Lignocellulosic Ethanol in Brazil

Subtitle: Technical assessment of 1st and 2nd generation sugarcane ethanol in a Brazilian setting

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Abstract

Brazil is currently the largest ethanol-biofuel producer worldwide. Ethanol is produced by fermenting the sucrose part of the sugarcane that contains only one third of the sugarcane energy. The rest of the plant is burned to produce energy to run the process and to generate electricity that is sold to the public grid, making the process a net energy producer. This paper evaluates current technology from an energy efficiency point of view and quantifies additional benefits from extra energy generated in during sugarcane processing. In addition to that, two 2nd generation technologies are proposed, which in combination with the traditional (1st generation process) utilize the whole sugarcane plant for biofuels production, while still being fossil-energy independent. It was shown that conversion of these sugarcane residues to ethanol is energetically more favourable than producing electricity by burning bagasse and trash. Energy for running 1st generation sugarcane distillery amounts 29% of the energy stored in bagasse and trash. Burning the remaining part of bagasse and trash could generate equivalent of only 10% electrical energy of the total bagasse and trash energy content due to the conversion losses. This could result in 30.3% overall energy efficiency of the process. Installing an additional capacity for bagasse and trash conversion to ethanol increases overall efficiency to 37%. Converting sugarcane residues to ABE (acetone, butanol and ethanol) decreases overall energy efficiency of the process. To run the process independently of fossil fuel energy, using ABE fermentation technology for converting lignocellulosic residue, only 50.5% of the bagasse should be converted to ABE and the rest should be burned together with trash to obtain power to run the process. Energy efficiency of such kind of process would be 27%.

Content

1 Technical potential of the 2nd generation biofuels in Brazilian setting

This chapter presents the potential of sugarcane for production of the 2nd generation biofuels in Brazil. The main difference between 1st and 2nd generation feedstock lays in their suitability for human nutrition. While 1st generation feedstock like grains or sugarcane are used as food, lignocellulosic biomass is non-digestible for humans. Thus, it represents feedstock that doesn’t interfere with the human food chain. Similarly, technology that processes this feedstock into fuel is quoted as 2nd generation technology, and corresponding fuels as 2nd generation fuels. It is important to note here that while the difference between 1st and 2nd generation feedstock is obvious, 1st and 2nd generation fuels could be essentially the same. For instance ethanol can be regarded as 1st generation ethanol (from corn, wheat or sugarcane), but also as 2nd generation ethanol (from lignocellulosic materials). Processing technology is largely determined by the type of feedstock and in most of the cases there are differences between the two generations.

The focus is set on the yields of end-product energy carriers, specifically liquid biofuels and (electric) energy. Current sugarcane ethanol processing is given as base for comparison with proposed novel technologies. Several plant configurations are proposed that make use of bio-ethanol and ABE (acetone-butanol-ethanol) technologies producing both 1st and 2nd generation biofuels. In all plant configurations increase of the current plant output capacity is carried out through employing additional processing capacity for the lignocellulosic residue producing additional amounts of 2nd generation liquid fuels and increasing the efficiency of the production process.

1.1 Traditional sugarcane-to-ethanol processing technology

Sugarcane is traditionally being used for sugar (sucrose) production. This used to be the main product and molasses was used as a medium for ethanol fermentation. Depending on the demand, amount of sucrose used for ethanol production can be changed. Nowadays, with increasing fuel prices ethanol becomes the main product of sugarcane processing and new distilleries are built to use all sugar for ethanol fermentation.

1.1.1 Mass Balances

Typical sugarcane composition is given in the table 1. As much as 120kg sucrose could be obtained from 1 ton sugarcane. Molasses, which is residual juice after sucrose crystallisation, contains about 50% sugars and could be used as fermentation medium yielding about 7l ethanol. In most of the plants today half of the sugarcane is used for sugar production and other half for ethanol fermentation producing 42l ethanol and 67kg sucrose per one ton of sugarcane. A residual stillage (vinasse) after ethanol distillation is normally sent back to the field for fertilization and it amounts 12-15l of vinasse per litre of ethanol distilled. Productivity per hectare is given in the table 2.

Table 1 Typical products of sugarcane ethanol process [1]

1 Ton Sugarcane	Sugar Only	1:1 w/w Sugar/Ethanol	Ethanol Only
Sucrose, kg	120	67	0
Molasses, l	30	0	0
Bagasse*, kg	280	280	280
Cane Trash*, kg	280	280	280
Ethanol, l	7**	42	85

* Wet, 50%wt water

** Ethanol obtained from molasses

Figure 1 shows the scheme of present Brazilian ethanol process. After being harvested sugarcane is transported to the plant. Sugarcane is then crushed in the mills and the sugar is extracted. Solid residue or bagasse is burned together with cane trash from the field to provide energy for the process [2-6]. Water from the sugar solution is evaporated and sugar is separated upon crystallization.

Table 2 Yields of typical sugarcane products per hectare

1ha of Sugarcane	Sugar Only	1:1 Sugar/Ethanol	Ethanol Only
Sugarcane, t	85	85	85
Sucrose, t	10.2	5.7	0
Molasses, m^3	2.6	0	0
Bagasse, t	23.8	23.8	23.8
Cane Trash, t	23.8	23.8	23.8
Ethanol, m^3	**0.6**	**3.6**	**7.2**
Vinasse, m^3	8.3	50.0	101.2

* Wet, 50%wt water

** Ethanol obtained from molasses

Liquid residue after crystallization, called molasses, is rich in sugars and like that excellent medium for fermentation. Molasses is used together with the part of sugar solution after sugars extraction for ethanol fermentation. Mills that produce only sugar use only molasses for ethanol production, while ethanol-only distilleries don't even have crystallization units and after sugars extraction everything is sent to ethanol fermentation unit.

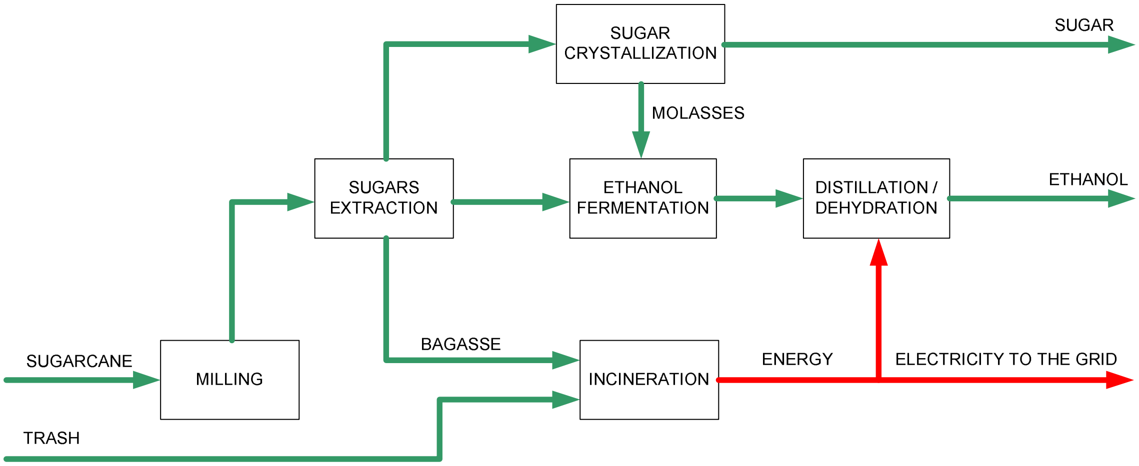

Figure 1 Brazilian sugarcane ethanol process

One mole of sucrose contains 2 moles of glucose which is fermented to give 4 moles of ethanol. One part of ethanol is consumed by the yeasts and a small part is lost during the processing.

$$C_{12}H_{22}O_{11} + H_2O \rightarrow 2C_6H_{12}O_6 \rightarrow 4C_2H_5OH + 4CO_2$$

After the fermentation ethanol concentration in "beer" is 7-10%vol and must be distilled. Distillation is carried out in the series of distillation columns, where ethanol concentration is increased to 96%vol. Heat required for the distillation is obtained from bagasse and trash burning. Further purification could be done ether by molecular sieves (dehydration) or in an azeotropic or extractive distillation. Dehydration appears to be the most used option among the three alternatives. Stoichiometric ethanol yield during fermentation normally reaches as much as 91% [7]. Steam generated in the boilers is converted to electricity and sold to the grid. About 102kWh of electricity per ton of sugarcane can be produced and sold to the grid in this way.

Table 3 presents typical ethanol yields depending on the type of plant. Note that the yields are region specific and different values could be found in the literature. Moreover sugar content in the sugarcane constantly increases with introducing new improved species.

Table 3 Sugarcane ethanol yields

1 Ton Sugarcane	Sugar Only	1:1 Sugar and Ethanol	Ethanol Only
Ethanol, l	7	42	85
Sucrose, kg	120	67	0

Beside ethanol, yeasts are largely produced in ethanol fermentation. After fermentation large amounts of yeast are available in the distilleries. About 13%vol is yeast concentration after the fermentation [7]. Yeast is dried and sold as animal feed because of the high nitrogen content.

Also some specialty chemicals with high value are obtained. Upon breaking the yeast structure and releasing citoplasmatic material, various amino acids are produced.

1.1.2 Energy Balance

On energy basis ethanol contains almost one third of the energy that could be derived from sugarcane. Bagasse and cane trash account for two thirds of sugarcane energy (Table 4). Total energy of one ton sugarcane is equivalent to 0.16 TEP or 1,15 barrel of petroleum. Bagasse and trash are burned and the energy is used for ethanol distillation. As much as 5.27GJ energy is available from trash and bagasse, from which 36.5% is used internally and the rest is sold to the grid. Price that electricity industrial user have to pay is 0.11US$/kWh compared to the gain from the electricity sold to the grid of 0.066US$/kWh [8]. It means that converting energy to electricity is the least beneficial. Once it has been produced in excess benefits from it are marginal.

Efficiency of primary energy conversion to steam is about 80%. Further steam conversion to electricity has 20-40%. Steam for distillation is the major share in the energy demand of the whole process. Distilleries use steam for ethanol distillation, employing 80% of the original energy content of the biomass. To convert steam to electricity only 20-40% of the steam energy content could be used. Energy efficiency is therefore another reason why the benefits of using primary energy for own needs is a better option than selling electricity.

Table 4 Energy content of sugarcane

1 Ton Sugarcane	Yield	Energy, MJ	TEP*
Ethanol, l	85	1997	0.044
Bagasse, kg	280	2638	0.058
Cane Trash, kg	280	2638	0.058
Total		7273	0.16

* TEP – Tone of Equivalent Petroleum; 1TEP = 45220MJ = 7,21 barrel

Figure 2 shows the conversion of primary energy from sugar cane to ethanol and electricity for 1st generation technology. About 24.7% of the sugarcane primary energy is converted to liquid ethanol. Another 6.6% are sold as electricity resulting in 31.3% energy efficiency. Thus more that one third of energy is lost during the conversion. About 19% of energy is recycled and used within the system for running the plant.

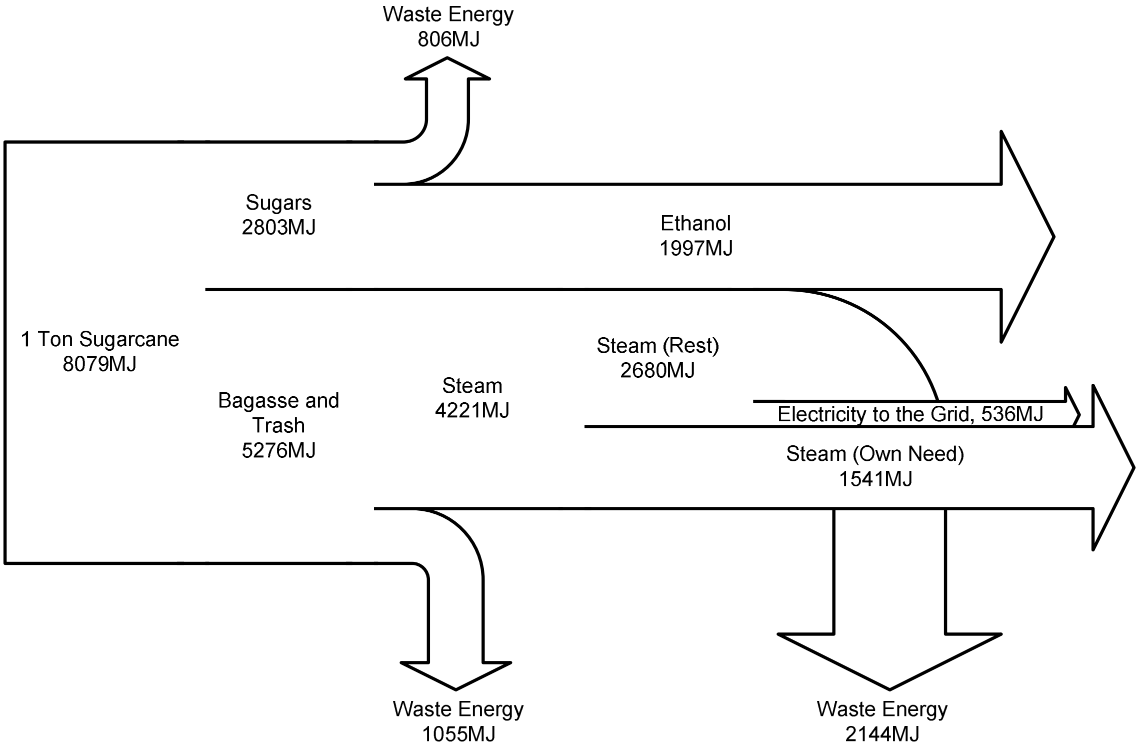

Figure 2 Energy dissipation during 1st generation ethanol production from sugarcane. No sugar production is considered.

Even though only 29% of the bagasse and trash energy is required for running the plant, only 10% of electrical energy can be produced from the remaining part due to the conversion losses. As figure 2 shows highest losses are associated to the conversion of steam to electricity. Using state-of-the-art technology for conversion of steam to electricity this amount might be doubled, but this has to be economically justified. Figure 2 shows also that conversion of sugars to ethanol is a way more efficient than conversion of bagasse and trash to electricity. Waste energy term stands for losses of energy during conversion steps.

1.2 2nd generation ethanol production technology

Large surplus of sugarcane processing co-products, specifically bagasse and trash, is an important resource for 2nd generation sugarcane ethanol production. Several 2nd generation plant design options are possible in respect of using lignocellulosic co-products for ethanol production. In general two types of plants are discussed here. Plants that use only lignocellulosic feedstock to produce ethanol and combined plants that use both 1st and 2nd generation technology. Possibility of using co-products from the conventional plant as a feedstock for a separate plant is not further discussed because it is argued that integration of 1st and 2nd generation processes offers more benefits. Possible integration of the fermentation and distillation sections is an example of that. However, second option will be simply regarded as a traditional plant with an additional installed capacity for processing 2nd generation feedstock for the sake of transparency.

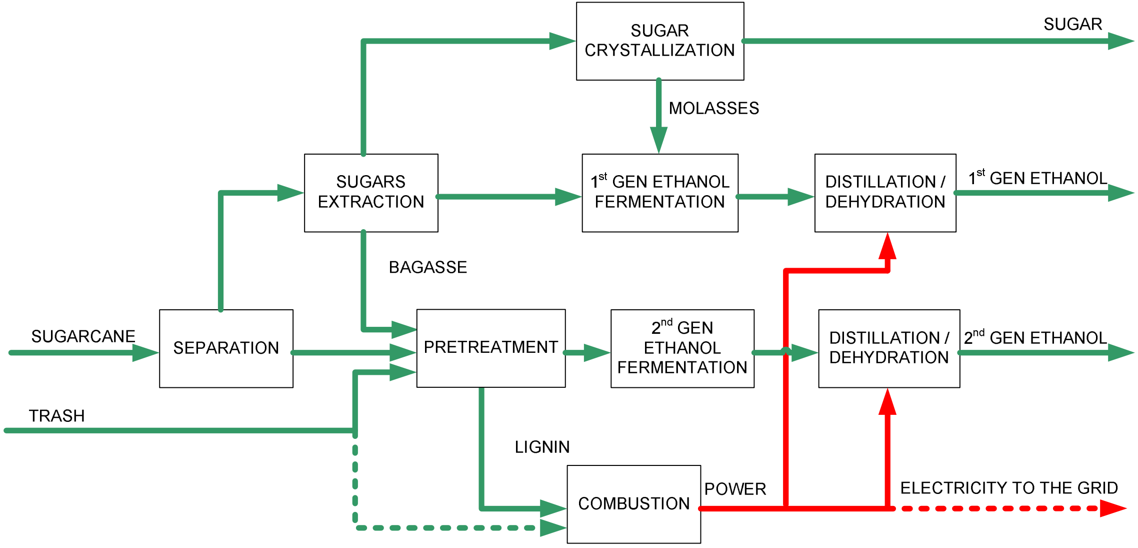

Figure 3 Integrated 1st and 2nd generation ethanol process

Option shown on the figure 3 assumes conventional process that uses half of the sugarcane for sucrose and other half for ethanol production. Trash collected at the field and bagasse, are treated to release sugars, which are further fermented to ethanol, and lignin and other solids are burned to produce energy for the process. In case extra energy is produced it is sold to the grid. In the case of process that produce only ethanol sugar crystallization section is omitted and all extracted sugars are fermented to ethanol.

It is obvious from the figure 3 that fermentation and ethanol separation could be integrated into single operations. However, integration of ethanol fermentation might not be interesting enough due to the throughput limitations. Long residence times in the fermentors cause extremely large fermentor volumes. This problem is normally solved by employing several fermentors in parallel (scale-out). Increasing the throughput of the plant with additional capacity for 2nd generation ethanol system can only be scaled-out (increase number of fermentors), since maximum volume of the fermentor is reached. On the other hand distillation and dehydration units can easily be scaled-up (by employing larger columns), offering the advantage to systems integration.

Table 5 Ethanol yields

1 Ton Sugarcane		**1:1 Sugar Ethanol**	**Ethanol Only**
Ethanol, l	1st gen	42	85
	2nd gen	60	60
Total, l		**102**	**145**

Expected ethanol yields from combined 1st and 2nd generation process are shown in the table 5. It is obvious that a potential of 2nd generation ethanol is significant. Depending of the type of process, production of ethanol could be more than double, from the same quantity of feedstock. In other words, land used for sugarcane growth could be halved if 2nd generation technology is employed. Long-term sustainability of removing trash on a continuous basis should be further investigated.

Table 6 Yields of typical sugarcane products per hectare

1ha of Sugarcane		1:1 Sugar/Ethanol	Ethanol Only
Sugarcane, t		85	85
Sucrose, t		5.7	0
Bagasse, t		23.8	23.8
Cane Trash, t		23.8	23.8
Ethanol, l	1st gen	3600	7200
	2nd gen	5100	5100
Total, l		**8700**	**12300**
Vinasse, m^3		121.4	172.6

Productivities per one hectare land are given in the table 6. Beside increased ethanol amounts, vinasse (stillage) quantity is almost doubled when 2nd generation technology is employed (compared to values from table 2). It is stated already that vinasse is used for ferti-irrigation. However in the regions with large rainfall vinasse might have to be treated as waste.

1.2.1 Energy Balance for combined 1st and 2nd generation process

Depending of the type of process applied power demand changes. If the sugar is one of the products, process is not likely to produce electricity, but it will require extra energy for operations. Figure 4 presents energy balance for combined 1st and 2nd generation ethanol production for a process that produces only ethanol. Sugars from sugarcane are used for 1st generation ethanol production, while bagasse and cane trash are converted to 2nd generation ethanol.

Energy recovered through ethanol is almost doubled, which is in line with increased ethanol productivities. Steam available for running the process (own need) is obtained from lignin and other solids left after bagasse and trash are converted to sugars. This is, however, not enough since ethanol amount is doubled, together with steam demand for its separation. In fact additional 2164MJ of steam is required to run the process. Nevertheless, energy efficiency of such process is improved compared to conventional process.

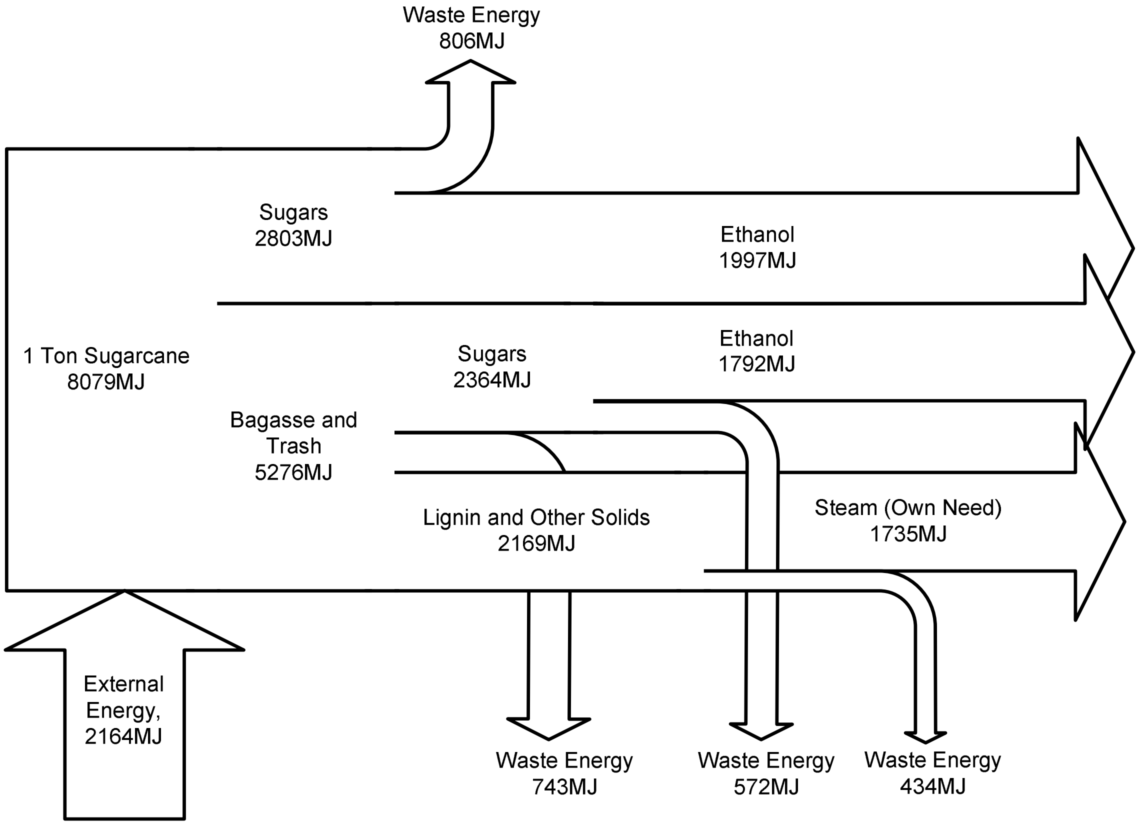

Figure 4 Energy dissipation during 2nd generation ethanol production from sugarcane. No sugar production is considered.

As much as 37% of energy is recovered in produced ethanol, taking into account additional energy make-up. This process option doesn't produce electricity as an output stream. Waste energy streams are also significantly lower compared to 1st generation technology. Only 2555MJ is wasted, compared to 4005MJ from conventional process (table 2), where 2144MJ is wasted during the conversion of steam to electricity.

It is possible to optimize energy balance through minimizing external energy input. There are two reasons why external energy input should be minimized. External energy in this case would probably have to be of fossil origin, annulling fossil-fuel energy independency, which is a comparative advantage of sugarcane ethanol technology. Second reason would be energy efficiency. By minimizing external energy input energy efficiency is optimized (figure 5). However change is almost insignificant. The more trash burned, the less ethanol is produced, decreasing the energy requirement for its processing. At one point external energy demand is zero, because enough trash is burned to give energy to the process. Further increasing of the amount of trash burned doesn't change efficiency. To be independent of external energy, bagasse and at least 10.7% trash should be used for ethanol production.

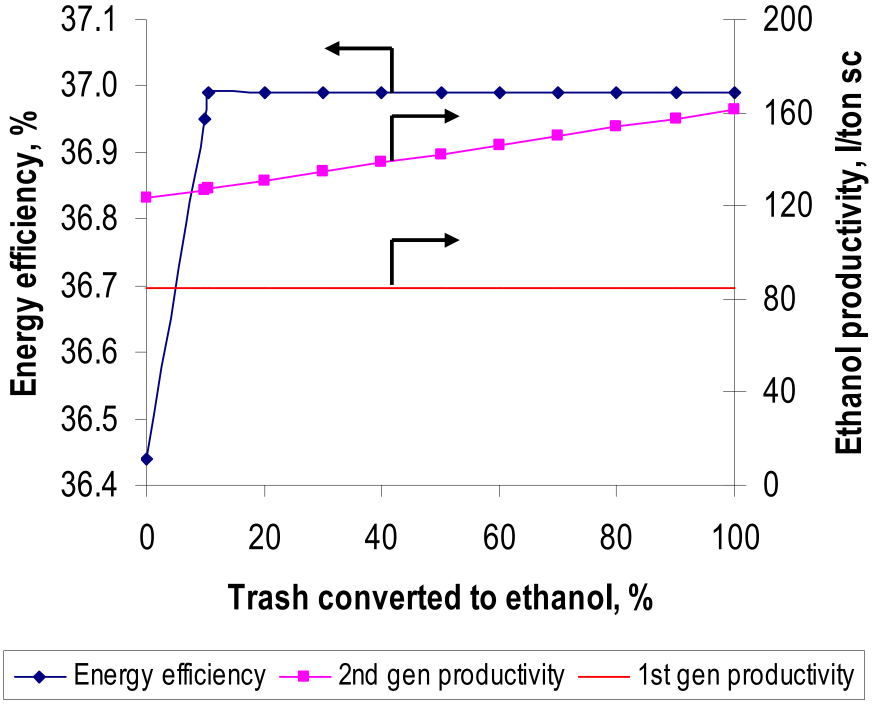

Figure 5 Energy efficiency as a function of the amount of trash burned

Remaining trash should be burned together with produced lignin from bagasse to obtain steam for running the process. Energy efficiency of the process could be little improved in this way reaching as much as 37%. It is obvious that in this case economics will have to be considered to define optimal co-products utilization, since energy efficiency is not a sensitive indicator.

1.3 Production of acetone, butanol and ethanol (ABE)

Acetone, butanol, ethanol fermentation by means of solvent-producing strain Clostridium was one of the first large-scale industrial fermentation processes to be developed at the beginning of 20th century. Technology is abandoned (at least on the large-scale) in the 60's, due to inability to economically compete with fossil-based butanol producing routes [9, 10]. Recent year's energy crisis increased interest in ABE fermentation once again, due to interesting properties of butanol as potential fuel.

Sugar-rich substrates are potential feedstock for solvent-producing Clostridia. Although productivities are much lower than those of ethanol, butanol is regarded as more advanced biofuel in both technical and energetic point of view [9, 11].

Table 7 Estimated yields of integrated ethanol-ABE process

1 Ton Sugarcane	1:1 Sugar Ethanol	Ethanol Only
Sucrose, kg	42	0
Ethanol 1st gen, l	67	85
Ethanol 2nd gen*, l	4.3	4.3
Ethanol total, l	71.3	89.3
Acetone*, l	12.9	12.9
Butanol*, l	16.3	16.3
ABE, l	33.5	

* Yields are based on in-house experimental and literature data

Conventional sugarcane ethanol technology could be integrated with ABE fermentation in such way that ethanol is produced as 1st generation fuel using the existing process, while bagasse and/or cane trash could be used for ABE fermentation. Tables 7 and 8 presents estimated yields of sugarcane ethanol and ABE products. For ethanol and sucrose typical yields for new distilleries in Sao Paolo region are taken [5], while the yields of ABE products are based on AFSG in-house and some literature data [9, 10].

Yield of ABE products is similar to 2nd generation ethanol. About 0.4kg ABE is produced per kg of sugars [9]. Productivity of ABE per hectare is 2.8m^3, while as much as 5.1m^3 of 2nd generation ethanol could be obtained (table 6). This difference is due to the fact that bagasse and trash are used for ethanol fermentation, while only bagasse is considered as raw material for ABE fermentation. Trash is burned for energy, which is required in greater extent for ABE separation.

Table 8 Estimated yields of integrated ethanol-ABE process per hectare

1ha of Sugarcane		1:1 Sugar/Ethanol	Ethanol Only
Sugarcane, t		85	
Sucrose, t		3.6	0
Bagasse, t		23.8	
Cane Trash, t		23.8	
Acetone, l		1390	
Butanol, l		1710	
Ethanol, l	1st gen	5700	7200
	2nd gen (from ABE)	370	
Ethanol Total, l		**6170**	**7570**
Total ABE* products, l		3470	

* Only bagasse is converted to ABE

1.3.1 Energy Balance for Combined Sugarcane Ethanol and ABE Production

Relatively low concentrations of ABE are possible to obtain in the fermentation. Toxicity of the solvents, especially butanol inhibits solvents production. To convert all the sugars to ABE, in-situ removal of the products has to be carried out. Being toxic in low concentrations (~10g/l) separation of the solvents is not efficient and requires large energy input. Energy required for ABE production and separation is 4.55 times energy contained in ABE. Compared to ethanol which requires 0.77 times for 1st and 1.32 times more energy for 2nd generation this is 5.9 and 3.4 times more energy, respectively. Figure 6 shows energy dissipation diagram for ABE production from bagasse integrated with conventional sugarcane ethanol process. Trash is burned to provide energy for both ethanol and ABE processing. That is, however, not enough and additional 2627MJ are required to run the process. Energy efficiency of such process is 27% in contrast with 37% efficiency of combined 1st and 2nd generation ethanol process or 31.3% efficiency of 1st generation sugarcane ethanol.

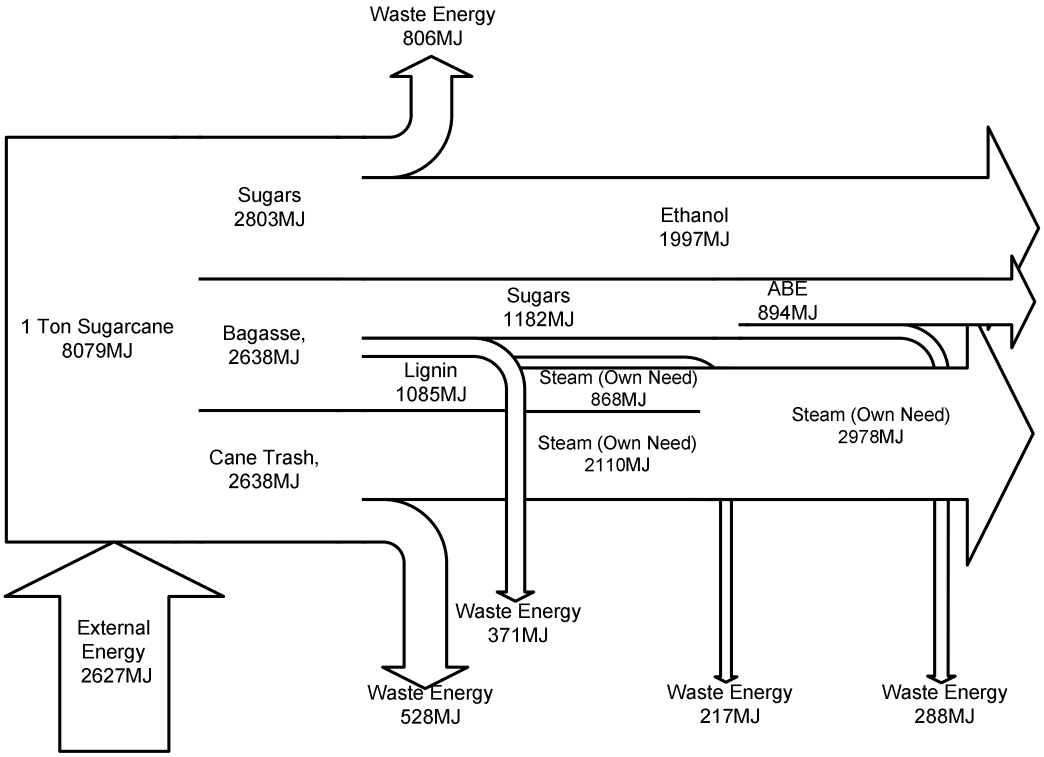

Figure 6 Energy dissipation during combined sugarcane ethanol and ABE production from sugarcane. No sugar production is considered.

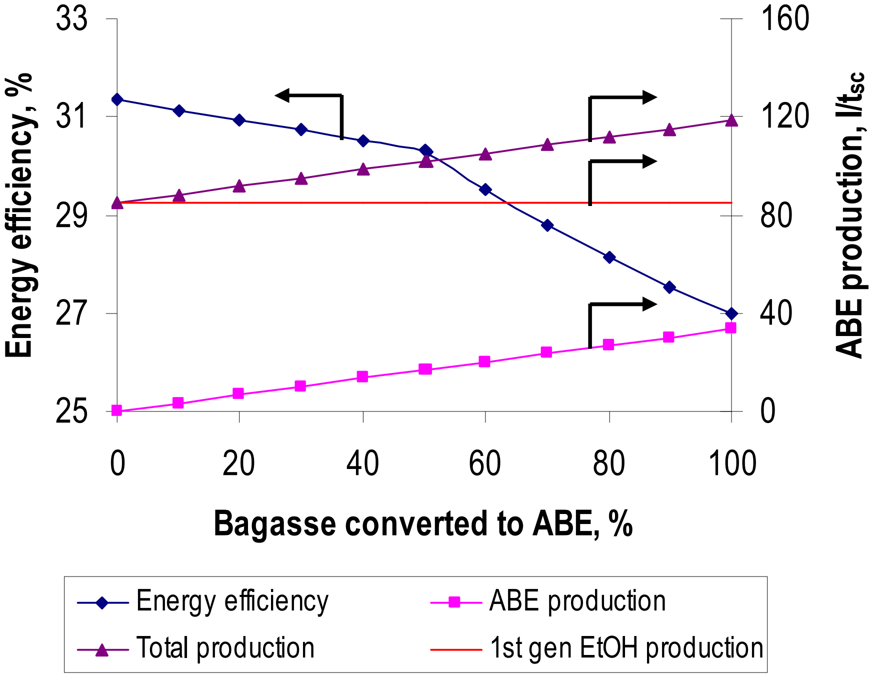

Figure 7 Energy efficiency as a function of bagasse fraction used for ABE fermentation. Remaining part is burned for energy.

In chapter 1.3 products yields were given for the case where ABE is integrated into conventional ethanol process, where bagasse is used as feedstock for ABE fermentation and trash is used only for energy. Dependence of energy efficiency and production per ton sugarcane of such process on the fraction of bagasse used for ABE fermentation is given on the figure 7. Due to the low intrinsic efficiency of ABE process overall process efficiency declines when the fraction of bagasse used for ABE production increases. For the fractions of bagasse bellow 50% energy available from sugarcane and co-products is enough to cover the processing demand and the surplus is converted to electricity. At one point energy efficiency continues to drop faster. That is the point when process itself cannot generate enough energy for internal use and additional amount has to be put in. Optimum between the amount of ABE produced and energy efficiency is found at the breaking of the energy efficiency line. Thus using 50.5% of bagasse for ABE production allows the process to run independently of external energy. However, reduction of the ABE production capacity increases efficiency of the process. From an efficient energy utilization point of view it is better to just burn bagasse and trash rather than converting them to ABE. From an economic point of view though, this may be efficient.

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