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# ENERGY EXPENSE BY LOGISTICS WITHIN SUGARCANE'S ENERGY PRODUCTION CHAIN – TWO CASE STUDIES

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**ABSTRACT** An energy source is determined by the net energy it provides and this is due to the energy output and energy input within a system. Biofuels have posed as a prosperous alternative to fossil fuels, but unfortunately, it has been driven mostly by political and economical reasons rather than the physics intrinsic to them. Exportation of biofuels have been announced as "green" solutions without checking if the fuels would arrive to the final user as an energy source or drain. Actually, this is not even known in domestic markets such as Brazil, where ethanol has an outstanding development. This study aims to evaluate the energy expenditures of two case studies within the ethanol production chain – ethanol for road transportation and the baled straw, from mechanical harvesting of sugarcane, for electricity cogeneration. For ethanol road transportation, the two most commons tanker-trucks used were evaluated (30 and 45 m³). For the baled straw, two kinds of bale (prismatic and cylindrical) and three kinds of raking (single, double and triple) were evaluated. Although the largest vehicul for ethanol transportation presented higher gross energy consumption, it expended 12.42% less energy per distance and transported mass (0.626 versus 0.715 MJ $km^{-1}$ $t^{-1}$), and had proportionally lower $CO_2$ emission, 12.28% (41.47 versus 47.28 g $CO_2$ $km^{-1}$ $t^{-1}$). The baled straw presented 19.72% lower consumption for prismatic bales, due to the truck loading capacities of these bales. The results provide incite on the selection of alternatives operation within energy production systems.

**Keywords:** Energy flows, energy balance, transportation, straw, ethanol

## INTRODUCTION

Brazil is the largest sugarcane producer having processed 612 million Mg in the 2008/2009 crop, cultivated in 7.5 million ha (UNICA, 2009). Besides, sugarcane is the most important renewable source in the Brazilian energy matrix, corresponding to 16.4%, only less than oil and its derivates (36.7%) and more than hydroelectricity (13.8%) (EPE, 2009). The annual ethanol production is 27.5 million m³, either as anhydrous (9.3 million m³) or as hydrated ethanol (18.2 million m³). The former is mixed with gasoline as required by law from 20 to 25% and the latter is used purely as fuel.

Besides the liquid fuel, the Brazilian production of biomass is among the largest electricity co-generators. The energy supplied through cogeneration (sugarcane bagasse, wood etc.) was around 24 TWh, representing 5.3% of the total energy offer in Brazil (EPE, 2009). Moreover, the sugarcane biomass has a great potential to increase its participation in the energy matrix due to the industrial and agricultural evolution in the last decades (Das et al., 2004; Macedo, 2007). Studies done in the states SP, MG, GO and MS identified 210 sugar mills and ethanol distilleries with a installed capacity of 14.8 GW, with a surplus of 10.2 GW for the external grid, which is comparable to the potential of the Itaipu dam. (UNICA, 2009).

Another important aspect is the increasing adoption of mechanized harvesting, due to environmental constraints (Law N. 11241/2002 – SP) for extinguishing manual harvesting and consequently the previous burning of the straw and the particulate emission into the atmosphere. So, there will be more straw available that can be used for co-generation purposes together the bagasse. For the straw to be taken up to the boiler, it needs to be collected and transported, in order to do so, several studies have applied rakes and balers to do so (Ripoli et al., 2005a; Ripoli et al., 2005b). For this purpose, raking and baling are the most important field operations, but loading and transporting the bales to the boiler besides completing the process present the same importance.

Regarding energy sources one could ask “what is an energy source?”. It is not just where energy comes from. A source provides more energy than it is possible to obtain from it. For example, oil will end as an energy source before it ends as a raw material, because it requires the same amount of energy to extract as the energy it provides, so that its extraction will be useless in energy terms (Romanelli, 2009). Considering a bioenergy source, the gross energy obtained from the conversion process has to be enough to compensate the energy required for the biomass production, for the conversion process and the collection and transport of residues used in the process. Even after the net energy output is available, e.g. ethanol in the sugarcane production chain, there will be energy demand for its transportation and distribution. So, its energy potential is going to decrease due to the energy embodiment that the truck depreciation, the fuel use and labor required to take ethanol up to the final consumer (Romanelli, 2009).

Road transportation is the most important one in Brazil and it consumes 91.9% of the total energy applied in transportation (2.61 EJ or $2.61*10^{18}$ J). Diesel oil represents 51.7%, followed by gasoline (25.3%), hydrated ethanol (13.0%), anhydrous ethanol (6.2%) and natural gas (3.8%) (EPE, 2009). Car with diesel engines are not allowed since diesel oil is subsidized (cheaper than gasoline) in order to benefit production costs. So, diesel consumption is mostly due to load transportation, while gasoline and ethanol are used for personal transportation. The energy return on investment (EROI) of ethanol varies from 1.34 (U.S. corn ethanol, Shapouri et al., 2007) to 8.3 (ethanol and surplus from bagasse cogeneration in the Brazilian sugarcane production chain) (Macedo et al, 2008). The output energy from sugarcane is 8.1% fue to cogeneration and 91.1% to ethanol 91.9% (Macedo et al, 2008). Due to the importance of sugarcane sector in the Brazilian energy matrix and potential of co-generating electricity from sugarcane biomass, this study aims to survey two distinct parts of the production chain approaching the energy demand in the logistics of baled straw and of the ethanol distribution.

## MATERIAL AND METHODS

### Straw baling

The evaluated scenario is located in the state of Sao Paulo, Brazil (Latitude: 22º40'30''S, Longitude 47º36'38''W and altitude of 605 m) and reported by Ripoli et al., (2005a; 2005b). The harvested sugarcane had a yield of 78 t/ha. The yield of the remaining straw was 27.0 Mg/ha. The machinery used in the operations was: Tractor 4x2 TDA (90 kW, 6100 kg); Rake (358 kg), Conventional sugarcane loader (55 kW, 2300 kg); Prismatic baler (6650 kg), and Cylindrical baler (2452 kg). Besides, the two distinct kinds of balers, the kind of raking also varied. For cylindrical bales, single and double rakings were performed, while for prismatic bales, it was performed single, double and tripled rakings. The options studied were: P/S (prismatic bale and single raking), P/D (prismatic bale and double raking), P/T (prismatic bale and triple raking), C/S (cylindrical bale and single raking) and C/D (cylindrical bale and double raking). According to Ripoli et al. (2005a), the average dimensions and mass of the cylindrical bales was diameter of 1.19 m, length of 1.64 m and mass of 449 kg. While the average dimensions and mass for prismatic bales were 0.81 m wide, 0.90 m high, 2.15 m long and mass of 331.18 kg (Ripoli et al, 2005b). For raking and baling operations, the relation between area and time is determined through other means since this kind of machinery present a processing capacity, i.e., mass per time. The processing capacity and the yield provide the data in area basis (Equation 1). The processing capacity data can be obtained with the manufacturer, although it also varies according to field conditions (slope, weed infestation level). For loading, the EFC was determined considering the total mass loaded within a work hours in a day and the straw yield (Equation 2).

$$EFC = PCH / Y \qquad (1)$$

$$EFC = MBL / (Y * WH) \qquad (2)$$

Where: EFC = Effective field capacity (ha/h), PCH = processing capacity (Mg/h), Y = yield (Mg/ha), MBL = mass of bales loaded and WH = daily working hours (h).

The labor applied through mechanization (either the driver or the support staff); depend on the number of workers and the effective field capacity of each operation of the evaluated operation (Equation 3). For instance if there is a worker helping two tractor-implement set, its labor flow may be considered as 0.5 man in addition to the labor of the tractor driver. If there is data about how many man-day is necessary it is necessary to know how many hours per day the work is done.

$$EL = RW * E_{Labor} \qquad (3)$$

Where: EL = energy demanded in labor (MJ/ha); RW = rate of work (h/ha); $E_{Labor}$ = energy embodied in labor (MJ/h). The energy embodiment indices are presented in Table (2), at the end of this section.

The machinery physical depreciation is based on the useful life and the mass of the machinery, and on effective field capacity they perform in the mechanized operations; it is possible to determine the machinery depreciation (Equation 4). The physical depreciation does not mean that the equipment loses weight, but it means that after its useful life, the same amount of mass will be required to build a new one on order to replace it, i.e., it accounts the convergence of the environment, e.g., steel (iron ores + coal), rubber (oil) etc. that will be applied indirectly into a production system.

$$EDM = (E_{Mach} * M) / (UL * EFC) \qquad (4)$$

Where: EDM = energy on machinery depreciation (MJ/ha); machinery mass (kg); $E_{Mach}$ = energy content of machinery (MJ/kg); UL = machinery useful life (h).

The operational consumption is determined by relating the hourly consumption and the effective field capacity (Equation 5).

$$EEF = E_{Fuel} * FC \qquad (5)$$

Where: EEF = energy demand in fuel consumption (MJ/ha); $E_{Fuel}$ = energy embodied in fuels (MJ/L); FC = fuel consumption (L/ha).

The fuel consumption considered in the loading operation (CLO) was determined by index provided by UNICA (2009), regarding the fuel consumption for mass loaded (CML) multiplied by yield (Y) (Equation 6).

$$ELO = E_{Fuel} * Y * CML \qquad (6)$$

Where: ELO = energy consumed for loading (MJ/ha), CML = consumption for mass loaded (L/Mg).

The determination of the fuel consumption due to the truck transportation (CTT) up to the boiler was done considering the fuel consumption per transported mass (CTM) and the truck load (TL), which was determined by the number of bales times its average weight (Equation 7).

$$ETT = E_{Fuel} * YB * CTM \qquad (7)$$

Where: ETT = energy consumed in truck transportation (L/ha), CTM = fuel consumption per transported mass (L/Mg), YB = bale yield (Mg/ha). The consumption for transporting cylindrical bale is 3.55 L/Mg (Ripoli et al., 2005a) and 2.82 prismatic ones (Ripoli et al., 2005b). For transportation only the fuel consumption was considered, since old trucks are used for bale transportation, increasing their useful life which makes machinery depreciation minute.

The truck considered has a load capacity of 18750 kg and the loading area is 2.44 m wide and 7.00 m long. For cylindrical bales the load was arranged in two layers of two rows of four bales each (2x2x4), summing 16 bales each load. For prismatic bales it was arranged three layers of three rows of three bales each (3x3x3), summing 27 bales each load.

The input energy collecting the sugarcane harvesting residue considers the energy on labor, machinery depreciation, fuel consumption, loading and transport (Equation 8). The Output energy is due to the bale yield and the net energy value of this source of biomass (Equation 9)

$$IE = EL + EDM + EEF + ELO + ETT \qquad (8)$$

Where: IE = input energy for collecting biomass (MJ/ha).

$$OE = YB * NEV$$

Where: OE = output energy from collected biomass (MJ/ha), NEV = net energy value, in this case, 17.01 GJ/Mg).

**Ethanol distribution**

For this evaluation, two kinds of truck-tank compositions were chosen, since they are the most used in Brazil: the truck and the 3-ax[illegible]k trailer (A) and the tanker road train, with two tanks (B). Composition A presents a truck with 260.2 kW, 7308 kg and the tank weights 8350 kg with a capacity for 30m³. Composition B presents a truck 294.7 kW, 8662 kg, the first tank weights 6600 kg (capacity for 23 m³) and the second one 5950 kg (capacity for 22 m³). The compositions present distinct operational data only for fuel consumption (2.50 km/L for A and 1.9 km/L for B) and the number of tires (18 for A and 26 for B), the other parameters are the same for both (Table 1). The daily trip considered was 380 km and the work day of 10 h.

Table 1.Operational data (inputs without A or B indications are common for both).

| Input | Unit | Value | Frequency<br>km | Material flow<br>Unit/km |
|---|---|---|---|---|
| Truck A | kg | 7.308 | 1000000 | 0.0073 |
| Trailer A | kg | 8.350 | 1000000 | 0.0084 |
| Tire A | unit | 18 | | 0.0067 |
| Truck B | kg | 8.662 | 1000000 | 0.0087 |
| Trailer B1 | kg | 6.600 | 1000000 | 0.0066 |
| Trailer B2 | kg | 5.950 | 1000000 | 0.0060 |
| Tire B | unit | 26 | | 0.0097 |
| Lubricant oil (engine) | L | 30 | 15000 | 0.0020 |
| Lubricant oil (transmission) | L | 10 | 100000 | 0.0001 |
| Lubricant grease | kg | 2 | 2000 | 0.0010 |
| Labor | h | 10 | 380 | 0.0263 |
| Tire* | kg | 80 | | 0.0004 |
| Tire body | kg | 64 | 300000 | 0.0002 |
| Tire retread | kg | 16 | 100000 | 0.0002 |

The data about the mass and useful life determine the material flow of the machinery depreciation (Equation 10)

$EDM_{rt} = (E_{Mach} * M) / UL_{rt}$ (10)

Where: $EDM_{rt}$ = energy on machinery depreciation in road transportation (MJ/km), $UL_{rt}$ = machinery traveling useful life (km).

The specific fuel consumption is due to the fuel consumption and the transported load (Equation 5). The energy required by labor is basically due to the time labor is required (Equation 11).

$EL_{rt} = (TW * E_{Labor}) / DT$ (11)

Where: $EL_{rt}$ = energy demanded in labor for road transportation (MJ/km),TW = time worked in a day (h), DT = daily trip (km).

The input energy for road transportation is the sum of the energy demanded by machinery depreciation, labor and fuel consumption (Equation 12).

$IE = EDM_{rt} + EEF + EL_{rt}$ (12)

Where: IE = input energy (MJ/km).

The output of the transportation process is the energy delivered itself, i.e., the ethanol, and it is determined by the transported volume and its useful energy content (Equation 13). It is fixed independently of the distance it had to be transported, but this can be compensated when the energy balance is calculated.

$OE= LM * E_{ethanol}$ (13)

Where: OE = output energy (MJ); LM = load mass (kg); $E_{Ethanol}$ = energy available in ethanol (MJ/L).

The energy balance evaluates the net energy available after a process is performed. Since the output flow of ethanol transportation is fixed, it is necessary to balance the energy input with the transported distance (Equation 14)

$EB= OE – (IE * DT)$ (14)

Where: EB = energy balance (MJ); OE = output energy (MJ); IE = input energy (MJ/km); DT = daily trip (km).

The determination of the $CO_2$ emission was done according to the Brazilian Inventory of Green-House Gases emissions (MCT, 2002), that considers the carbon content of diesel from its cetane number (CN), which is variable depending upon the refinery. So, the emission from diesel was 2.799 g/L, according Bartholomeu (2006) (Equation 15).

$EM_{CO2} = CO_2F / FC$ (15)

Where: $EM_{CO2}$ = emission index of $CO_2$ from diesel (g/km); FC = fuel consumption (km/L); $CO_2F$ = carbon dioxide emission factor (g/L).

The energy inputs are determined by the demand on fuel, machinery depreciation, labor and maintenance (Table 2).

Table 2. Energy indices for some inputs.

| Input | Unit | Energy index MJ/unit | Reference |
|---|---|---|---|
| Labor | h | 2.2 | Serra et al. (1979) |
| Diesel oil | L | 38.6 | Comitre (1995) |
| Lubricant oil | L | 35.9 | Comitre (1995) |
| Grease | L | 39.0 | Comitre (1995) |
| Machinery depreciation | kg | 68.9 | Ulbanere & Ferreira (1989) |

## RESULTS AND DISCUSSION

### Straw baling

The energy flows for the five evaluated options for the straw collection showed the importance of transportation in the process. The average energy demand for transportation was 51.4% for the prismatic bale treatments, while the cylindrical ones got an average of 69.5% of the total demanded energy (Table 3). Loading was the less energy intensive operation. The energy required for baling was higher in the prismatic bale treatments (from 25.4 to 28.6%). This can be explained by the power demanded to pressure the prismatic bales (211 kg/m³) which were denser than the cylindrical ones (185 kg/m³). The disadvantage during the baling is compensated by transportation, since loads of prismatic bales occupy more efficiently the truck. Labor and machinery depreciation did not present major importance on the energy demand, indicating that improvements should be focused on baling and transporting. The highest energy demand were presented by the double raking treatment, that also presented the highest bale yield (11.2 Mg/ha for C/D and 8.9 Mg/ha for P/D). Triple raking did not show advantage for straw collection (7.2 Mh/ha) in comparison to the single ones (8.3 Mg/ha for C/S and 7.2 Mg/ha for P/S). The net energy value for the collected straw was 17.01 MJ/kg, directly applied to the bale yield, providing the output energy.

The highest energy balance came in the treatment C/D (188288 MJ/ha), followed by P/D (148701 MJ/ha), C/S (139137 MJ/ha), P/T (121569 MJ/ha) and P/S (120748 MJ/ha). So, although C/D has showed the highest demand, it is the best energy source since it delivers more energy to be used by the boiler. This is explained by its output (190342 MJ/ha) which is explained by the bale yield it provided.

Table 3. Energy demand in the straw collection operations.

| Options | Operation | Labor MJ/ha | Fuel MJ/ha | Mach. Dep. MJ/ha | Total MJ/ha | Total % |
|---|---|---|---|---|---|---|
| C/S | Raking | 0.7 | 183.0 | 15.2 | 198.8 | 11.7 |
| | Baling | 2.1 | 203.8 | 47.5 | 253.5 | 14.9 |
| | Loading | 2.8 | 99.6 | 16.5 | 118.9 | 7.0 |
| | Transport | | 1134.6 | | 1134.6 | 66.5 |
| Total | | | | | *1705.8* | 100.0 |
| C/D | Raking | 0.8 | 213.1 | 17.9 | 231.8 | 11.0 |
| | Baling | 1.9 | 185.3 | 42.7 | 229.9 | 10.9 |
| | Loading | 2.8 | 99.6 | 16.5 | 118.9 | 5.6 |
| | Transport | | 1533.4 | | 1533.4 | 72.5 |
| Total | | | | | *2113.9* | 100.0 |
| P/S | Raking | 0.7 | 183.0 | 15.2 | 198.8 | 12.8 |
| | Baling | 1.5 | 393.3 | 50.3 | 445.1 | 28.6 |
| | Loading | 2.8 | 99.6 | 16.5 | 118.9 | 7.7 |
| | Transport | | 791.0 | | 791.0 | 50.9 |
| Total | | | | | *1553.8* | 100.0 |
| P/D | Raking | 0.9 | 215.8 | 19.3 | 236.0 | 12.8 |
| | Baling | 1.1 | 470.9 | 37.2 | 509.2 | 27.7 |
| | Loading | 2.8 | 99.6 | 16.5 | 118.9 | 6.5 |
| | Transport | | 973.6 | | 973.6 | 53.0 |
| Total | | | | | *1837.7* | 100.0 |
| P/T | Raking | 0.9 | 245.9 | 18.6 | 265.3 | 16.8 |
| | Baling | 0.7 | 376.7 | 24.8 | 402.3 | 25.4 |
| | Loading | 2.8 | 99.6 | 16.5 | 118.9 | 7.5 |
| | Transport | | 796.5 | | 796.5 | 50.3 |
| Total | | | | | *1583.0* | 100.0 |

Fuel was the major energy consumer in the mechanized operations. Labor posed a minute role in this sense and depreciation represented around 4% (Table 4). Thus, further studies about residues of sugarcane biomass harvesting should focus on fuel consumption. In the straw collection scenario, fuel was mandatory, but the operations performed do not directly apply any kind of input such as fertilizer application or spraying do.

Table 4. Share of energy demand in input classes for straw collection operations.

| Options | Labor % | Fuel % | Depreciation % |
|---|---|---|---|
| C/S | 0.33 | 95.03 | 4.64 |
| C/D | 0.26 | 96.09 | 3.65 |
| P/S | 0.32 | 94.40 | 5.28 |
| P/D | 0.26 | 95.77 | 3.97 |
| P/T | 0.28 | 95.94 | 3.79 |

## Ethanol transportation

The energy flow analysis for the ethanol considering the inputs used for ethanol transportation show, as expected, that the composition B consumes 31.4% more energy

(Table 5). The highest increase in the composition B was the trailer depreciation due to the larger mass depreciated in the same time. On the other hand, when the load is considered for both alternatives (50% more in B), the specific energy consumption reaches 12.4% of savings in B.

Table 5. Energy flows of ethanol road transportation.

| Inputs | Unit | Material flow (unit/Km) | | Energy flow MJ/km | | Δ % |
|---|---|---|---|---|---|---|
| | | A | B | A | B | |
| Truck | kg | 0.0073 | 0.0087 | 0.5032 | 0.5965 | 18.5 |
| Trailer | kg | 0.0084 | 0.0126 | 0.5750 | 0.8642 | 50.3 |
| Tire (body) | kg | 0.0038 | 0.0047 | 0.1480 | 0.1809 | 22.2 |
| Tire (retread) | kg | 0.0029 | 0.0035 | 0.1110 | 0.1357 | 22.2 |
| Lubricant (Engine) | kg | 0.0018 | 0.0018 | 0.0645 | 0.0692 | 7.3 |
| Lubricant (Transmission) | kg | 0.0001 | 0.0001 | 0.0032 | 0.0035 | 7.3 |
| Lubricant (Grease) | kg | 0.0010 | 0.0010 | 0.0390 | 0.0386 | -1.2 |
| Labor | h | 0.0264 | 0.0264 | 0.0581 | 0.0581 | 0.0 |
| Diesel | L | 0.4000 | 0.5263 | 15.4200 | 20.2895 | 31.6 |
| Total | | | | 16.9221 | 22.2360 | 31.4 |
| Specific energy demand (MJ $km^{-1}$ $t^{-1}$) | | | | 0.7149 | 0.6263 | -12.4 |

The activity of ethanol transportation demands a lot less energy than it delivers (Table 6). For a trip of 380 km composition B delivers 750.9 GJ of net energy and composition A delivers 499.6 GJ. The $CO_2$ emission per volume of ethanol transported is lower for B, by the same reason discussed for the specific energy demand. The distance limit that would make transportation to consume the total amount of energy the composition carries was 30003 km and 34250 km, for composition A and B, respectively. The energy expended in road transportation showed to be little in comparison to the energy carried in ethanol loads.

Table 6. Energy and carbon emission indices for ethanol transportation.

| Índex | Unit | Composition A | Composition B |
|---|---|---|---|
| Output Energy | GJ | 507.7 | 761.6 |
| Energy Balance | GJ/Load | 499.6 | 750.9 |
| $CO_2$ emission | g/m³ | 14.18 | 12.44 |

When evaluating energy flows for agricultural production systems, one generally does not consider the transportation required to take inputs into the farm, since destination and origin would have to be known, bringing a lot of complexity into the analysis and probably it would not make a significant difference in the indicators.

## CONCLUSIONS

Baling is an energetically viable alternative for using the residues of sugarcane mechanically. Cylindrical bales expand more energy in transportation but less in baling, since it was obtained less dense bales than the prismatic ones. The double raking was the most efficient on providing larger bale yield, which affected directly the output energy from the five alternatives. Among the inputs quantified: labor, machinery depreciation and fuel; the latter was mandatory and labor can be omitted in further studies.

For ethanol the larger composition was more efficient on using energy and emitting carbon dioxide regarding the energy transported. Ethanol road transportation did not showed to be an energy constraint in the whole chain, since the distance limit for the carried energy to be consumed is similar to the Earth's circumference at the Equator. Studies on ethanol overseas transportation would be interesting for the ethanol energy potential abroad Brazil to be evaluated.

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