

Comparative analysis of sugarcane processing technologies for environmental impact and energy efficiency

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abstract

An evaluation of the energy performance and greenhouse gas (GHG) emissions of front end (preparation and extraction) and boiling house process (evaporation, crystallization, curing and drying) equipment of a sugarcane factory has been carried out and is presented. Different technologies have been compared and have highlighted that technologies supplied by Fives Cail give significant energy advantages. Compared with conventional technologies, Fives Cail's In-line Shredder (cane preparation), Millmax® (milling), continuous vacuum pans (compared with batch pans) and 5 effect falling film evaporators (compared with 5 effect rising evaporators) showed decrease in energy consumption by 16%, 37%, 10% and 3%, respectively, and thereby making available additional 11 kWh per tonne cane for export and revenue generation. Energy efficient technologies lead to reduced GHG emissions and GHG emissions for the manufacture and end-of-life disposal of sugar processing equipment are very small compared to those generated during operation of the equipment.

Keywords: batch pans, cane preparation, cane sugar processing, continuous vacuum pans, diffusion, energy efficiency, evaporators, green house gas emissions, milling

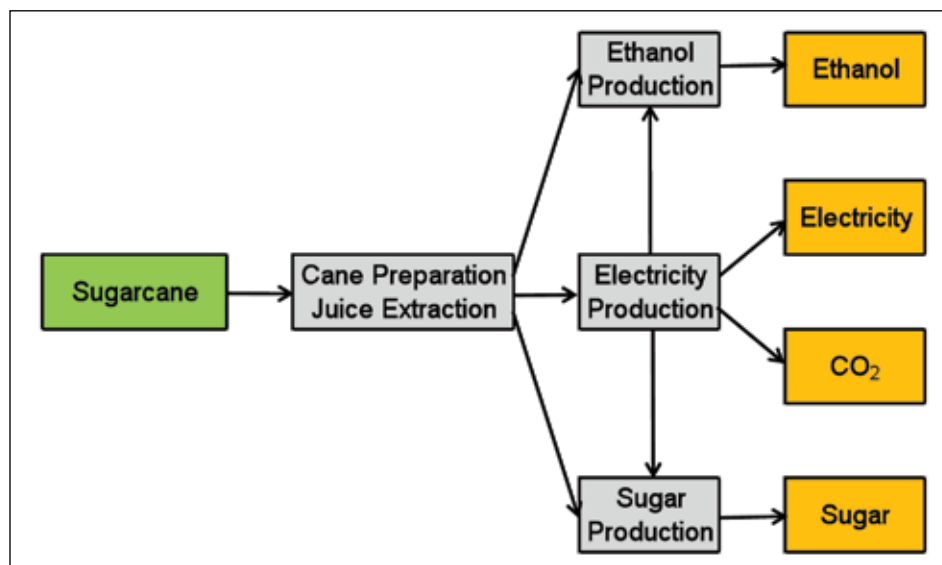
1: Introduction

In recent times the sugarcane industry has undergone some important changes with respect to energy conservation, diversification and environmental factors.

The first of these changes has been a focus on energy conservation and environmental issues leading to a better appreciation of the value of bagasse as an important resource. In the first instance, for satisfying both the steam and electricity generation needs for sugar processing and in the second instance to use surplus electrical production capacity to maximize cogeneration. These surpluses are typically sold to the local electric network or are used for other needs such as irrigation. To carry out this change effectively, it is necessary to reduce steam and electricity consumptions of the energy consuming operations by increasing the capacities and by optimizing the processes and the technologies. This change is in progress and is far from being completed: many sugar factories could benefit from comprehensive optimisation.

This production of electricity from biomass (bagasse) makes it possible to avoid greenhouse gas (GHG) emissions that would have been incurred if this electricity had been produced from other sources such as oil, coal or natural gas. Moreover, funding for projects that avoid or achieve a reduction in GHG emissions can be obtained through a United Nations programme called the "Clean Development Mechanism" (CDM). Currently (in 2010) there are 90 cogeneration projects, in 16 countries, that have received financing through this mechanism. These projects will achieve a reduction in, or avoid, GHG emissions of 4.3 million tons of CO₂e each year (UNFCCC). CO₂e is an abbreviation for 'carbon dioxide equivalent' and is the internationally recognised measure

Figure 1. Multiple uses of sugarcane



of greenhouse gas emissions.

The second of these changes involves diversifying the use of sugarcane, particularly in the field of bioethanol production.

Sugarcane is no longer just a food crop, but also a feedstock to generate new revenue streams from the production electricity, ethanol and CO₂ (Figure 1).

Therefore, in addition to the traditional areas of focus for the cane industry, of agriculture and sugar processing, new concerns relating to energy and the environment have to now also be included (Moor 2008, Rein 1995). These new concerns have had far reaching implications, which even extends to manufacturers communicating to consumers information about their carbon emissions; Tate and Lyle, and British Sugar have published the GHG emissions of their productions of raw, white or refined sugars. On another aspect the bioethanol industry is the subject of detailed environmental analyses, in particular in Brazil (BNDES and CGEE 2008, Macedo *et al* 2008, Wang *et al* 2008).

In this context where the industrial, economic and environmental requirements are closely dependant, this article aims at quantifying the environmental impact of the main technologies used in the sugarcane processing industry. For the environmental aspects, there is particular focus on energy and GHG.

Table 1. Technologies evaluated

Process	Evaluated technologies	End products
Front-End		
Cane preparation	Set of cane knives and gravity shredder In-Line Shredder	Energy, sugar, ethanol
Juice extraction	Mills MillMax® Diffuser	Energy, sugar, ethanol
Sugar-End		
Juice concentration	Falling film evaporators Rising evaporators	Sugar
Crystallization	Continuous vacuum pans Batch pans	Sugar
Curing	Batch centrifugals Continuous centrifugals	Sugar
Sugar drying	Multi-tube dryer	Sugar

2: Evaluations

Selected technologies evaluated in this study are:

- Cane preparation: Cane knives and heavy-duty gravity shredders which represent conventional technology, versus the In-Line Shredder,
- Juice extraction: Conventional mills, versus the MillMax® and cane diffusers,
- Sugar processing: Roberts and rising film evaporators versus falling film evaporators; batch and continuous and vacuum pans; batch and continuous centrifugals; and finally sugar dryers.

For these technologies we have evaluated energy and material consumption, then GHG emissions. Life cycle phase of technologies which were taken into account are manufacture, transport and installation on site, then operation and, finally,

Table 2. Cane characteristics

Item	Value
Cane processing rate	10000 t/day
Fibre	14%
Pol % cane	14%
Juice purity	85%
Crop duration	210 days

Table 3. General characteristics of the base case factory

Item	Value
Boiler	60 bar 470 °C Process steam: 2 bar
Front-End	Set of cane knives, gravity fed shredder 5 conventional mills Electric motors Imbibition: 250% on fibre
Process	5-effect rising evaporation station Crystallization: A three strike boiling system (with remelted B-sugar and double cured C-sugar), using batch pans

Table 4. Emission factors

Item	Emission factory	Reference
Electricity (Brazil)	283 kg CO ₂ e/MWh	BNDES and CGEE
Recycled steel	1.1 kg CO ₂ e/kg	ADEME
Concrete	0.37 kg CO ₂ e/kg	ADEME



dismantling at the end of the equipment's lifetime.

Data used for all these evaluations are specified in section 3. The evaluations of technologies are then presented in section 4.

3: Data

The base case example factory considered for this study is one which produces raw sugar, cogenerates power with surplus

Table 5. Comparison of cane preparation technologies

Technology	Conventional preparation	In-Line Shredder
		
Main components	1 main conveyer 1 leveller 2 sets of cane knives 1 auxiliary conveyor 1 gravity fed shredder Electric drives	1 main conveyer 1 leveller 1 In-Line Shredder Electric drives
Preparation index (PI)	> 90%	> 90%
Absorbed power	4064 kW	3403 kW
Annual electricity consumption	20482 MWh	17151 MWh
GHG annual emissions (electricity consumption)	5800 t CO ₂ e/year	4900 t CO ₂ e/year

electricity being supplied to a local network, and which employs older, some may say conventional technology. The selected operational characteristics are example values considered reasonably typical nowadays.

Tables 2 and 3 features base data on cane quality and factory operations. With these it is then possible to size equipment and to determine their energy consumption and their GHG emissions.

All electricity consumption estimates reported for the considered equipment result either from values published in the sugar literature (Rein 2007) or, for Fives Cail equipment, from measurements carried out on site by Fives Cail or its factory staff. Steam consumption evaluations are estimated based on Fives Cail models of factories, used and validated during surveys carried out for our customers over many years.


To evaluate GHG emissions of equipment, it is necessary to consider all single activities of the life cycle of this equipment. These activities are the use of materials for manufacture, maintenance, operation, recycling of waste or de-commissioned equipment, together with the use of energy resources for manufacture, operation, and transporting of both freight and of staff. GHG emissions for these single activities are characterized by their emission factors, which represent the quantity of GHG emitted during these activities. Many emission factors are available in public international databases. Table 4 specifies those which are used.

4: Assessing the environmental balance of sugarcane processing technologies

4.1: Cane preparation

Cane preparation entails rupturing the cells containing the cane juice for later extraction. This operation must proceed without juice losses and is typically characterized by a measured parameter termed preparation index. Two different technologies are evaluated; conventional preparation (gravity fed heavy duty shredder) and wholestick cane preparation with an In-Line Shredder (Inskip 2010). These two technologies are able to

Table 6. Typical installation and factors for GHG emission evaluation of an In-line Shredder (including leveller + shredder + drives)



Item	Value
Equipment weight (steel)	89 t
Civil engineering (concrete)	134 t
Annual maintenance (steel)	3500 kg
Recycling steel equipment	80%
Recycling steel for hammers refurbishing	0%
Recycling concrete from civil engineering	0%

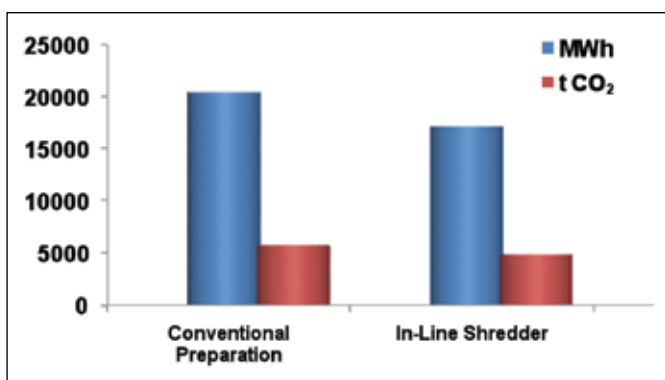
Table 7. GHG emissions of an In-Line Shredder (leveller + shredder + drives)

Item	GHG emissions
Manufacture - erection	148 t CO ₂ e
Operation	4900 t CO ₂ e/year
End-of-life disposal	-78 t CO ₂ e

achieve the same level of performance with regard to the preparation index. The In-Line Shredder has, compared to conventional shredders, several benefits which include less required equipment and a smaller footprint. It has been assumed for this study that electric drives are used for both of these two technologies, as this would generally be the case for a factory co-generating power. Table 5 shows the main characteristics of these two technologies.

The data presented in Table 5 shows that the In-Line Shredder consumes some 16% less energy than conventional cane preparation technology. GHG emissions, being effectively in direct proportion to the electricity consumption, are also 16% lower for

Figure 2. Annual electricity consumption and GHG emissions of conventional preparation and In-Line Shredders



the In-Line Shredder compared with conventional preparation.

Concerning the In-Line Shredder, a more detailed analysis of the GHG emissions during the life cycle of this product is presented in Tables 6 and 7.

This analysis shows that GHG emissions are mainly concentrated on the operational phase of the equipment. Equipment manufacture and end-of-life considerations account for only 0.05% of the emissions, based on a 30 year equipment lifetime assumption. Annual maintenance accounts for only 0.1% of the emissions.

Cane preparation is an energy-intensive process. With conventional technology steam turbines are often used to provide motive power for shredder and cane knives. It is of course important, in the first instance, to replace turbines with electric (or hydraulic) drives because this significantly reduces overall factory steam consumption which consequently improves the total energy balance. In addition to this the In-Line Shredder technology is comparatively more energy-efficient than the conventional preparation (see

Figure 2), thereby facilitating the export of more surplus power to an external network. The power use is reduced by 660 kW in our example, resulting in additional surplus of 3300 MWh available for sale by the factory to national grid.

4.2: Juice extraction

Two different principles are employed today to extract juice from prepared cane; extraction by pressure between the rollers of mills and extraction by a lixiviation, or leaching process in a diffuser. In both cases this operation is mainly evaluated by the in terms of extraction (pol in extracted juice % pol in cane) and the bagasse moisture. Technologies which have been evaluated for this study are conventional mills and MillMax® for the extraction by pressure and the fixed screen diffuser with two dewatering mills for the extraction by lixiviation (Rein 1995, Trancart 2008). For the sake of simplicity the same level of imbibition, extraction and final bagasse moisture has been assumed for all three technologies. Table 8 notes the main characteristics of these three technologies.

The comparison in Table 8 shows that a diffuser has the

Figure 3. Annual electricity consumptions and GHG emissions of alternative extraction technologies

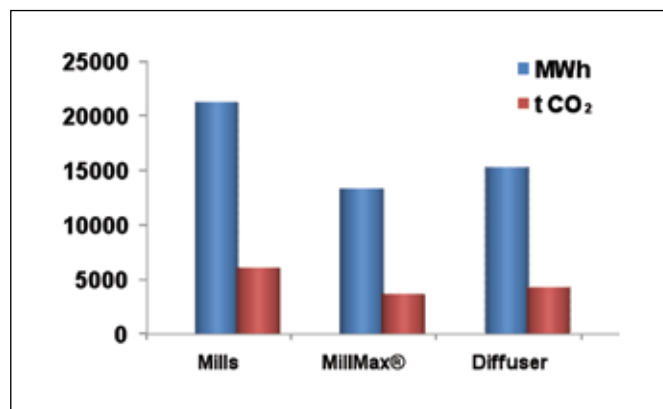


Table 8. A comparison of the juice extraction technologies




Technology	Conventional Milling Tandem	MillMax® Tandem	Diffuser
			
Main components	5 mills Intermediate conveyers Donnelly chutes Electric drives	5 MillMax® Intermediate conveyers Donnelly chutes Electric drives	1 diffuser 2 dewatering mills Electric drives
Imbibition on fibre	250%	250%	250%
Performances:			
Pol extraction	96.3%	96.3%	96.3%
Bagasse moisture	50%	50%	50%
Absorbed power	4215 kW	2646 kW	2196 kW
Annual electricity consumption	21244 MWh	13336 MWh	11068 MWh
Extra steam consumption			6.3 t/h
Export of electricity for extra steam	0*	0	-4202 MWh
Annual GHG emissions (electricity and extra steam)	6000 t CO ₂ e/year	3800 t CO ₂ e/year	4300 t CO ₂ e/year
(*) Reference			

Table 9. Corresponding characteristics of extraction technologies

Technology	Conventional mills tandem	MillMax® tandem	Diffuser
Equipment weight (steel)	1016 t	777 t	641 t
Civil engineering (concrete)	1015 t	775 t	930 t
Recycling steel from annual maintenance	80%	80%	80%
Annual maintenance (steel)	18 t	11 t	7 t
Recycling steel equipment	80%	80%	80%
Recycling concrete from civil engineering	0%	0%	0%

lowest electricity consumption, followed by MillMax® and then conventional mills. However, it is necessary to take into account the steam consumption required for maintaining the temperature in the diffuser. Having the same imbibition for these technologies, there is no other difference of steam consumption. This steam consumption leads to a reduction of the amount of exported electricity for a diffuser which, in our example, gives 4202 MWh less when compared with conventional mills or MillMax® technology. The total balance, taking into account both electricity and steam consumption, gives the advantage to the MillMax®, followed by a diffuser and, finally, to conventional mill (Figure 3).

A more detailed analysis of the GHG emissions of these three technologies during their life cycle is presented in Tables 9 and 10.

Table 10. GHG emissions of alternative extraction technologies

Technology	Conventional mills tandem	MillMax® tandem	Diffuser
Manufacture - assembly	1500 t CO ₂ e	1100 t CO ₂ e	1000 t CO ₂ e
Operation	6000 t CO ₂ e /year	3800 t CO ₂ e /year	4300 t CO ₂ e /year
End-of-life disposal	-900 t CO ₂ e	-700 t CO ₂ e	-600 t CO ₂ e

This analysis shows that, as for cane preparation, GHG emissions are mainly produced during the operational phase of the equipment. Whatever the technology selected, manufacturing and end-of-life disposal account for only 0.3 to 0.4% of the emissions when based on an assumption of an equipment life of 30 years. Annual maintenance accounts for only 0.3% of the emissions.

As with cane preparation, juice extraction is also energy-intensive. Further the conventional technology still often uses steam turbines to provide this energy. As for preparation, it is

important to replace these turbines with electric drives when overall energy consumption is being considered. Thereafter, in order to further reduce electricity consumption and GHG emissions, MillMax® technology has been shown to be more energy-efficient than conventional mills with savings of 7900 MWh becoming available for export and additional revenue for the factory.





4.3: Juice evaporation

For the evaluation of juice evaporation two technologies have been considered: traditional “rising” evaporation (using Roberts or Kestner type evaporators) and falling film evaporation with tubes (Coustel *et al* 2009). In addition each of these technologies is evaluated with quadruple or quintuple effect stations.

Table 11 presents performance data of these two technologies.

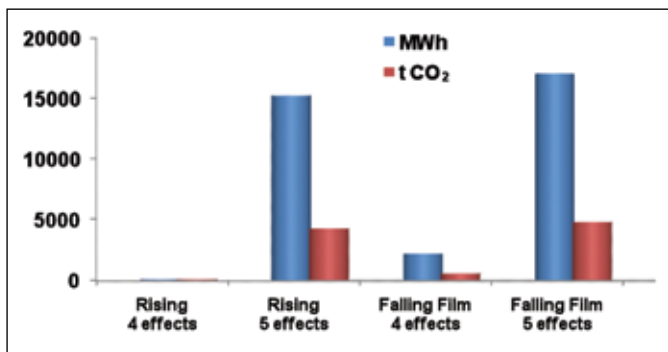
From the energy point of view, the difference between these technologies comes mainly from the factory’s steam

Table 11. A comparison of the juice evaporation technologies

Technology	4 effect rising evaporators	5 effect rising evaporators	4 effect falling film evaporators	5 effect falling film evaporators
				
Main components	4 evaporators	5 evaporators	4 evaporators	5 evaporators
Total installed area	17000 m ²	19000 m ²	13500 m ²	15000 m ²
Crystallization	3 strikes Batch pans Optimized bleedings	3 strikes Batch pans Optimized bleedings	3 strikes Batch pans Optimized bleedings	3 strikes Batch pans Optimized bleedings
Sugar process steam consumption	414 kg/tc	360 kg/tc	403 kg/tc	350 kg/tc
Annual exported electricity	0*	15290 MWh	2240 MWh	17110 MWh
Annual GHG avoided emissions	0	4300 t CO ₂ e /year	600 t CO ₂ e /year	4800 t CO ₂ e /year

(*) Reference

Figure 4. Electricity exports and avoided GHG emission comparisons for evaporator station options



consumption. For all comparisons we have considered the same front-end, the same crystallization workshop and steam bleedings have been optimized.

Compared with conventional evaporators, falling film evaporators makes it possible to reduce the temperature difference between the various effects due to the absence of a hydrostatic head. This enables some additional vapour bleeding optimisation to be implemented which, in turn, results in approximately 3% reduction in overall factory steam consumption when falling film evaporators are used instead of conventional evaporators and this is the same whether 4 or 5 effects are used.

In addition to this, a quintuple effect evaporator station gives an approximately 13% reduction in steam consumption compared with a quadruple effect station, for both conventional and falling film evaporators.

In addition to the difference in steam consumptions between falling film and conventional evaporators an account has also been taken of the electricity consumed by pumps which are necessary for falling film evaporators.

To evaluate the total impact of the various evaporator station alternatives the net quantity of electricity available for export has been evaluated, which depend on both the electrical consumption of each evaporator station as well as steam consumption of the factory. To do this a base case has been set as that of an evaporator station using a quadruple effect and conventional evaporators. Compared to this reference, the falling film technology is slightly more efficient than the rising evaporators and the 5 effects are much more efficient than the 4 effects.

With falling film evaporators it is possible to export approximately 2000 MWh more than with rising evaporators, whether one operates with 4 or 5 effects. A quintuple effect station makes it possible to export between 15000 and 17000 MWh more than a quadruple effect station, either for rising or for falling film technology (Figure 4).

When a factory exports or uses its surplus electricity, it has a

Table 12. Corresponding characteristics of evaporator station options



Technology	4 effect rising evaporators	5 effect rising evaporators	4 effect falling film evaporators	5 effect falling film evaporators
Equipment weight (steel)	430 t	480 t	300 t	340 t
Civil engineering (concrete)			100 t	110 t
Recycling steel equipment	80%	80%	80%	80%
Recycling concrete civil engineering			0%	0%

Table 13. GHG emissions of the evaporator station options

Technology	4 effect rising evaporators	5 effect rising evaporators	4 effect falling film evaporators	5 effect falling film evaporators
Manufacture - assembly	470 t CO ₂ e	530 t CO ₂ e	370 t CO ₂ e	410 t CO ₂ e
Operation	0*	-4300 t CO ₂ e/year	-600 t CO ₂ e/year	-4800 t CO ₂ e/year
End-of-life	-380 t CO ₂ e	-420 t CO ₂ e	-260 t CO ₂ e	-300 t CO ₂ e

(*) Reference

Table 14. Vacuum pan crystallization technologies

Technology	CVP	Batch pans
		
Main components	3 strikes CVPs Seed pans Massecuite receivers	3 strikes batch pans Massecuite receivers
Sugar process steam consumption	330 kg/t cane	330 kg/t cane
Annually exported electricity	10400 MWh	0*
GHG avoided emissions	-3000 t CO ₂ e/year	0

(*) Reference

strong economic incentive to invest in quintuple effect falling film evaporator station.

With respect to GHG emissions, we have the same trend as that for electricity exports; the falling film evaporator station gives 500 to 600 tons of avoided CO₂e emissions per annum

Figure 5. Exports of electricity and GHG avoided emissions for crystallization technologies

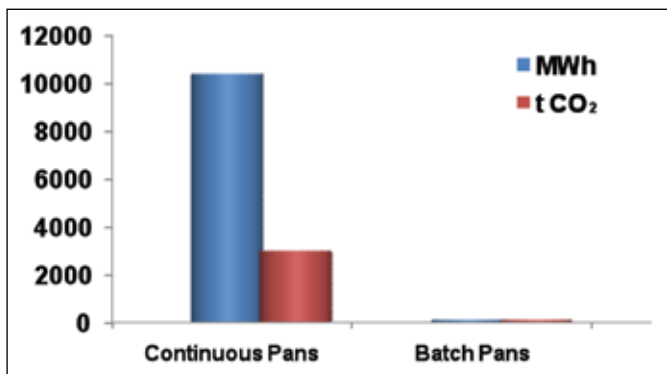


Table 15. Complementary characteristics of crystallization technologies

Technology	CVP	Batch pans
Mass equipment (steel)	530 t	800 t
Recycling steel equipment	80%	80%

Table 16. GHG emissions of crystallization technologies

Technology	CVP	Batch pans
Manufacture - assembly	150 t CO ₂ e	230 t CO ₂ e
Operation	-3000 t CO ₂ e /year	0
End-of-life	-120 t CO ₂ e	-180 t CO ₂ e

compared with traditional evaporation technology. A quintuple effect station gives 4200 to 4300 tons of avoided CO₂e emissions per annum compared to a quadruple effect.

Once again it can be seen that GHG emissions are mainly concentrated on the operational phase of the equipment. Whatever the technology selected, manufacture and end-of-life aspects represent approximately 100 tons of CO₂e which are very low compared to the difference in avoided emissions of falling film evaporation compared to conventional evaporators or between quintuple and quadruple effects.

4.4: Crystallization



Crystallization involves growing sugar crystals under controlled conditions, with the main portion taking place during the boiling of massecuite in vacuum pans. Two alternative vacuum pan boiling technologies are evaluated here: batch pans and continuous vacuum pans (CVPs). Table 14 shows the main characteristics of these two technologies.

From the energy point of view, the difference between these technologies comes mainly from their steam consumption. Continuous vacuum pans make it possible to operate with lower pressures than batch pans, which reduces the total consumption of the factory. After optimization of bleedings, this total consumption is decreased by approximately 10% with a 3 strikes continuous pans boiling scheme compared with a 3 strikes batch pans boiling scheme. CVPs are thus essential for energy savings.

With regard to electricity, the reduction of steam consumption with CVPs makes it possible to export more electricity. The difference between continuous and batch crystallization is 10400 MWh per year. When a factory exports or develops its surpluses of electricity, it has a strong economic interest to be equipped in continuous crystallization.

Concerning GHG emissions, continuous crystallization avoids

Table 17. Characteristics of batch and continuous centrifugals

Technology	Batch centrifugals ZUKA® 1750	Continuous centrifugals FC 1550
		
Main components	4 centrifugals	7 centrifugals
Electricity consumption per ton of cured massecuite	0.65 kWh/tmc (A strike)	4 kWh/tmc (B strike) 6 kWh/tmc (C strike)
Annual electricity consumption	330 MWh/year	1250 MWh/year
Mass equipment (steel)	40 t	35 t
Recycling steel equipment	80%	80%
GHG emissions (manufacture)	45 t CO ₂ e	40 t CO ₂ e
GHG emissions (operation)	90 t CO ₂ e /year	350 t CO ₂ e /year
GHG emissions (end-of-life)	-35 t CO ₂ e	-30 t CO ₂ e

emitting 3000 tons of CO₂e per annum compared to batch crystallization.

A more detailed analysis of GHG emissions during the life cycle of these technologies is presented in Tables 15 and 16.

GHG emissions are mainly concentrated on the operation phase of equipment. However, manufacture of CVPs requires less material, which leads to GHG emissions 35% lower than for batch pans.

4.5: Centrifugation

Concerning curing, we considered ZUKA® batch centrifugals for curing of strike A and FC 1550 continuous centrifugals for curing of strikes B and C (Pelletan 2004, Pilot 2006).

Electricity consumptions of these centrifugals are presented in Table 17. The yearly power consumption of all centrifugals is 1580 MWh (20% for batch centrifugals and 80% for the continuous ones).

GHG emissions are mainly concentrated on the operation

phase of the equipment. Manufacture and end-of-life account for only approximately 0.2% of emissions.

4.6: Sugar drying

Concerning the drying of sugar, we considered the multitube cooler - dryer. The power consumption of this unit is presented in Table 18. Its annual consumption is 1000 MWh.

GHG emissions are mainly concentrated on the operation phase of the equipment. Manufacture and end-of-life account for only approximately 0.3% of emissions.

5: Conclusions and perspectives

We have evaluated in detail the energy performances and the GHG emissions of the front-end and of the sugar process of a sugarcane factory. These evaluations result from experimental measurements realized in many factories. When that was possible, various technologies were compared.


These evaluations emphasize that technologies supplied by Fives Cail are highly energy-efficient:

- In-Line Shredder (-16% consumption compared to the conventional preparation) and MillMax® (-37% consumption compared to the conventional mills) for which concerns the front-end,
- continuous vacuum pans (-10% consumption compared to batch pans),
- 5 effect falling film evaporators (-3% consumption compared to 5 effect rising evaporators and -13% consumption compared to 4 effects rising evaporators) for which concerns the sugar process,
- In total this adds up to 23 GWh per year or 11 kWh / tonne cane being additionally available for export and revenue generation.

With regard to GHG emissions, since these are proportional to energy consumption, it is apparent that energy-efficient technologies will emit less GHG. Manufacture and end-of-life of the equipment represent less than 1% of the emissions of the operation phase of the products.

The combined use of high pressure boilers in cogenerating more power on the one hand and using energy-efficient technologies from front-end through to sugar manufacture on the

Table 18. Characteristics of the multitube dryer

Technology	Multitube dryer
	
Main components	1 multitube dryer Cold air equipment Hot air equipment Gas scrubber
Final sugar moisture	< 0.04%
Absorbed power	190 kW
Annual electricity consumption	1000 MWh
Weight of dryer (steel)	140 t
Recycling steel equipment	80%
GHG emissions (manufacture)	160 t CO ₂ e
GHG emissions (operation)	280 t CO ₂ e/year
GHG emissions (end-of-life)	-130 t CO ₂ e

other hand, offers a significant opportunity in expanding revenues from surplus power. Further, with the development of high yielding energy cane with higher fibre content than conventional cane cultivars, and fuller utilization of crop residues (leaves and tops) will herald increased energy production from sugarcane (Lora *et al* 2006, Lora *et al* 2008) in the foreseeable future.

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