Solar Process Heat for South African Sugar Mills

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Abstract

Solar thermal (ST) systems for the South African (SA) sugar industry could reduce coal consumption in the boilers and partly replace bagasse (pressed sugar cane fibres) as a heating fuel. Based on the heat and mass balance of a representative sugar mill, the most promising solar heat integration points were identified and pre-ranked according to their potential energetic and economic benefits.

The identified opportunities for solar process heat (SPH) are the generation of live steam and exhaust steam, the pre-heating of boiler feed water, the drying of bagasse and raw sugar, and the heating of clear juice. Without additional thermal storage, ST systems can supply between 12 and 27 % of the heat demand of these processes. The estimated levelized costs of heat (LCOH) for the SPH systems range from 2.57 Eurocent/kWh (0.42 ZAR/kWh) for solar drying of raw sugar during the crushing season (CS) to 4.57 Eurocent/kWh (0.75 ZAR/kWh) for all-year solar live steam generation.

This study assumes that SPH has to compete with coal, which is the cheapest energy source in SA, to replace bagasse. Using current coal prices and past price increase rates, the estimated achievable internal rate of return (IRR) for solar live steam generation is 4.6 % if the steam can be used during the whole year, e.g. for electricity export. The highest IRR of 9.1 % is expected for sugar drying during the crushing season.

Keywords: *solar process heat, energy efficiency, sugar production, electricity export, feasibility study*

1. Introduction

South Africa (SA) produces about two million tons of raw and refined sugar per year as well as a wide range of sugar by-products. Six milling companies operate 14 sugar mills. The vast majority of 12 mills are located in the KwaZulu-Natal province with the remaining two in Mpumalanga. The industry employs 79 000 people directly. SA is one of the leading exporters of sugar, competing with, among others, Brazil, Australia and India (DAFF, 2013). The crushing season usually stretches from March/April to November/December, depending on the amount of cane available in a particular year. On average, about 22 million metric tons of sugarcane are being processed per year (Wienese and Purchase, 2004, p. 41). The capacities of the SA sugar mills vary between 90 and 550 tons of cane per hour (t/h), with an average of about 300 t/h (Smithers, 2014, p. 917). The average length of the 2012/13 crushing season was 254 days and the overall time efficiency (OTE) was about 75.7 % (Smith et al., 2013, p. 30).

A decrease in coal consumption due to improved process management and energy efficiency directly reduces running costs. New income streams can be accessed if a share of the bagasse can be utilized for purposes other than energy generation for the sugar mills. This bagasse can be used to produce fertilizer, animal feed, or paper. It can also be used as feedstock for bio-ethanol production. Particularly interesting in the context of solar process heat (SPH) utilization is the use of steam from bagasse boilers to generate electricity for export to the SA national grid.

2. Sugar Production und Current Energy Supply

To provide a background for the SPH integration analysis to follow, this chapter gives a short introduction to the production of sugar from sugar cane, and on the energy supply to the different processes involved. The descriptions are all based on Rein (2007), unless otherwise stated.

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2.1 Sugar production process

A simplified representation of the main processes, the intermediate product streams, and the energy supply is given in Figure 1.

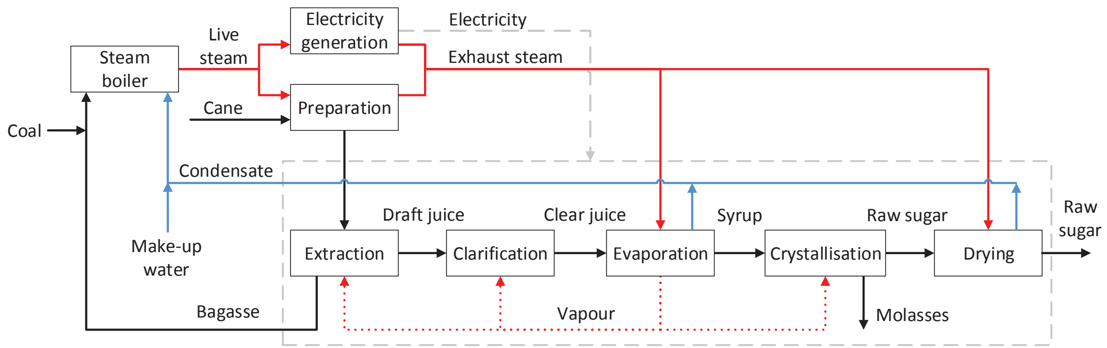

Figure 1: Processes and energy supply of a South African sugar mill

In SA, the cane is usually burned on the field to simplify manual harvesting even though this results in some of the biomass from the leaves being lost. The cane is cut, bundled and transported to the mills. It has to be processed as soon as possible to avoid a loss in sucrose.

Cane preparation refers to the removal of dirt and rocks, the cutting of the cane, and the fiberization of the cane by shredders. Modern sugar factories no longer mill the cane but use diffusers for the extraction of sucrose. In the diffuser, the sucrose is leached by repeatedly spraying heated juice onto a bed of cane fiber moving in counter-flow direction. The bagasse exiting the diffuser is pressed in roller mills to reduce the moisture content and to extract the maximum amount of sucrose. Cane knives, shredders and roller mills are referred to as ‘prime movers’. They are usually run by live steam. In the clarification process, the impurities in the juice are removed. Therefore, the juice is pre-heated, flashed, and chemicals such as milk of lime are added.

By evaporation, the clear juice is concentrated to syrup by increasing its sucrose content. This is done in multiple effect evaporators, which have four or five heat exchangers that utilize low-pressure steam as a heating medium. The operating pressure is reduced in each consecutive effect to lower the saturation temperature of the vapor and the boiling point of the syrup. The first effect consumes exhaust steam, after which each successive effect consumes vapor bled from the preceding effect. Additionally, vapor is bled from the evaporators to serve as a heating medium for most of the other processes within the factory (cp. red dotted lines in Figure 1). To achieve crystallization, the syrup is boiled under vacuum in order to concentrate it to saturation. This is usually done by three different batch or continuous boiling pans, referred to as pans A to C. At the outlet of each pan, crystallizers cool the syrup and a centrifuge splits the mass in sugar and molasses. The molasses from the centrifuges of pans A and B is fed into the following pans, while the molasses from the pan C centrifuge is sold as a by-product, used for the production of ethanol, yeast, fertilizer or animal feed.

In the final drying process, the surface moisture content of the raw sugar is reduced by evaporation. For this, usually rotary cascade drums with counter flow hot air are used. After the sugar is dried, it is cooled with ambient air. Raw sugar can be sold directly, or be further refined at a refinery.

2.2 Current energy supply of SA sugar mills

For this study, the steady-state energy and mass balance of a theoretical South African sugar mill without energy efficiency measures is used. Temperatures, pressures and flow-rates are simulation results from the Biorefinery Techno-Economic Modelling project (BRTEM, Starzak and Zizhou, 2015). The BRTEM sugar mill represents the current practice in SA and assumes a throughput of 250 tons cane per hour.

Figure 2 shows besides a first SPH integration concept also the energy supply of the BRTEM sugar mill. The main energy source is bagasse from the roller mills after the extraction process. Live steam is used to perform mechanical work by driving the three prime movers, but it also drives a turbine, which runs a turbo alternator to generate the electricity needed in the production processes. The resulting exhaust steam is used to run the thermal processes of the plant with the highest exergy requirements.

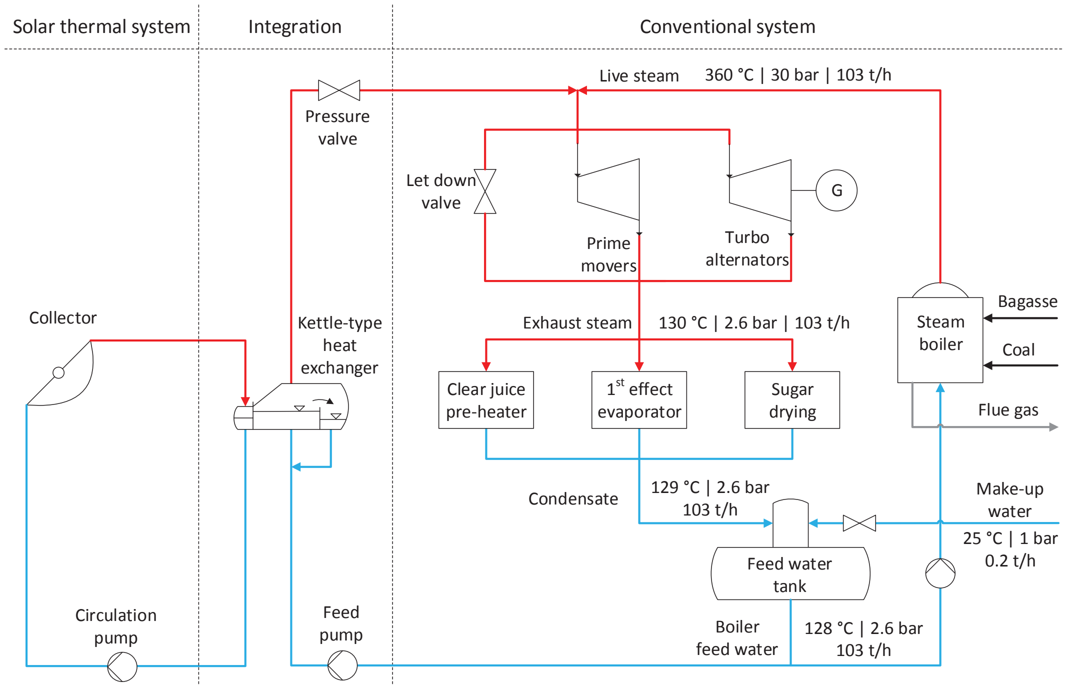

Figure 2: Integration scheme for indirect solar live steam generation (process values from Starzak and Zizhou, 2015)

Raw-sugar factories could be energy self-sufficient as the energy content of the bagasse is higher than their thermal and electrical energy demand. However, in SA, coal is used as an auxiliary fuel to supplement the bagasse. Factories without bagasse-export, electricity-export or a back-end refinery usually only need supplementary coal for abnormal occurrences. In the 2012/13 season, the SA mills had an average coal consumption of approximately 11 t per 1 000 t of cane. The industry consumes roughly 200 000 t of coal per season (Reid, 2006; Smith et al., 2013). The calorific value of 1 t coal equals that of 4 t of bagasse (Smith et al., 2013, p. 48).

3. Solar Heat Integration

3.1 Available solar resource

Figure 3 shows the annual variation of the mean daily global tilted irradiation (GTI) and direct normal irradiation (DNI) at characteristic sugar milling locations in KZN and Mpumalanga. The available irradiation in the KwaZulu-Natal (KZN) coastal region is about twice as high as in Central Europe and similar to other sugar milling locations in Brazil or India (Solar GIS, 2015).

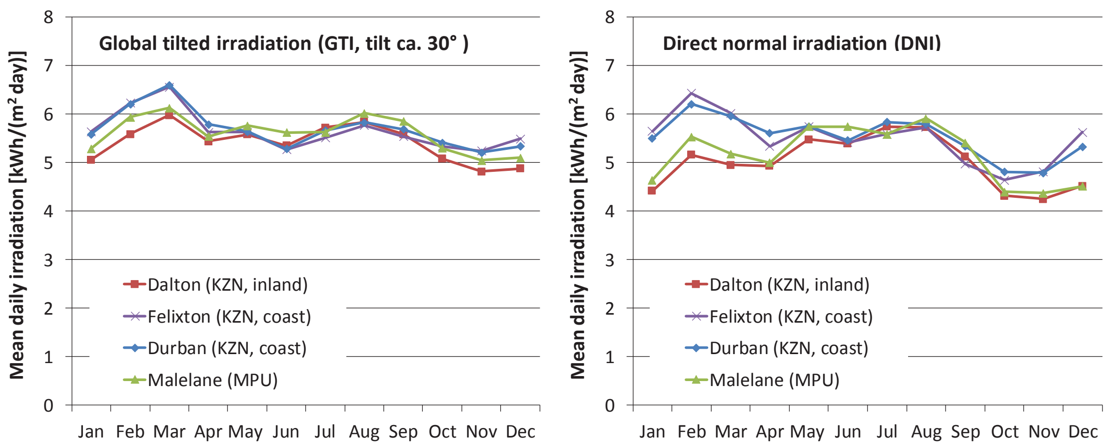

Figure 3: Mean daily GTI and DNI at sugar mill locations (values from PVGIS, 2015)

The GTI in Figure 3 is valid for a surface of 1 m^2 tilted approximately 30° towards the equator, i.e. orientated north. The DNI is the beam irradiance onto a surface of 1 m^2 tracking the sun. The annual sums of irradiance for the four locations in Figure 3 are shown in Table 1.

Table 1: Annual solar irradiation at sugar mill locations in South Africa (values from PVGIS, 2015)

Location	GHI [kWh/(m2 a)]	GTI [kWh/(m2 a)]	DNI [kWh/(m2 a)]	Optimal slope for GTI [°]	Fraction of diffuse [%]
Durban (KZN, coast)	1 825	2 077	2 018	32	34
Felixton (KZN, coast)	1 840	2 062	2 008	31	34
Malelane (MPU)	1 854	2 044	1 883	29	37
Dalton (KZN, inland)	1 737	1 975	1 825	33	37

Figure 3 and Table 1 show that the annual GTI varies by only 5 % between the SA milling locations; DNI varies by 10 %. The irradiance in Mpumalanga is very similar to KZN inland. For a first assessment, Durban can be used as a representative location for the SA sugar mills.

3.2 Integration point assessment

By analyzing the mass and energy flows of the BRTEM model (Starzak and Zizhou, 2015), 23 potential solar heat integration points (IPs) within the model sugar mill were identified. IPs are physical locations, e.g. heat exchangers, in the mill at which solar heat can replace conventional heating media. The potential SPH integrations points were evaluated considering the methodology discussed in the SPH Integration Guideline of Muster et al. (2015). The most relevant criterion was that the support of a heat sink with solar heat would result in direct savings of bagasse or coal. The next priority was saving live steam and then saving exhaust steam. In this first study, the potential integration points saving bleeding vapor were not considered further as the internal value of this steam is lower than that of live steam, and the reduction of bleeding vapor consumption would, without modification to the processes, not directly result in overall energy savings in the mill.

Other ranking criteria were a significant heat demand at the integration point, a sufficient temperature difference to transfer solar heat, and no interference of solar heating with present or future efficiency measures, e.g. the economizers of the boilers. This resulted in the selection of six integration points for further consideration. On supply level these are live steam generation, pre-heating of boiler feed water, exhaust steam generation, and the drying of bagasse. On process level, it is raw sugar drying and clear juice heating.

For each of these processes, integration schemes were developed following the scheme suggested by Helmke and Hess (2015). These schemes were published in Hess et al. (2016). The two most promising integration schemes are discussed in the following.

3.3 Solar live steam generation

Figure 2 above already showed a potential integration scheme for solar live steam generation. According to the BRETM model, the processing of 250 t cane per hour requires about 103 t/h of live steam, as indicated. The boiler in this reference sugar mill provides a power of 74.4 MW_{th}, calculated from the enthalpy difference between feed water and live steam. This is equivalent to the total power demand of the factory. Thus, solar generation of live steam parallel to the existing boiler is a way to utilize very high amounts of solar heat. From Smith et al. (2013) it can be calculated that every ton of solar generated live steam has the potential to offset approximately 0.5 t of bagasse or about 0.125 t of coal.

If we consider a value of 700 W_{th} peak power per square meter of solar collector area (Mauthner, 2015, p. 5), an area of 106 336 m^2 could at peak performance supply the whole power demand of the reference mill (neglecting the heat exchanger efficiency). However, since the SPH is normally only off-setting the fuel consumption of the existing bagasse boiler, the ability of this boiler for power modulation also has to be taken into account. In this paper, we assume that the boiler can only maintain its current efficiency if it produces 37 MW^{th} or more, i.e. more than 50 % of its BRTEM power. To maintain this condition, maximally 37 MW_{th} of solar steam power could be added without solar heat storage. This corresponds to a collector field of about

53 168 m^2. In Durban, high-temperature PTCs producing the required live steam parameters would yield approximately 1 110 $kWh_{th}/(m^2\,a)$, as shown in Table 2. If the collector field is only operated during the crushing season, the specific yield reduces to 768 $kWh_{th}/(m^2\,a)$. The field size mentioned above could substitute 12 % of the boilers' annual energy production if it operated throughout the crushing season, not considering OTE, and 17 % if operated all year. Collector field size and solar fraction can be further increased if a solar heat storage is installed.

By 2012, in India a total capacity of approximately 5 GW_{el} of bagasse-fueled power stations was installed (Tongaat Hulett, 2013). In Mauritius, 90 % of the sugar factories export electricity to the grid (Smithers, 2014). In Brazil, in 2013 a total amount of 15,067 GWh_{el} was produced by bagasse-fueled power plants for the national grid, and this shall be increased by a factor of 13 until the year 2022 (Burin et al. 2015).

Tongaat Hulett (2013, p. 12) estimates that the 14 SA sugar mills could generate about 800 MW_{el} to 1 000 MW_{el} for export to the SA grid. Tongaat Hulett's eight sugar mills in Mozambique, SA and Zimbabwe, in some instances, already feed electricity back to the grid. In the 2014/2015 season, Tongaat Hulett exported 32.65 GWh_{el} (Tongaat Hulett, 2015). Smithers (2014) estimated that the South African sugar industry could potentially produce a total of 600 MW of electricity by the end of 2016, accounting for approximately 1.5 % of the country's total generation capacity. In a financial viability and macro-economic impact analysis, Conningarth Economists (2013) strongly advocate for export of electricity by SA sugar mills. However, no large scale projects with electricity export are in place at SA sugar mills yet. The prices offered by the national SA power grid operator for electricity from sugar mills are all negotiated individually. The revenue being offered is apparently currently not making it viable to invest in equipment for increased export.

3.4 Solar drying of bagasse

An integration scheme for solar drying of bagasse is shown in Figure 4. The typical moisture content of bagasse after the dewatering mills in the juice extraction unit is approximately 50 % of weight. In the 2012/13 season, the average bagasse moisture content ranged between approximately 46 % and 52 % (Smith et al., 2013).

According to Rein (2007), the advantages of bagasse drying include improved boiler efficiency, reduced fuel consumption, higher flame temperature and reduced excess air requirements. Rein (2007) further states that the technical lower limit for the moisture content of bagasse is in the order of 30 %. According to Loubser (2015), however, the moisture content should not be reduced to below 40 % because of the risk of spontaneous combustion. It is expected that the gross calorific value of bagasse can be increased by approximately 20 % by reducing the moisture content from 50 % to 40 %.

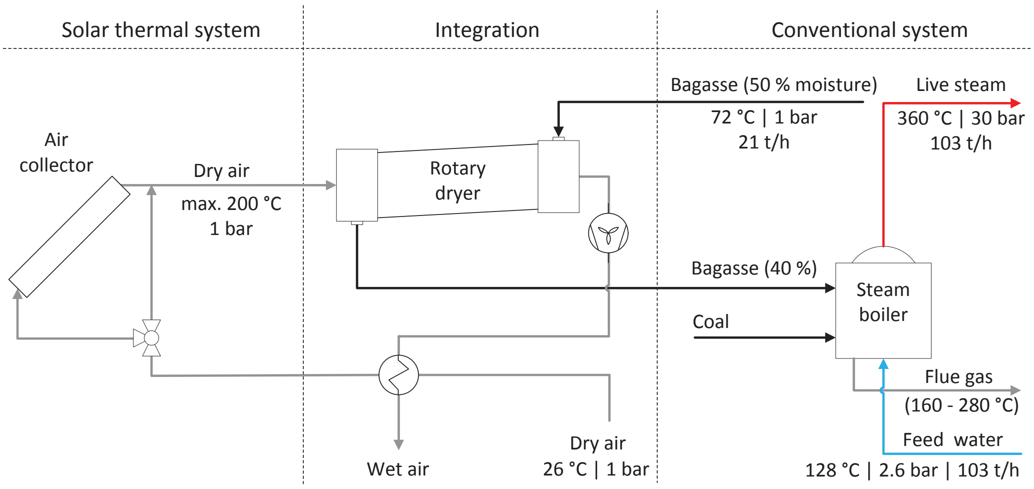

Figure 4: Integration scheme for solar drying of bagasse with air collectors (process values from Starzak and Zizhou, 2015)

Solar air collectors have already for long been applied for drying, e.g. of wood chips or fruit. Direct solar pre-heating of ambient air has the advantage of low collector absorber temperature to achieve high efficiencies. For bagasse drying, a fan would suck ambient air through an air collector field and into the rotary dryer. If a constant dryer inlet temperature is needed, or the dryer inlet temperature is controlled automatically depending on output bagasse moisture, a mixing device can add some ambient air into the collector outlet stream. The drying air cannot be recirculated as the relative air humidity at the dryer inlet must be low. However, heat recovery can be implemented to pre-heat the collector air inlet from the dryer outlet air.

A first rough dimensioning of a rotary dryer for the task of evaporating a water amount of about 2 t/h resulted in an energy demand of approximately 6 GJ_{th}/h to achieve such an evaporation rate (based on Bruce and Sinclair, 1996). For heating of ambient air to a maximum dryer inlet temperature of 200 °C, the mean load of the dryer system without heat recovery would be 1.67 MW_{th}. The simulation results given in Table 2 indicate that the specific solar gains at the bagasse drying temperature level can reach 779 $kWh_{th}/(m^2\ a)$ during the crushing season. About 24 % of the overall bagasse drying heat demand during the crushing season could be supplied by a SPH system without storage. If the dryer could operate throughout the year, the solar gain would increase to 1 058 $kWh_{th}/(m^2\ a)$ and the solar fraction for drying the same amount of bagasse would increase to 33 %.

A pilot plant test for solar drying of bagasse in a sugar mill in the Dominican Republic showed a reduction in moisture from 50 % to between 36 % and 44 %, but it was noted that on a large scale the results could vary considerably (Rein 2007, p. 610). In his overview on bagasse drying technologies, Sosa-Arnao (2006) points out that a study on the trade-off between combustion air pre-heating, the economizer in the boiler and the drying of bagasse is still to be done. The option of solar drying could be included in such a study.

4. Solar Gains and Performance Indicators

Table 2 shows the heating power demand of each heat sink and the performance indicators that were estimated from literature (Live steam) or simulated (all other).

The heat demand is the maximum solar energy that could be fed in at this point. It is calculated from the mass flow at the integration point and the enthalpy difference between heat exchanger inlet temperature and pressure (process return), and heat exchanger outlet temperature and pressure (process feed). The maximum field size for all variants results from dividing the heating power demand by 700 W/m^2 peak power by 1 m^2 of collector area. This ensures that the solar heat generated is always below the demand (no storage). For live steam generation, the maximum area is additionally limited by the capability of the boiler for power modulation.

Table 2: Solar collector field dimensions with annual (A) and crushing season (CS) performance estimation in Durban without thermal storage

Heat sink	Heating power demand [MW_{th}]	Max. field size [m^2]	Process return temp. [°C]	Max. feed temp. [°C]	Collector type*	System efficiency on GHI [%]		Specific gains [kWh/m^2]		Solar fraction [%]	
						A	CS	A	CS	A	CS
Live steam	74.4	53 168	128	360	PTC-HT	61	61	1 110	768	17	12
Feed water	9.0	12 880	128	200	PTC-HT	61	61	1 110	768	34	24
					PTC-MT	31	32	567	402	18	12
Exhaust steam	62.5	89 238	128	130	PTC-MT	32	32	577	309	18	13
					ETC	38	40	688	510	21	16
Bagasse drying	1.7	2 381	26	200	FPC (water)	58	62	1 058	779	33	24
Sugar drying	0.6	899	26	80	FPC (water)	66	70	1 203	883	37	27
Clear juice	4.7	6 739	100	114	ETC	43	46	781	577	24	18

* parabolic trough collectors (PTC) for high temperature (HT) and medium temperature (MT) applications, evacuated tube collector (ETC), and flat-plate collector (FPC) with water as collector fluid

For the simulations, the software Polysun V8.011.21 (Vela Solaris 2014) was used. Since the objective was only to calculate realistic estimates of potential energy gains, very simple system hydraulics and control principles were used (cp. Figure 5). This was based on existing schemes in the Polysun library for the simulation of solar process heat systems.

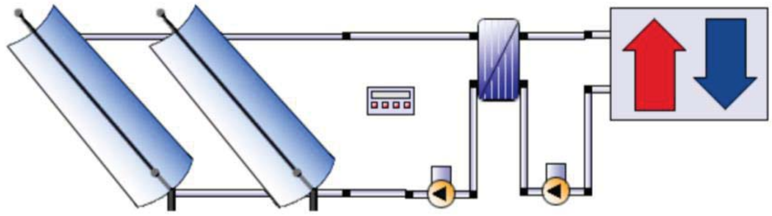

Figure 5: Simple hydraulic scheme in Polysun to estimate annual gains for solar feed water pre-heating with medium temperature parabolic troughs (PTC-MT)

On the right hand side of Figure 5 is a heat sink. In the simulations for the solar heating of feed water with PTC-MT collectors, the process return temperature was 128 °C, as given in Table 2. The mass flow of the process loop pump was constant and set to a value at which 200 °C is achieved if a power of 9 MW_{th} can be provided. The solar loop pump was speed controlled to ensure that a positive temperature gradient is always maintained between the solar loop and discharging loop of the heat exchanger. For a PTC-MT, for example, the parabolic trough of the company NEP (NEP, 2015) was used in Polysun. The receiver tube of this collector is not evacuated. It therefore has significant thermal losses at higher temperatures. For a highly efficient ETC, for example, the Ritter Aqua Plasma collector (Ritter, 2015) was used. The selected FPC is the Solid Gluatmugl HT (Solid, 2013). The solar drying processes should ideally be realised with air collectors. Since these collectors cannot be simulated in Polysun, the two drying processes were also simulated with the Gluatmugl HT flat-plate, ensuring that the air heating demand was correctly represented on the secondary side of the heat exchanger. However, for the case of applying air collectors (FPC-Air), the given gains have to be seen as a maximum value as this technology usually has higher heat losses than flat-plates with water as collector fluid, especially at higher working temperatures.
The annual gains of the high-performance parabolic trough collectors (PTC-HT) were also not simulated, but roughly assessed as follows: The average annual thermal solar field efficiency of concentrating solar power (CSP) PTC fields is in the range of 50 % to 60 % for DNI, according to Geyer et al. (2002, p. 6), Sargent and Lundy Consulting Group (2003, p. D 17), and Günther et al. (2012, p. 80). For this study, an efficiency of 55 % is used. The system efficiencies given in Table 2 all relate to GHI in Durban (GHI = 1 825 kWh/(m^2 a), DNI = 2 018 kWh/(m^2 a)). Thus, in Table 2 an annual system efficiency of 61 %, to allow for comparison to the other technologies, is given.

The *system efficiency* indicates which share of the global horizontal irradiance can be converted to useful solar heat for the process. The annual (A) efficiency considers the mean efficiency during the whole year; the efficiency during the crushing season (CS) considers only 1 March to 30 November. The efficiencies differ slightly due to varying irradiance and ambient temperatures. It is assumed that all solar heat can be used (no OTE influence on solar field operation). The *specific solar gains* per square metre of collector gross area give the useful heat produced per year (A) and during the crushing season (CS). Again, it is assumed that there is no OTE effect on the solar field operation. The *solar fraction* is the share of the annual heat demand of the heat sink, which can be covered by solar heat. It is valid for systems without heat storage. The solar fraction can be increased significantly when storage is installed, but this would also mean an increase in the solar thermal system costs. For this pre-condition, the *overall annual solar energy gains* can be calculated from Table 2. The PTC-HT field of 53 168 m^2 would yield 40 833 MWh_{th} during the crushing season, and about 59 016 MWh_{th} if it could be operated throughout the year. As explained above, the CS duration used is 254 days, with an OTE of 75.70 % (cp. season 2012/2013, Smith et al., 2013), so the boiler operates 4615 h/a. This results in an overall boiler steam energy generation of 343 356 MWh_{th}.
With these assumptions, the solar fraction would be 12 % if the solar field operates during the whole CS (not considering OTE), and 17 % if it operates the whole year. To roughly assess how the specific solar gain would be affected if the collector loop only operated at times of boiler operation, the specific gains during the crushing season can be multiplied by the OTE.

5. Economic Assessment

5.1 Solar heat as an alternative to coal

As outlined above, the heat demand of SA sugar mills is covered by steam from burning bagasse, in some cases supported by coal. Since bagasse is a by-product of sugar production, the costs of this steam are obviously very low. However, the true value of bagasse is determined by the opportunity costs. Integration of solar heat will only be considered if such an opportunity is pursued, i.e. if the heat demand of the mill increases e.g. from production of bio-ethanol, or export of electricity), or if bagasse is used for purposes other than heating e.g. the production of animal feed, fertiliser, or paper. In all scenarios, the cheapest alternative energy source in SA would be coal. Thus, this assessment of SPH for SA sugar mills compares solar heat to the heat from coal.

The price paid for coal by the different SA sugar mills varies as it includes the price for mining ('ex mine'-price) and the costs of transport to the respective mills. To estimate the costs of life steam from coal, a coal price of 1100 ZAR/t, an energy content of 27 GJ/t and a boiler efficiency of 75 % can be assumed (Peacock, 2016a). Thus, this work uses a current value of life steam from coal of 0.20 ZAR/kWh (1.2 EUR-ct/kWh) for comparison[1]. Since one ton of live steam can be let-down to approximately 1.2 tons of exhaust steam (Rein, 2007, p. 666), the current value of exhaust steam is considered to be 0.16 ZAR/kWh (1.0 EUR-ct/kWh). An analysis of annual coal prices for a large SA sugar producer provided by Peacock (2016b) revealed that the price after delivery increased on average by 12.3 % p.a. from 2004 to 2014.

5.2 Investment costs for SPH systems

In order to obtain reference values for the costs of SPH systems, the SHIP Plants (2015) database was analysed. By mid-April 2016 it included ca. 190 systems, but for many entries no cost data were given. However, it could be observed that the system costs per m^2 of collector gross area depend highly on the collector technology, the system size, and the country of installation.

The systems to consider for the SA sugar industry would be of several hundred or several thousand square metres (cp. Table 2), and for this first assessment have no thermal storage. Thus, to get a more realistic cost estimate, the database was filtered for systems above 200 m^2, and installation dates from the beginning of the year 2000 to end 2015. Since the number of systems without storage was too small, systems both with and without storage were included. For each technology, the median value of the investment costs per m^2 was determined. This resulted in 183 EUR/m^2 for installations with FPCs with air as collector fluid (based on data of only two plants), 188 EUR/m^2 for ETCs (10 plants), 388 EUR/m^2 for FPCs with water as collector fluid (16 plants), and 445 EUR/m^2 for PTCs-MT (nine plants).

The SPH plant database does not contain examples with CSP technology so for the PTC-HT troughs the costs had to be assessed from literature. According to Turchi et al. (2010, p. 6), the installed costs of a large PTC-HT field in the United States operating at 391 °C are expected to be 335 USD/m^2, including heat transfer fluid, in 2015. The authors give similar costs for a heliostat field with central receiver (HCR).

It must be noted that within each collector technology group, very high variances, even between similar installations, were found both in the SHIP Plants database and in the literature. Many of the SHIP plants have thermal storages included so that installed costs for the investigated systems in SA could be lower. To conclude, the costs used for this study are only a rough estimate. They cannot replace quotes for specific cases in future feasibility studies.

5.3 Levelized cost of heat (LCOH)

The levelized cost of energy LCOE is a common measure to assess and compare the financial feasibility of renewable energy projects. In this work, this measure is referred to as LCOH to stress that it reflects the levelized costs of heat, not of electricity. Note that the LCOH is the average heat price per unit of energy generated throughout the lifetime of a heating project; it is independent of the value of the energy replaced. Equation 1 gives the LCOH (NREL, 2014).

$$LCOH = \left. \sum_{n=0}^{N} \frac{C_n}{(1+d)^n} \middle/ \sum_{n=1}^{N} \frac{Q_n}{(1+d)^n} \right. \quad \text{[EUR/kWh]} \qquad \text{(eq. 1)}$$

[1] In this work, the exchange rates of 1.128 USD/EUR and 16.46 ZAR/EUR as of 13 April 2016 are used.

The LCOH compares the annual project costs (C_n) to the annual yield (Q_n) for each year n over the lifespan of the system in years (N). Costs and yields are discounted with the rate d to account for the time value of money. Figure 6 below shows the calculated LCOH from coal and solar thermal energy over 20 years.

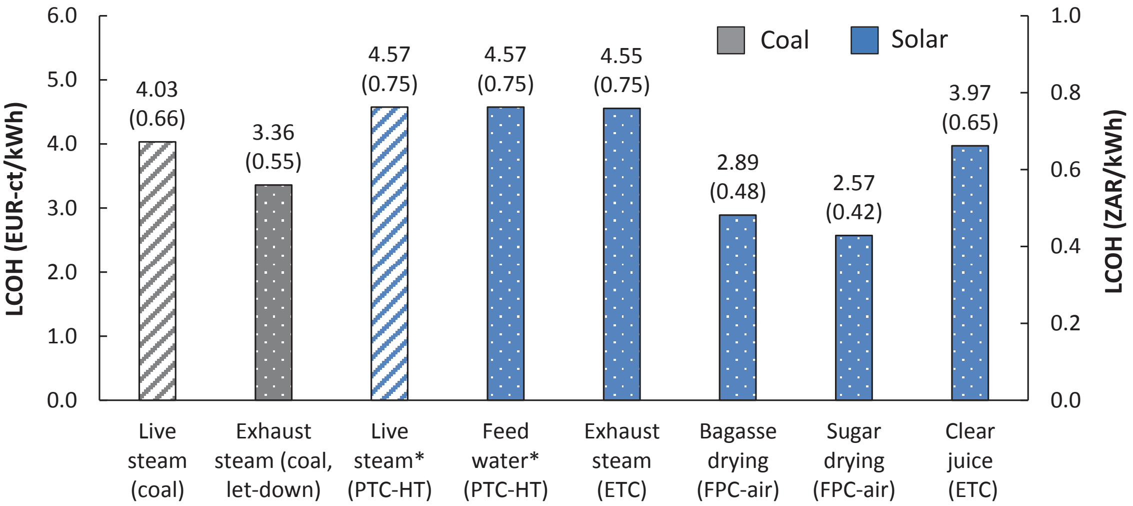

Figure 6: Estimated levelized costs of heat (LCOH) for SA sugar mills from coal and from solar thermal energy (*SPH systems for live steam and feed water operate for the whole year and the others only from March to November)

The PTC-LT variant, for both feed water and exhaust steam generation, had higher LCOHs than the technical alternative (cp. Table 3). In Figure 6, for each integration point only the variant with the lowest LCOH is indicated. In addition to the investment costs, annual operational costs were taken into account. These include maintenance and auxiliary energy consumption. For the annual maintenance, including replacement, of the large-scale non-tracking ST systems in this study, a value of 1 % of the capital expenditure was used (VDI, 2004, p. 65). For the annual auxiliary energy consumption of these systems, 2 % of the yearly energy yield was considered (VDI, 2004, p. 65), with a constant auxiliary energy tariff of 0.50 ZAR/kWh$_{el}$ (3.04 EUR-ct/kWh$_{el}$). The annual operational costs increase with the consumer price index (CPI) of South Africa of 6 % per annum (inflation). For the two parabolic trough systems, combined maintenance and auxiliary energy costs of 2 % of the capital costs are used, as is common for CSP power plants (Hernández-Moro and Martínez-Duart, 2012, p. 186). This was annually increased by the CPI as well.

To calculate the LCOH of the solar heating projects, a nominal discounted rate of 10 % has been used. This corresponds with the expected weighted average cost of capital (WACC) of the SA sugar industry (for 30 % equity with a return of 14 %, and 70 % debt with an interest rate of 8 % and a loan period of 10 years) (Foxon, 2015). A financial project life of 20 years was assumed, even though the service life of SPH systems may well exceed this. The LCOH for solar live steam and feed water generation was calculated from specific system yield Q_n of whole-year operation (cp. Table 2) as in this case an electricity export scenario independent from the sugar mill operation was assumed. The other four SPH systems operate during the crushing season only so the theoretical gains from November to January were not taken into account.

For comparison, the estimated LCOH from coal within the potential duration of a SPH project of 20 years is also given. For this, it is assumed that an existing boiler can burn variable amounts of coal without additional costs. Thus, for comparison with solar heat, only the fuel costs are considered. The levelized costs per kWh steam were calculated from current costs of 1.2 EUR-ct/kWh for live steam and 1.0 EUR-ct/kWh for exhaust steam, both increasing by 12.3 % annually. The LCOH was then calculated by using the CPI discount rate of 6 %.

Comparing the LCOH values of the six different SPH integration variants suggests that the solar drying of sugar and bagasse is possible at lower levelised costs than exhaust steam generation from coal. Note that for this first assessment equal gains of air flat-plates and water flat-plate collectors within the working temperature range were assumed (cp. comment above on flat-plate gains).

5.4 Internal rate of return (IRR)

Contrary to the LCOH, the internal rate of return (IRR) can be used as an indicator for the financial viability of a project because it takes the value of the conventional energy, which is replaced by SPH, into account. The IRR is an estimation of the discount rate that would result in a zero net present value (NPV). Table 3 summarises the results of the economic assessment of the most promising SPH variants. The estimated capital expenditure of the different collector fields is given under the premise that the maximum area possible without solar heat storage is installed.

Table 3: Estimated economic figures of the six SPH integration variants

Integration Point	Collector type	Heat demand [MW_{th}]	Max. field size [m^2]	System costs [EUR/m^2]	Capital expenditure [Mio. EUR]	LCOH [EUR-ct /kWh]	IRR [%]
Live steam*	PTC-HT	74.4	53 168	378	20.10	4.57	4.6
Feed water*	PTC-HT	9.0	12 880	378	8.46	4.57	2.6
Exhaust steam	ETC	62.5	89 238	188	16.78	4.55	3.3
Bagasse drying	FPC-Air	1.7	2 381	183	0.44	2.89	7.8
Sugar drying	FPC-Air	0.6	899	183	0.16	2.57	9.1
Clear juice	ETC	4.7	6 739	188	1.06	3.97	4.6

* Solar live steam generation and feed water heating for whole year operation (electricity export scenario), other SPH integration points operate during crushing season only (March to November)

The NPV is obtained by discounting all net cash flows (C_n) of each year (n) over the lifespan of the project (N) (NREL, 2014). Solving the NPV equation for the discount rate d gives the IRR. The income cash flows depend on the internal value of the energy, and thus the heating fuel, that is being substituted by SPH. In this first assessment it was assumed that only live steam from SPH replaces the actual internal live steam value from coal; all other integration variants replace the exhaust steam value (cp. hatched and dotted bars in Figure 6). The hurdle rate for projects or investments by the SA sugar milling industry is in the range of 10 % to 15 % (Foxon, 2015). A project is feasible if the IRR exceeds this hurdle rate.
The formula for the calculation of the NPV is provided in equation 2.

$$NPV = \sum_{n=0}^{N} \frac{C_n}{(1+d)^n} \quad \text{[EUR]} \qquad \text{(eq. 2)}$$

The results in Table 3 indicate that currently none of the prioritised six SPH integration schemes offers the expected return. The two solar drying applications are closest to financial viability and should be investigated in more detail. Their IRR would increase to 11.7 % for bagasse drying and 13.1 % for sugar drying if they could be operated the whole year.

6. Conclusions

For an electricity export scenario, *solar live steam generation* should be considered as an option if solar steam can also generate electricity independent of the mill operation, i.e. outside the crushing season. This SPH variant can cover a significant share of the heat demand of a mill. The feasibility here depends highly on the price received for export electricity.
Solar *drying of bagasse* is the only solar technology that has been demonstrated in sugar mills. To determine financial feasibility, the effect of dried bagasse on boiler efficiency must be studied in more detail, an energy balance of the solar drying process itself must be worked out, and the investment in a suitable dryer must be taken into account. LCOH and IRR of both drying applications have high uncertainties because the estimated system costs are based on data of two plants only, and the gains were simulated with FPCs with water as collector fluid. In addition, the drying processes seem well-suited for waste heat recovery.

With the framework conditions used for this first study, none of the six SPH integration variants achieved an IRR of the required 10 % to 15 %. The main reason for this is the very low coal price, even though a price increase of 12.3 % p.a. was taken into account. Another factor is the limited duration of the crushing season which limits the time of the year that solar heat can be used for processes within the mill. At more beneficial framework conditions, e.g. with government subsidies for SPH or a fixed minimum feed-in tariff for power export from cogeneration, including ST collectors, financial viability would be possible.

Further work on SPH for sugar mills must be based on the energy balance of a mill with all feasible heat recovery measures implemented. For such a mill, different scenarios like the implementation of high pressure boilers with condensing extraction steam turbine, or the production of bio-ethanol on site, have to be described so that more detailed SPH feasibility assessments can be performed.

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