, and 2.5 km L^{-1} for the loaded one (Souza, 2010).

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Table 3. Technical coefficients of sugarcane production to produce quality cachaça and farm fuel ethanol.

Farming operation	Tractor Power	Labor Man	Labor Tractorist	Diesel (consumption)	
	CV	Hours ha^{-1}		L h^{-1}	L ha^{-1}
Sugarcane plant					
Plowing [1]	105	–	2.16	13.07	28.23
Harrowing (2x) [1]	105	–	3.67	13.00	47.71
Soil corrective application [1]	105	0.50	0.50	13.32	6.66
Grooving [1]	105	–	3.17	12.98	41.15
Fertilizer application, cutting and loading of seedlings; unloading, distribution, rive and covering of sugarcane [1]	–	320.00	–	–	–
Manual harvest [1]	–	196.26	–	–	–
Subtotal	–	516.76	9.5	52.37	123.75
Sugarcane soca					
Chemical weeding [2]	–	5.16	–	–	–
Fertilizer application [3]	–	2.28	–	–	–
Subtotal	–	7.44	–	–	–
Truck loading of cut cane (loader) [1]	88	–	2.45	10.0	24.53
Total	–	24.20	11.95	62.37	148.24

Note: [1] Data obtained from the micro-distillery. [2] Obtained from a sugarcane producer in the Zona da Mata of Minas Gerais, Brazil. [3] Neves (1973).

The distances from the micro-distillery to the crop were used to determine the fuel consumption for the transportation of the raw materials used by the producer, that is, of the soil corrective soil, the fertilizer for soca and the sugarcane plants, as well as for the seedlings.

The fuel consumption for the transportation of the sugarcane and inputs was obtained through Equation 1.

$$\mathrm{C.C.}\left(\frac{\mathrm{L}}{\mathrm{ha}}\right) = \frac{\mathrm{Q.t.(kg\ ha^{-1})}}{\mathrm{Cap.c.(kg)}} \times \mathrm{Dis.\ perc.\ (km)} \times \mathrm{C.\ m.\ comb.\ (L\ km^{-1})} \qquad \textbf{Equation (1)}$$

Where:
C.C.: consumption of diesel oil;
Q.t.: amount of input transported;
Cap.c.: average capacity of the truck that transports the input;
Dis.perc..: round trip distance traveled between the micro-distillery and the crop; and
C.m.comb. average consumption of diesel oil per kilometer.

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After the cutting of the sugarcane cultivation treatments of the soca cane such as chemical weeding and applying fertilizer application are effected. The weeding is done by using back carried sprayers with herbicides such as the Velpar K.

Table 4 shows the amounts of fertilizers, limestone, herbicide and diesel oil used in the sugarcane culture.

Table 4. Amount of inputs applied to the sugarcane culture.

Input	Fertilizer consumption, kg ha^{-1}		Total comsumption kg ha^{-1} [1]	Average consumption [2] kg (ha year)$^{-1}$
	Cane plant 600 kg 00-25-15	Cane soca 500 kg 20-00-20		
Nitrogen N	-	100	500	83.33
Phosphate P_2O_5	150	-	150	25.00
Potassium K_2O	90	100	590	98.33
Limestone	2000	-	2000	333.33
Herbicide	-	1.17	5.85	0.98
Diesel oil [3]	104.00	-	104.00	17.33

Note:[1] Refers to the sum of the amounts applied to the sugarcane plant plus five times the amount applied to the soca cane (500 = 0 + 5 x 100). [2] Annual average over the six-year cycle. [3] Taken from Table 3 here in kg (ha year) -1, it does not include the transportation of sugarcane. The conversion of liter ha-1 to kg ha-1 uses 0.84 kg L-1 as the density of the diesel oil (National Energy Balance, 2014).

Energy inventory of the agricultural and industrial phases

For the calculation of the indirect energies involved in the production of the agricultural inputs used in the sugarcane culture, the energy intensity factors indicated in BIOGRACE (2008) were used and are presented in Table 5.

Table 5. Energy intensity factors of the agricultural inputs applied in the sugarcane cultivation (BIOGRACE, 2008).

Parameter	Energy intensity	Unit
Nitrogen	48.99	MJ kg^{-1}
Phosphate	15.23	MJ kg^{-1}
Potassium	9.68	MJ kg^{-1}
Limestone	1.97	MJ kg^{-1}
Herbicides	268.40	MJ kg^{-1}

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The seedlings used in the sugarcane planting were produced at the farm, with an average of 12 tons per hectare; they were transported from their production site to the planting location by a 12 tons capacity truck.

The energy consumption in the production of the seedlings was computed as a fraction of the total energy used in the sugarcane production stages, which was proportional to the amount of seedlings used, as in Souza (2010) and the Equation 2.

$$E1\left(\frac{MJ}{ha\ year}\right)=\frac{12\ (tc\ ha^{-1})}{6\ years}\times\frac{1}{Pc}\left(\frac{ha\ year}{tc}\right)\times Ea1t1\left(\frac{MJ}{ha\ year}\right)$$ **Equation (2)**

Where:
E1 - energy used in the production of seedlings;
Pc - average sugarcane productivity; and
Ea1t1 -energy total used in the planting (agricultural inputs, cultivation, harvesting, and agricultural machinery and implements).

For the calculation of the indirect energy due to the production of the machinery and agricultural implements used in the field operations, the methodology described in Bowers (1992) was adopted. It considers 86.77 MJ kg^{-1} as the energy used in production of the raw materials added to the one required by the manufacturing process, and 8.8 MJ kg^{-1} for the transportation and the distribution. Regarding the energy required for maintenance and repairs, the values for the type of machinery and implements used were utilized.

The methodology used in Santos (2011) was adopted for the calculation of the energy embedded in the trucks used to transport the inputs. The mass of each empty truck used to transport the inputs, the sugarcane and the seedlings was obtained by weighing them at the micro-distillery, thus determining the following values: 5770 kg, 7760 kg and 9160 kg. According to Souza (2010), 18% of the total truck mass corresponds to the tires and the remainder is considered as steel. In the present case, 62.79 MJ kg^{-1} was considered as the energy incorporated into the steel, while the energy for the truck manufacture was 14.62 MJ kg^{-1}. With these values and the steel mass, the energy embodied in the steel and the truck manufacture was determined.

The energy spent with the maintenance and repair of the machinery was obtained by applying the repair and maintenance factor (R & M) of 60.7% on the total energy spent with the manufacturing and the materials used; also considered was a portion of energy related to the energetic costs of the labor and the maintenance by applying the 0.202 factor concerning these costs, as done by Santos (2011).

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The energy embodied to the material added to the manufacturing should be adjusted to the useful life of the equipment. As by Santos (2011) the useful life coefficient of 0.82 was adopted. The adjusted energy was added to the repair and maintenance ones which, when divided by the useful life and the sugarcane productivity per hectare, determines the energy cost due to the use of the trucks.

The energy costs of labor were estimated for both the agricultural and the industrial phases. For the first one the work of the tractor driver and of the laborers (man hours) was recorded, and for the industrial phase the number of employees involved in the production of quality cachaça and farm fuel ethanol was recorded. The workforce involved in the industrial phase was 8 workers working 8 hours per day for 86 days a year. The energy factor used for human activities involved in the whole process (both phases) was 2.28 MJ h^{-1} per worker (Fluck, 1992).

For the harvest and loading of sugarcane stages it was assumed that one man reaps an average of three tons of raw sugarcane per day in an 8-hour working day, as informed by the producer. Loading the sugarcane to the truck was effected by a loader with an average time of 20 minutes to load a truck with a capacity of 10 tons.

The consumption of electricity in the industrial phase was estimated by the product of the rated power of each equipment versus its time of use, and assuming the motors adequate to their charge. The energy incorporated in the capital goods, as in Silva (2012), was not considered due to the difficulty in quantifying the mass and the type of material of the equipments.

The sugar cane arriving for processing at the micro-distillery is hoisted from the truck by means of a claw attached to a bridge crane and guided to the set of knives where it is chopped. The chopped sugarcane is driven by a conveyor to the mill where its broth is extracted and passes through a first filter. The broth is directed through channels into a stainless steel tank to decant, followed by filtering, and then mixed with water to achieve Brix 14%. After this procedure the juice is pumped into the fermentation vats which already contain the yeast, and staying there for an average of 36 hours.

The bagasse leaving the mill is driven by belts to power two boilers; these boilers provide steam for driving the steam engine that drives the mill and the slicer, and also for the distillation of the broth and the sterilization of the bottles for bottling the cachaça. The surplus bagasse is then belt-driven to a covered area where it is deposited.

After the fermentation time the wine is conducted to a stainless steel deposit from which it is pumped to the stills. After the distillation the heart fraction is pumped to the storage and aging

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sector. The vinasse, the restilo and the wash water are pumped into a tank and subsequently to a storage tank. Table 6 shows the rated power of the engines used in these operations and their time of use per day.

Table 6. Electricity consumed in the industrial phase

Operation	Nominal Power (Kw)	Time of use (hours)
Hoisting of the sugarcane	3.68	0.6
Motion to centralize the lock	0.736	0.36
Motion of the lock by the bridge crane	1.472	0.6
Mincing of the culms (set of knives)	36.8	8
Transportation of the sugarcane to the mill	3.68	8
Transportation of the bagasse to the belt	2.208	8
Transportation of the bagasse to feed the first boiler	2.208	8
Transportation of the bagasse to feed the second boiler and the surplus to storage	2.208	8
First filtering	2.208	8
Second filtering	0.736	8
Pumping the broth to the fermentation trough	1.472	8
Pumping between troughs	1.472	8
Pumping of the fermented wine to the destilation	2.208	8
Pumping of the *cachaça* to the hogshead	0.368	8
Pumping of the vinasse, restilo and washing water to storage	2.208	8
Boiler ventilation	7.36	8
Water pumping to the boilers	4.42	3.49

The number of employees involved in the whole processing of the sugarcane was 8 workers, with 8 hours working hours per day for 86 days of production. The amount of bagasse and broth during the extraction was obtained by weighing a certain amount of sugarcane. This procedure was performed three times to obtain a mean value.

To calculate the amount of steam produced the value informed by the manufacturer of each boiler to be 2000 kg of steam per hour for each boiler was used, although it is known that the boiler did not operate at full throttle. The amount of bagasse necessary for the production of 4000 kg of steam per hour was determined according to equation 3:

$$\dot{Q}b = \frac{\dot{Q}steam\,.(hv-ha)}{\eta boiler.PCIbagasse} \qquad \textbf{Equation (3)}$$

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Where:
Q̇ steam = mass flow of steam, kg h-1;
hv = 2753 kJ kg-1, assuming saturated steam x = 1 e P = 552585 kPa;
ha = 188.9 kJ kg-1, assuming water temperature at the boiler inlet as 45°C;
ɳboiler = boiler yield, 66% (based on the manufcturer's catalog); and
PCI = inferior calorific power of bagasse with 50% b.u., 8916.18 kJ kg-1 (EPE, 2014).

To calculate the average power consumption in the cycle, the number of times that the input and/or the equipment was used in this cycle was utilized; some of them were applied once, while others were applied five times.

The output/input energetic ratio was obtained by taking the ratio between the energy contained in the biofuel plus the surplus bagasse (output), and the total energy expended for the integrated farm fuel ethanol production (input).

To determine the rate of renewability of the farm fuel ethanol the Energy Renewability Efficiency (ErenEf) indicator suggested by Malça and Freire (2006), Equation 4, was used. An ErenEf between 0 and 1 indicates that biofuel is renewable; values below 0 indicate that the biofuel is non-renewable, and consequently it is not recommended to replace a fossil fuel.

$$ERenEf = \frac{(FEC - E_{in,fossil,prim})}{FEC}$$ **Equation (4)**

Where:
FEC - energy content of the biofuel, MJ kg^{-1};
Ein,fossil,prim - total of accumulated fossil inputs in terms of primary energy, MJ kg^{-1}.

Results and discussion

The results presented in this article can be found in detail in Roque (2015).

Energy balance- Agricultural phase

The average annual amount of fertilizer applications, limestone and herbicide with the fossil energy used in their production are shown in Table 7.

The nitrogen fertilization was responsible for over 64% of the total indirect energy due to the use of synthetic fertilizers. This fact shows the importance of the replacement of the synthetic nitrogen fertilizers by less energy-intensive ones, such as the organic fertilizers.

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Vinasse, waste generated in the production of cachaça and stored in tanks, can be used to fertilize sugar cane through fertigation, reducing the need for conventional ferilizers.

The amounts of energy embedded in the agricultural equipment used in the cultivation of sugar cane are shown in Table 8.

Table 7. Amount of the fossil energy consumption in the production of the fertilizers, limestone and herbicide used in the production of the sugarcane.

Input	Amount. kg (ha year)$^{-1}$	Energy factor [1] MJ kg^{-1}	Energy MJ (ha year)$^{-1}$	Energy MJ TC^{-1}	%
Nitrogen	83.33	48.99	4082.34	55.47	64.4
Phosphate	25	15.23	380,75	5,17	6,0
Potassium	98.33	9.68	951.83	12.93	15.0
Limestone	333.33	1.97	656.67	8.92	10.4
Herbicide	0.98	268.40	263.03	3.57	4.2
Total	-	-	6334.62	86.1	100

Note: [1] BIOGRACE (2008).

Table 8. Amounts of energy embedded in the agricultural equipment used in the cultivation of sugarcane.

Machinery and implements	Total Mass (kg) [1]	Manufacture Energy (MJ)	Transpor-tation (MJ)	Repair + Maintenance Energy (MJ)	Equipment Lifespan (hours)	Adjusted Energy with the Lifespan (MJ h^{-1})	Hours per ha (h ha^{-1})	Energy (MJ ha^{-1})	%
Tractor 105 cv	5936	515066	52237	252382	12000	68.31	9.5	648.95	18.91
Plow 3 discs	470	40782	4136	39558	1400	60.34	2.16	130.33	3.80
Harrow 18 discs	4385	380468	38588	232096	1400	465.12	3.67	1707	49.75
Spreader With 500 kg capacity	295	25597	2596	14078	1400	30.19	0.50	15.09	0.44
Trencher with 2 lines	295	25597	2596	14078	1400	30.19	3.17	95.70	2.79
Loader	2800	242956	24640	133626	1400	286.59	2.45	702.14	20.46
Tractor 88 cv	4675	405649	41140	198768	12000	53.79	2.45	131.79	3.84
Total								3431	100

Note: [1] Obtained from manufacturers catalogs.

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The energy cost of the agricultural machinery and implements of 3.431 MJ ha^{-1} that was obtained, if compared to the 1.110 MJ ha^{-1} found by Souza (2010), seemed to be too high because the worked area was small when compared to the one of the large power plants; however, these results are difficult to compare due to the different methodologies employed, as well as the lifespans and energy intensity factors considered, and the size of the area.

Table 9 presents the energy costs of the trucks employed in the internal transportation of the inputs and seedlings, and the transportation of the sugarcane from the crop to the micro-distillery.

Table 9. Average energy cost with trucks

Trucks	
Weight of the trucks steel (kg)*	18605
Energy of the material (MJ ha^{-1})	23364
Energy of the manufacturing (MJ ha^{-1})	5440
Energy for repair and maintenance (R&M) (MJ ha^{-1})	3532
Energy for material + manufacture corrected by the lifespan (MJ ha^{-1})	23619
Lifespanl	10
Energy Cost (MJ TC^{-1})	36.48

Note: value obtained from the tares of the 3 trucks employed.*

The energy costs for the trucks without considering the energy embedded in the tires, for a density of use of 372.1 kg ha^{-1} (three trucks) was 36.48 MJ TC^{-1}.

Knowing that the sugarcane productivity was 73.6 tons per hectare (Table 1), it follows that the energy cost for the machinery and implements was 46.61 MJ TC^{-1}, while it was 36.48 MJ TC^{-1} for that one required by the trucks used to transport the supplies, sugarcane and seedlings. Thus, the energy value of the machines and agricultural equipment utilized was 83 MJ TC^{-1}, which is less than the 100.38 MJ TC^{-1} found by Santos (2011). However, the comparison of these figures is difficult due to the different methodologies, the lifespan and the power factor adopted, as well as the size of the area planted with sugarcane.

The fuel consumption in the transport of the inputs and of the sugarcane from the crop to the micro-distillery is shown in Table 10. Although at the time of the research in Brazil 11% of biodiesel were added to the mineral diesel, for the calculations only 5%, when this study was carried out, was considered. With this percentage for each ton of diesel resulted 11% of

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methanol. Table 11 presents the energy consumption related to the use of fossil fuels in the farm operations and the transportation of sugarcane to the micro-distillery.

Table 10. Fuel consumption

Operation	Diesel Oil	
	(L ha^{-1})	(kg ha^{-1})[4]
Internal transportation of the limestone	1.77 [1]	1.49
Internal transportation of the fertilizer for the cane soca	0.44 [1]	0.37
Internal transportation of the fertilizer for the cane plant	0.53 [1]	0.45
Tranportation of the cane by the loader	24.53 [2]	20.60
Transportation of the seedlings	5.00 [3]	4.2
Transportation of the cut cane to the micro-distillery	65.06 [1]	54.65
Total	97.33	81.76

Note: [1] Values obtained through equation 1, using the Table 4 data and considering the average distance of 13 km from the crop to the distillery. [2] Table 3 [3] Producer. [4] To convert L ha^{-1} to kg ha^{-1} multiply by the specific mass of the diesel oil 0.84 kg L^{-1} (Balanço Energético Nacional, 2014).

Table 11. Average annual consumption of energy related to fossil fuel use in the agricultural operations of the sugarcane culture and the transportation of the cane and inputs

Categories	Quantity (L ha^{-1}year^{-1})	Diesel energy fator (MJ L^{-1})	Methanol percentage in diesel (%)	Power factor in the manufacture of methanol (MJ L^{-1})[2]	Total energy (MJ ha^{-1}year^{-1})	%
Agricultural operations	20.63	47.78	11	26.1864	939.39	21.30
Loader	20.44	47.78	11	26.1864	930.74	21.10
Sugarcane transportation to the micro-distillery	54.22	47.78	11	26.1864	2468.91	55.97
Sugarcane plant fertilizer transportation to the micro-distillery	0.08	47.78	11	26.1864	3.64	0.08
Cana soca fertilizer transportation	0.37	47.78	11	26.1864	16.85	0.38
Limestone and seedlings transportation	1.13	47.78	11	26.1864	51.45	1.17
Total					4410.98	100

Note: [1] Average of the 6 years cycle. [2] BIOGRACE (2008).

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The average fuel consumption of the transportation means used by the producer, 54.22 L (ha year)$^{-1}$, was below the 218.25 L (ha year)$^{-1}$ found by Maroun (2013). This is because Maroun used as mean of transportation a tractor coupled to buckets with a capacity of only 2 to 2.5 tons of sugarcane, instead of the three 10 ton trucks of this study.

The Table 12 the amounts total energy of all field operations, including transportation and labor.

Table 12. Total energy of all field operations and labor

Category	Energy Consumption MJ (ha year)$^{-1}$	Energy consumption MJ (TC year)$^{-1}$	Energy consumption %
Fertilizers	5414.92	73.57	30.01
Limestone	656.67	8.92	3.64
Herbicide	263.03	3.7	1.46
Agricultural machinery and implements	3.431	46.62	19.02
Trucks	2685.1	36.48	14.88
Fuel in agricultural operations	929.39	12.63	5.15
Sugarcane transportation	2468.91	33.54	13.68
Internal transportation inputs	277.31	3.77	1.54
Transportation by the loader	930.74	12.65	5.16
Labor[1]	508.82	6.91	2.82
Seedlings	477.33	6.48	2.64
Total	18043.22	245.14	100

Note: [1] Includes the manual harvesting labor

In the agricultural phase the energy consumption was 245.14 MJ TC^{-1}, which is close to the 210.6 MJ TC^{-1} reported by Seabra (2008) for large power plants, but it is smaller than the 335.43 MJ TC^{-1} found by Souza (2010). The energy consumption was high due to both the use of nitrogen fertilizers, and the use of fossil fuel in the transportation of the sugarcane to the crop.

Energy balance- Industrial phase

The electricity consumption in the industrial phase is presented in Table 13, computed with the nominal power and the time of use of each equipment utilized in the processing of the sugarcane for the production of *quality cachaça* and *farm fuel ethanol*. The values were estimated by adopting for the energy balance the consumption obtained in the electricity bills of the micro-distillery for the production period. The consumption registered in the invoices was 552.62 kWh ha^{-1}, corresponding to 7.51 kWh TC^{-1}. As the plant in question does not generate electricity, the value obtained was considered as an entry into the energy balance of the quality cachaça and the farm fuel ethanol.

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Table 13. Electrical energy consumption

Operation	Rater power (kw)	Usage Time (h day^{-1})	Production days (days)	Total area (ha)	Energy consumption per hectare (kWh ha^{-1})
Sugarcane hoisting	3.68	0.6	86	50	3.798
Motion to centralize the heap cane	0.736	0.36	86	50	0.456
Motion of the heap cane by the brigde crane	1.472	0.6	86	50	1.519
Mincing of culms (knife set)	36.8	8	86	50	506.4
Transportation of the sugarcane to the mill	3.68	8	86	50	50.64
Transportation of bagasse to the running conveyor	2.208	8	86	50	30.38
Transportation of bagasse to the first boiler	2.208	8	86	50	30.38
Transportation of bagasse to the second boiler and the surplus to the deposit	2.208	8	86	50	30.38
First filtering	2.208	8	86	50	30.38
Second filtering	0.736	8	86	50	10.13
Pumping of the broth to the fermentation trough	1.472	8	86	50	20.25
Pumping between troughs	1.472	8	86	50	20.25
Pumping the fermented wine for for distillation	2.208	8	86	50	30.68
Pumping of *cachaça* to the tun	0.368	8	86	50	5.064
Pumping of vinasse, restyl and wash water for the storage	2.208	8	86	50	30.38
Boiler ventilation	7.36	8	86	50	101.3
Pumping water for the boiler	4.42	3.49	86	50	26.53
Total	–	–	–	–	928.617

The average of bagasse produced per ton of ground sugarcane was 432 kg, and as during the 2013/2014 season 3680 tons of sugarcane were ground, resulted the production of 1589.760 tons of bagasse. The thermal energy for the distillation of the wine was exclusively generated by burning the bagasse resulting from the extraction of the sugarcane juice, thus yielding according to Equation 3 a total of 1199.184 tons of bagasse that were used in the furnace of the boiler for steam generation. Table 14 shows the amount of biomass and energy used.

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Table 14. Thermal energy consumption in the production of farm fuel ethanol

Biomass	Amount (kg year^{-1})	PCI (MJ kg^{-1}) [1]	Energy (MJ year^{-1})	Energy (MJ ha^{-1} year^{-1})
Bagasse	1200000	8.9	10680000	213600

Note: [1] EPE (2013).

Table 15 shows the energy consumption in the industrial phase related to the production of quality cachaça and farm fuel ethanol, including the labor. The energy from the bagasse was not considered because it was an input generated within the system itself.

Table 15. Energy consumption in the industrial phase of quality cachaça and farm fuel ethanol

Itens	Energy consumption MJ (ha year)$^{-1}$	Energy consumption MJ TC^{-1}
Labor	250.98	3.41
Electric energy	1989.432	27.03
Total	2240.412	30.44

In the industrial phase the highest energy consumption was of electricity in the production of quality cachaça and farm fuel ethanol. In similar studies it was observed that the highest energy consumption in the industrial phase resulted from the use of biomass, as shown by Silva (2012), which uses firewood for the thermal energy production. An alternative presented to reduce the energy consumption, is the use of firewood just to start the combustion of the bagasse, as shown by Santos (2011).

In the present study, the energy consumption in the industrial phase was 30.44 MJ TC^{-1}, below the 109.47 MJ TC^{-1} determined by Santos (2011), but whose average productivity of sugarcane and harvested area were smaller; Santos (2011) also considered the energy embodied in the buildings and equipment. Moreover, in the current study the energy of capital goods was not considered, such as done by Silva (2012).

Table 16 presents the consumption of energy in the agricultural and the industrial phases of the integrated production of quality cachaça and farm fuel ethanol and their respective participation.

Regarding the energy required for the integrated production of quality cachaça and farm fuel ethanol, the agricultural phase was the one corresponding to the highest energy demand, accounting for 88.95%.

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Table 16. Shares of the agricultural and industrial phases in the total energy consumption in the integrated production of quality cachaça and farm fuel ethanol

Category	Energy (MJ ha^{-1} $year^{-1}$)	Percentage (%)
Agricultural phase	18043.22	88.95
Industrial phase	2240.41	11.05
Total	20283.63	100

Energy balance of the production of sugarcane and bagasse

Table 17 shows the energy content of the inputs and the outputs in the process of extraction of the sugarcane broth for the production of quality cachaça and farm fuel ethanol.

Table 17. Energy content of the inputs and the outputs in the production of the sugarcane juice

Processes	Input (MJ TC^{-1})	Output (MJ TC^{-1})
Agricultural phase	254.14	-
Industrial phase	-	-
Bagasse [1]	-	3.845
Broth [2]	-	1.643
Total	254.14	5.488
Balance	+5242.83	

Note: [1] Bagasse production: 432 kg TC^{-1} (Producer). [2] sugarcane juice production: 640 L TC^{-1} (Producer), PCI broth: 2,595.32 kJ kg^{-1} (EPE, 2014), specific mass of the broth: 989 kg m-3 (Silva, 2012).

The positive value presented in the energy balance of the extraction of the sugarcane juice is due to the large volume of bagasse generated per ton of sugarcane crushed. Silva (2012), with mobile milling driven by tractor, also determined a positive balance for this extraction: 5382 MJ TC^{-1}.

The energy contained in the surplus bagasse (bagasse not burnt in the boilers) is shown in Table 18.

Table 18. Energy contained in the surplus bagasse

Category	Annual, quantity (kg)	Inferior calorific power (MJ kg^{-1})	Total energy (MJ)	Energy per ton of sugarcane – TC (MJ TC^{-1})
Surplus bagasse	389.760	8.9	3468.864	942.626

Note: [1] EPE (2014).

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Table 19 shows the energy inputs and outputs of the integrated production system of the farm fuel ethanol; also, it shows the resulting output/input ratio between (i) the energies contained in the farm fuel ethanol and in the by-products generated in its production (bagasse), and (ii) the energy existing in the system inputs.

Table 19. Energy inputs and outputs in the farm fuel ethanol production system

Category	Input (MJ TC^{-1})	Output (MJ TC^{-1})
Agricultural phase	245.14	-
Industrial pase	30.44	-
Farm fuel etanol	-	328.32 [1]
Surplus bagasse	-	942.63
Total	275.58	1270.95
Output/input ratio	4.61	

Note: [1] Farm fuel ethanol: PCI = 26.37 MJ kg^{-1}; specific mass = 0.809 kg L^{-1} (Santos, 2011). TC – ton of sugarcane.

The output/input ratio computed shows that for each unit of input energy 4.61 units, that are contained in the farm fuel ethanol and the surplus bagasse, are obtained. The surplus bagasse is employed (steam) at the plant for the sterilization of the bottles for bottling the quality cachaça. The energy gain obtained by Santos (2011) was 4.01, that is, the estimated output / input analysis was 5.01: 1. In large distilleries, as the bagasse is used to generate electricity, the output/input ratio is around 9.0 (Boddy et al, 2008).

Considering that all the energy input in the system is fossil and disregarding the electricity consumed in the production of quality cachaça and of farm fuel ethanol - because in Brazil about 70% of the energy supply is hydroelectric (EPE, 2014), the resulting energy indicator was 0.27 (equation 4), thus showing that the farm fuel ethanol produced in the integrated system is a renewable fuel.

Conclusions

The energy costs for the production of sugarcane were 245.14 MJ TC^{-1}, considering the transportation of the sugarcane from the crop to the micro-distillery, and the internal transportation of inputs and seedlings. The category that demanded the highest energy consumption was the use of nitrogen fertilizers and limestone in the sugarcane cultivation, followed by fossil fuel consumption when considering its use in the transportation of the sugarcane from the crop to the micro-distillery.

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In the industrial phase, the energy cost was 30.44 MJ TC^{-1}, thus yielding a positive energy balance in relation to the produced farm fuel ethanol and the surplus bagasse.

The energy used to produce the quality cachaça equals to 80% of the total expenditure in the agricultural and industrial phases of the integrated production of quality cachaça and farm fuel ethanol, that is, 197.11 MJ TC^{-1} and 24.35 MJ TC^{-1}, respectively.

The energy cost of the production of farm fuel ethanol from the head and tail by-products of the distillation was 48.03 MJ TC^{-1} in the agricultural phase and 6.09 MJ TC^{-1} in the industrial phase.

Thus, the farm fuel ethanol is a renewable fuel, since the renewability factor is 0.27.

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