**Abstract**

The South African (SA) sugar milling industry is seeking to improve energy efficiency and cost-competitive-ness. On-site solar thermal (ST) systems have the potential to reduce coal consumption in the boiler and to partly replace bagasse as a heating fuel. This paper, based on the heat and mass balance of a representative sugar mill with limited energy efficiency measures, identifies the most promising solar heat integration points and pre-ranks them according to their potential energetic and economic benefits. Hydraulic schemes to integrate solar heat into the processes are presented, system operation is discussed, and solar gains are calculated. The investigated opportunities for solar process heat (SPH) integration 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 levelised costs of heat (LCHH) for the SPH systems range from 2.57 Eurocent/kWh (0.62 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 with concentrated solar power parabolic troughs. This study assumes that SPH has to compete with coal, which is the cheapest energy source, to replace bagasse. Using current coal prices and past price increases, 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, followed closely by solar drying of bagasse.

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

**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, Austria and India (DAF, 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 (Wieneke 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 100 t/h (Smithers, 2014, p. 917). The average length of the 2011/13 crushing season was 254 days and the overall time efficiency (OTE) was about 75.7 % (Smith et al., 2013, p. 30).

The main energy source for sugar production from sugar cane is bagasse, the fibrous residue from the sugar cane after juice extraction. In SA, coal is also used as an auxiliary boiler fuel. The SA sugar industry can improve cost-competitiveness by decreasing running costs and opening up new revenue streams. 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 utilised for purposes other than energy generation for the sugar mills. This bagasse can be used to produce fertiliser, 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) utilisation is the use of steam from bagasse boilers to generate electricity for export to the SA national grid.

**Process 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 process sections. The data used are all based on Rein (2007), unless otherwise stated. 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**

Sugar production process

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 fibreisation of the cane by shredders. Modern sugar factories no longer mill the cane but use diffusers for the extraction of sucrose. A diffuser typically consists of 10 to 18 stages (Rein, 1995, p. 197). In the diffuser, the sucrose is leached by repeatedly spraying heated juice onto a bed of cane fibre 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 chemically processed 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 utilise low-pressure steam as a heating medium. The operating pressure is reduced at each consecutive effect to lower the saturation temperature of the vapour and the boiling point of the syrup. The first effect consumes exhaust steam, after which each successive effect consumes vapour bled from the preceding effect. Additionally, vapour 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). This improves the overall steam economy. The bleeding vapour from the first effect is referred to as V1, and the bleeding vapours following effects are referred to as V2 to V4 (in case of four effects). The condensate from the first effect is returned as boiler feed water. Some of the condensate from each effect is flashed to correspond with the vapour of the effect to supplement the heating of the next effect.

To achieve crystallisation, 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, crystallisers 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, fertiliser 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. The air is heated by exhaust steam or V1. After the sugar is dried, it is cooled with ambient air. Raw sugar can be sold directly, or be further refined at a refinery.

**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 Bioenergy Techno-Economic Modelling project (BRITE/M, Starzak and Zhaou, 2015). The BRITE sugar mill represents the current practice in SA and assumes a throughput of 250 tons cane per hour. Many theoretically possible energy efficiency measures are not represented in this model.

Figure 2 gives details on the energy supply of the BRITE sugar mill. The main energy source is bagasse from the roller mills after the extraction process. This bagasse fuels steam boilers that produce live steam. The 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, which is usable in the bagasse dryers and the main boiler, is referred to as ‘prime mover steam’. The steam from the 12th stage of the diffusers is used as ‘prime mover’ steam for the evaporation process. The energy supply to the bagasse dryers, the main boiler and the main turbine is calculated by adding the energy content of the steam from the bagasse boilers and multiplying the energy balance of the main boiler by the steam flow rate. The energy balance of the main boiler is calculated by subtracting the energy content of the steam from the bagasse boilers from the energy content of the steam produced by the boiler. The energy content of the steam produced by the boiler is calculated by subtracting the energy content of the exhaust steam from the energy content of the steam produced by the boiler. The energy content of the exhaust steam is calculated by subtracting the energy content of the steam from the bagasse boilers from the energy content of the steam produced by the boiler. The energy content of the steam produced by the boiler is calculated by subtracting the energy content of the exhaust steam from the energy content of the steam produced by the boiler. The energy content of the exhaust steam is calculated by subtracting the energy content of the steam from the bagasse boilers from the energy content of the steam produced by the boiler.

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is used to run the thermal processes of the plant that have the highest temperature and energy requirements. If more exhaust steam is needed than resulting from the operation of prime movers and turbo alternators, the let-down valve is used. This process is standard for South African factories and an exhaust steam shortage. Reid points out that a certain amount of let-down steam is necessary to control the exhaust steam pressure at a steady value. Let-down should be between 5% and 25% of the exhaust steam requirement and preferably closer to the upper end during normal operation (Rein, 2007, p. 671). Condensate from indirect heating flows back to a feed water tank where a small amount of make-up water is added. The feed water is evaporated in the steam boiler again.

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).

Solar Resource at Sugar Mill Locations

A brief background on the solar resource is provided to assess the use of solar heat for sugar mills. Sun rays are electromagnetic waves. While photovoltaic collectors convert these rays into electricity, solar thermal collectors convert them into heat. Solar energy reaches a collector in the form of beam and diffuse irradiance. Beam irradiance is received from the sun direction. Diffuse irradiance has been scattered or reflected by particles or objects in the atmosphere or surroundings before it reaches the sun’s incoming rays. Figure 3 shows a map of the annual sum of GTI for the KwaZulu-Natal (KZN) province.

The KZN coastal region has the lowest annual solar irradiation in South Africa but as the country is blessed with an abundance of sunshine, the available irradiation is still twice as high as in Central Europe and similar to other sugar milling locations in Brazil or India (SolarGIS, 2015). Figure 4 shows the annual variation of the mean daily GTI and DNI at characteristic sugar milling locations in KZN and Mpuumlanga in comparison with Durban.

The GTI in Figure 4 is valid for a surface of 1 m² tilted approximately 30° towards the equator, i.e. orientated north. The DNI is the beam irradiance onto a surface of 1 m² tracking the sun. The annual sums of irradiance for the four locations in Figure 4 are shown in Table 1.


Table 1: Annual solar irradiation at sugar mill locations in South Africa

<table>
<thead>
<tr>
<th>Location</th>
<th>GTI [kWh/(m² a)]</th>
<th>DNI [kWh/(m² a)]</th>
<th>Optimal slope for GTI [%]</th>
<th>Fraction of diffuse [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Durban (KZN, coast)</td>
<td>1 825</td>
<td>2 077</td>
<td>2 018</td>
<td>32</td>
</tr>
<tr>
<td>KZN (coast)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flexton (KZN, inland)</td>
<td>1 840</td>
<td>2 062</td>
<td>2 008</td>
<td>31</td>
</tr>
<tr>
<td>Malolotane (MPU)</td>
<td>1 854</td>
<td>2 044</td>
<td>1 883</td>
<td>29</td>
</tr>
<tr>
<td>Dalton (KZN, inland)</td>
<td>1 737</td>
<td>1 975</td>
<td>1 825</td>
<td>33</td>
</tr>
</tbody>
</table>

Figure 4 and Table 1 lead to three conclusions:

a) The mean daily GTI and DNI are relatively constant over the year.

b) In the summer months the irradiance is slightly higher in the coastal region, especially the DNI from November to April. There is, however, sufficient irradiance during the crushing season.

c) The annual GTI varies by only 5% between the SA milling locations; DNI varies by 10%. The irradiance in Mpuumlanga is very similar to KZN inland. For a first assessment, Durban can be used as a representative location for the SA sugar mills.

Solar Process Heat Technology

Table 2 gives an overview of the currently available solar collector categories. Non-tracking collectors use beam and diffuse irradiance. They should be sloped towards the equator at approximately the angle at which they receive the maximum GTI (cp. Table 1, column 5), but slope variances of 20° and azimuth variances of about ±30° do not significantly decrease the annual energy gain. These collectors usually do not concentrate the irradiance, which is why their application temperature level is restricted to below 150°C. Tracking collectors usually use only beam irradiance i.e. the DNI they receive. Single axis tracking collectors focus the irradiance onto a line-receiver, which is often enclosed in an evacuated glass tube. Two-axis tracking collectors focus the irradiance onto a point; they achieve the highest temperatures. As a starting point for the dimensioning of collector fields for specific heat demands, a value of 700 W/m² can be used for the specific thermal peak power output (Mueller, 2015, p. 5).

Collector area and, if necessary, the storage volume of SHP systems are usually optimised for certain heat demands and locations by means of annual simulations. Simple guidelines on pre-sizing of SHP systems for certain heat demands can be found in Hess and Oliva (2010).

A selection of commercial SHP systems in South Africa is documented by Blacked Energy (2016). About 190 systems from all over the world can be found at SHP Plants (2016).

The optimal integration of solar heat into industrial, commercial or agricultural plants is usually quite complex. Prior to planning a SHP plant, solar energy efficiency measures (heat recovery, insulation of pipes, etc.) and process optimisation (reduction of the energy demand per unit of product, e.g. by new machinery) have to be evaluated. These measures usually have significantly shorter amortisation periods than SHP. Additionally, oversizing of SHP systems can only be avoided if potential future reductions of the heat demand can be forecasted realistically.

Solar heat can be integrated at the supply- and/or the process level of an industrial plant. On process-level, solar heat is supplied to selected thermal processes. On supply-level, solar heat is supplied to the heating network of the production network. Here, the future performance of the SHP plant is usually much less affected by process changes (Hess, 2015).

Solar Heat Integration in Sugar Mills

Integration point assessment

By analysing the mass and energy flows of the BRTEM model (Starzak and Zizhou, 2015), 23 potential solar heat integration points are suggested for the sugar mill.
In a financial viability and macro-economic impact analysis, it was shown that the South African sugar industry could potentially produce about 4 000 GWh of electricity from the same amount of steam that a share of the produced electricity can be exported to the national grid. In this paper, we assume that the boiler can only generate electricity for use within the mill. Condensing extraction steam turbines produce more electricity from the same amount of steam than a share of the produced electricity can be exported to the national grid. In Figure 6, both concepts are distinguished in a simplified way.

Figure 6: Steam turbine configurations (adapted from Paula, 2002, p. 8f).

In general, solar steam can either be produced directly by the solar thermal system or by using the steam from a conventional boiler as feedwater (process values from Starzak and Zizhou, 2015). 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.

Electricity export from condensing extraction steam turbines

A short introduction to electricity export from sugar mills to the national grid follows below. Such a scenario can increase the financial viability of solar process heat as electricity export from solar steam can be a way to utilise the collector field throughout the year, including when the mill itself is not operational.

Most sugar mills in SA currently use back-pressure turbines to generate electricity for use within the mill. Condensing extraction steam turbines produce more electricity from the same amount of steam so that a share of the produced electricity can be exported to the national grid. In Figure 6, both concepts are distinguished in a simplified way.

Figure 5: Integration scheme for direct solar live steam generation (process values from Starzak and Zizhou, 2015).

As shown in Figure 5, indirect steam generation requires an additional heat exchanger, but has the advantage of the collector loop being able to be operated at lower pressure. This indirect concept is suitable for line-focusing collectors like parabolic trough collectors (PTC) and Fresnel collectors, and also for central receivers with heliostats. For these systems, up to 400 °C working temperatures of thermal oil are used as collector fluid. Higher temperatures can be achieved by using molten salt or air.

Existing direct steam generation concepts use steam drums as feed vessel and steam separator, together with a pump and a pressure valve (cp. Figure 7). Concepts using the boiler itself as a steam drum are under development (Schenk et al., 2015). With point-focusing systems like heliostat fields, direct steam generation can be realised easily as only a central receiver has to be pressurised. A concentrated solar power (CSP) plant of this kind is the Kh Solar One located near Upington in SA. About 4 000 heliostats reflect solar irradiance onto a central receiver tower with 250 MW, power rating, which generates superheated steam at 530 °C and 120 bar. In a high-efficiency power block (turbine and generator) of 50 MW, electricity is generated and fed to the grid. The system also has a steam storage, which allows the plant to produce electricity continuously, when the sun is not shining (OMI Energy, 2016).

If we consider a value of 700 Wc, peak power per square metre of solar collector area (Mauthner, 2015, p. 5), an area of 106 336 m² could at peak performance supply the whole heat demand of the reference mill (neglecting the heat exchange 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, or more. Therefore, the minute-by-minute load curve of the SPH would have to be adjusted to account for the additional power generation from the SPH.

It was estimated that the 14 SA sugar mills could generate about 800 MW, to 1 000 MW, 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 (Tongaat Hulett, 2013). Smithers (2014) estimated that 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.

The South African Department of Energy’s (DOE) Independent Power Producers (IPP) programme office issued a request for bids (RFB) for cogeneration projects under the Cogeneration Independent Power Producer Programme (IPPP) in June 2015. The programme caters for a maximum of 800 MW, in the first bidding round, which may be increased in the future. Approximately 25 % of the capacity is allocated towards combined heat and power projects. Priority is given to projects where energy output can be augmented by upgrading existing equipment or improving operating efficiencies, as would be the case for sugar mills (Department of Energy, 2015). The selling price of electricity under the programme are 1 ZAR/kWh, for electricity export from coal, and 1.20 ZAR/kWh, for export from biomass (Norton-Rose Fulbright, 2015), which includes bagasse.

However, no large-scale projects with the ability to 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.
Exhaust steam generation

Feeding solar generated steam into the exhaust steam line (cp. Figure 8) can have the following benefits:
- The amount of let-down steam can be reduced, leading to savings of bagasse and coal, and
- Electricity export from CESTs can be increased as less process steam has to be extracted. In this way, SPH can support electricity generation regardless of its comparably low integration temperature level.

At this integration variant, the feed water can be evaporated at comparably low temperature and pressure levels. This increases the collector efficiency. In principle, for the solar generation of exhaust, the indirect solar steam generation concept with kettle reboiler, as shown in Figure 5, could be applied. However, due to the much lower pressure and temperature, steam can be produced in the collectors directly. A steam drum is usually used for this. This is a feed vessel in which the two-phase fluid from the collectors can separate into water and steam. Such a steam drum is cheaper than a kettle reboiler and also allows for the collector to operate at a slightly lower temperature level as no heat exchanger is required between the collector loop and exhaust steam line.

When the sun rises in the morning, at first only the circulation pump operates until the exhaust steam temperature and pressure is reached. The steam drum has a variable fill level to compensate for the different volumes of water and steam. When the correct steam parameters are achieved, solar steam is released into the exhaust steam line. When the level in the steam drum falls below a set value, the feed pump adds additional feed water to the solar loop.

Figure 8: Integration scheme for direct solar exhaust steam generation (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 as a pre-heater adjacent to 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/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 MWth.

Table 4 and Figure 13 for economic assessment. It should be noted that this integration variant offers the highest collector field size of all investigated integration points of 89 238 m² as the modulation capacity of the steam boiler limits the collector area at solar live steam generation. The temperature level is at the upper end for stationary collectors. It is expected that the solar gains of ETCs would slightly improve if the feed water temperature could be decreased to e.g. 105 °C, but the bulk of solar heat will still need to be around 130 °C to achieve evaporation.

Drying of bagasse

An integration scheme for solar drying of bagasse is shown in Figure 9. The typical moisture content of bagasse after the dewaterring mills in the juice extraction unit is approximately 50 % of weight. For 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 reduce by at least 20 % by reducing the moisture content from 50 % to 40 %.

Figure 9: Integration scheme for solar drying of bagasse with air collectors (process values from Starzak and Zizhou, 2015)

The temperature and pressure of exhaust steam are in a range where focusing, tracking solar collectors, and highly efficient evacuated tube collectors (ETCs), can be applied. The stationary ETCs have no moving parts and they can make use of both beam and diffuse irradiance. In the annual energy gain simulations, the gains of both collector types were compared. The results in Table 3 show that the specific gains of the ETCs during the crushing season are 510 kWe/(m² a) vs. 378 kWe/(m² a) from medium-temperature parabolic trough collectors (PTC-MTs). Both gains are below the gains of high-temperature PTCs, but the specific collector costs per m² are also lower (cp.

To investigate this further, heat recovery from the wet air outlet to the collector inlet should be considered. Potentially, condensate from V3 could also be used for air pre-heating. As opposed to the BREF model values, the drying air in Rein (2007, p. 470) suggests that heating of the sugar is not necessary for drying. Thus, the temperature of the dryer inlet can be at or below that of the sugar inlet. This is expected to further increase the collector efficiency.

Heating of clear juice

The solar heating of clear juice is a way to pre-heat the juice before it enters the first evaporator effect (cp. Figure 11). This is saving exhaust steam. To avoid heat flux from the process to the collector loop during start-up or irradiance fluctuations, the collector should have a variable speed pump. This pump must control the collector outlet temperature to 110 °C. Additionally, the heat exchanger should always be bypassed on the process side when there are no sufficient solar gains. The required temperature level favours evaporated tube collectors.

Figure 11: Integration scheme for solar heating of clear juice (process values from Starzak and Zizhou, 2015)

In order to optimise the internal heat recovery in a sugar mill, the bleeding vapours V1 to V3 from the multi-effect evaporator are used to heat the mixed juice before it is clarified. As an alternative to the solar heating of clear juice, the heating of this mixed juice between the secondary and the tertiary pre-heater was also considered. This mixed juice has a temperature of only 95 °C and a higher mass flow of 337 t/h (Starzak and Zizhou, 2015), so the solar gains are slightly higher for clear juice. However, because of the impurities in the mixed juice, a heating tank with a cleaning mechanism would be required to transfer the heat from the solar loop to the juice. Added to that, this would only save V1. For these reasons, solar heating of clear juice is the preferred option.

Solar Gains and Performance Indicators

Table 3 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 into this heat sink. 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.

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the heating power demand by 700 W/m² peak power by 1 m³ 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 capacity of the boiler to modulate its heating power, as has been discussed above.

For the simulations, the software PolySun V8.011.23 (Walas and 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 12). This was based on existing schemes in the PolySun library for the simulation of solar process heat systems.

**Figure 12: 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 12 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 3. 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, 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 is the Naftali Solardyne Field of 5000 m² with a concentration ratio of 150. Since this technology, the system size, and the country of installation is always below the demand (no storage). Thus, to pre-condition for the live steam system, the average annual energy gains can be calculated from Table 3. The PTC-MT field of 51 168 m² would yield 40 833 MWh, during the crushing season, and about 59 016 MWh if it could be operated throughout the year. As explained above, the CS duration is used for all OTE of 75.70 % (cp. season 2012/2013, Smith et al., 2013), so the booster operates up to 64.5. This results in an overall boiler steam energy generation of 343 356 MWh. 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.

**Economic Assessment**

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 supplied by sugar mills.

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 live steam from coal, the average annual price of 1100 ZAR/MMBTU, an energy content of 27 GJ and a boiler efficiency of 75 % can be assumed (Peacock, 2016a). Thus, this work uses a current value of live steam from coal of 0.20 ZAR/MMBTU (1.2 EUR-ct/kWh) for comparison.

Again, it is assumed that live steam can be let-down to approximately 1.2 tons of steam per ton of bagasse to allow for comparison to the other technologies. 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 LCOH compares the annual project costs (C) to the annual yield (Q) for each year n over the lifespan of the system in years (N). Costs and yields are discounted with the rate d to account the time value of money.

![Image](https://www.internationalsugarjournal.com)
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 SHP 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 13). The hurdle rate for projects or investments by the SA sugar milling industry is in the range of 10 % to 15 % (Faxon, 2015). A project is feasible if the IR ratio exceeds this hurdle rate.

Table 4 summarises the results of the economic assessment of the most promising SHP 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 invested. The results in Table 4 indicate that currently none of the prioritised six SHP integration schemes offers the expected return. The two solar drying applications are closest to financial viability and at a high investment level the dry bagasse drying concept would increase to 11.7 % for bagasse drying and 13.1 % for sugar drying if they could be operated the whole year.

Conclusions
This initial study identified the six most promising processes for solar heat integration in SA sugar mills without back-end refineries. For each heat integration variant, a hydraulic scheme for the collection and storage of solar energy was developed and discussed. The general system operation was explained, and system dimensions and investment costs of the most effective technologies were assessed. Based on literature values and energy gain simulation results, the LCOH and IR of the different concepts were calculated and compared to heat generation from coal.

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 crucial crushing season. SHP was shown to cover a significant share of the heat demand of a mill. The feasibility here depends highly on the price received for export electricity.

Feed water pre-heating has similar costs than live steam generation, with the two drawbacks being that the internal value of energy substituted is lower, and that it interferes with heat recovery in the boiler. It should therefore only be considered after realisation of solar live steam generation.

Solar drying of raw sugar was found to be the most economic SHP integration variant, offering IR ratios close to the expectations of the industry. However, the estimated SHP system size for solar drying without storage in the BRTD sugar mill would be below 1 000 m2, only offering a very limited impact on the overall energy consumption of the mill. On the other hand, the low investment costs make this an ideal candidate for a pilot plant and gaining experience with the technology.

Solar drying of bagasse offers higher overall energy savings than the drying of raw sugar. It is the only solar technology that has been demonstrated in sugar mills. To determine financial feasibility and to show that this technology has efficiency that 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 IR 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.

Solar heating of clear juice offers smaller LCOH than live steam generation, but the IR ratio is very similar as only exhaust steam can be used for processes within the mill. At more beneficial framework conditions, e.g. with government subsidies for SHP or a fixed 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 SHP or a fixed minimum feed-in tariff for power export from cogeneration, including ST collectors, financial viability would be possible.

However, investments in SHP must always be viewed in the context of energy efficiency. From analysing the BRITM model and from literature it was concluded that there is a high efficiency potential in SA sugar mills. Implementation of heat recovery is usually more economic than an investment into SHP, but combinations of heat recovery and SHP in one project e.g. for drying of raw sugar can offer synergies. Further work on SHP 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 CEST, or the production of bio-ethanol on site, have to be described so that more detailed SHP feasibility assessments can be performed.

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Table 4: Estimated economic figures of the six SHP integration variants

<table>
<thead>
<tr>
<th>Integration Point</th>
<th>Collector Type</th>
<th>Heat demand (MWh/year)</th>
<th>Max. field size (m²)</th>
<th>System costs (EUR/m²)</th>
<th>Capital expenditure (Mia. EUR)</th>
<th>LCOH (€/kWh)</th>
<th>IR [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Live steam*</td>
<td>PTC-HT</td>
<td>74.4</td>
<td>53.568</td>
<td>378</td>
<td>20.10</td>
<td>4.57</td>
<td>4.6</td>
</tr>
<tr>
<td>Feed water*</td>
<td>PTC-HT</td>
<td>9.0</td>
<td>12.880</td>
<td>378</td>
<td>8.46</td>
<td>4.57</td>
<td>2.6</td>
</tr>
<tr>
<td>Exhaust steam</td>
<td>ETC</td>
<td>62.5</td>
<td>89.238</td>
<td>188</td>
<td>16.78</td>
<td>4.55</td>
<td>3.3</td>
</tr>
<tr>
<td>Bagasse drying</td>
<td>PTC-Air</td>
<td>0.7</td>
<td>291</td>
<td>182</td>
<td>2.29</td>
<td>1.87</td>
<td>9.1</td>
</tr>
<tr>
<td>Sugar drying</td>
<td>PPC-Air</td>
<td>0.6</td>
<td>895</td>
<td>183</td>
<td>0.36</td>
<td>2.57</td>
<td>9.1</td>
</tr>
<tr>
<td>Clear juice</td>
<td>ETC</td>
<td>4.7</td>
<td>6.739</td>
<td>188</td>
<td>1.06</td>
<td>3.97</td>
<td>4.6</td>
</tr>
</tbody>
</table>

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


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