Opportunities for Solar Thermal Process Heat Integration in South African Sugar Mills

by

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Declaration

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March 2016

Dedication

I dedicate this dissertation to my wife, Emma, my parents and the Lord Almighty. Emma supported me in my endeavours and sacrificed a lot for the sake of my dreams. My parents granted me the opportunity to study and selflessly supported me. The Lord sustained me and opened many doors along the way. May this thesis bear testimony to His good works.

Abstract

The sugar milling sector is one of the major agro-processing industries in the South African economy. This sector, however, is under pressure to remain profitable under strenuous economic conditions. In order to enhance the competitive advantage of the industry, stakeholders are investigating opportunities to reduce the input costs of raw sugar production as well as alternative income streams, such as the production of bagasse by-products or the cogeneration of electricity.

Since the production of raw sugar is characterised by a significant demand for thermal energy, this study has been conducted to identify opportunities for the integration of solar thermal process heat into this process. Potential solar heat integration points have been identified by considering all of the heat sinks and input streams within a generic raw sugar factory. The suitability of each of the integration points have been assessed in terms of the heat demand and expected impact of solar heat integration. Integration opportunities that conserve bagasse and coal or enhance the potential for electricity cogeneration have been prioritised.

The sugar production process consists of various processes, such as sugarcane preparation and juice extraction, clarification, evaporation, crystallisation and drying of the raw sugar. Although there are numerous potential solar heat integration points within these processes, only six have been found to be potentially feasible in terms of the abovementioned criteria. The major opportunities for solar process heat integration into the sugar production process have been found to be the parallel production of live and exhaust steam, the drying of bagasse and sugar, the preheating of boiler feed water and, to a lesser extent, the heating of mixed juice.

Basic integration concepts have been developed for the abovementioned integration points in order to assess the potential solar gains. Rudimentary energy yield simulations have been used to estimate the expected solar gains of the proposed concepts and the collector fields have been pre-dimensioned according to the mean thermal loads of the processes. According to this preliminary study, solar thermal process heat can potentially supply between 10 and 27 % of the respective processes' heat demand without thermal storage. According to a basic economic assessment, the levelised cost of heat (LCOH) of the particular integration concepts is expected to be between R 0.43 and R 1.72 /kWh[1].

Although this study is only a preliminary evaluation of the potential of solar heat integration into the sugar milling industry, it has been shown that there are feasible integration points within the production process and that solar process heat integration can be considered as technically and financially feasible. However, owing to the intricacies of the heat supply and distribution network of a typical sugar factory, detailed studies should be conducted to optimise the integration of solar heat into the industry.

[1] An exchange rate of R 13: € 1 and R 12: $ 1 has been assumed for all financial calculations.

Opsomming

Die suikermeulsektor is een van die vernaamste agro-verwerkingsnywerhede in die Suid-Afrikaanse ekonomie. Hierdie sektor is egter onder druk om in die huidige strawwe ekonomiese toestande winsgewend te bly. Ten einde die mededingende voordeel van die bedryf te verbeter, ondersoek belanghebbendes geleenthede om die insetkoste van die ru suiker produksieproses te verlaag, sowel as alternatiewe inkomstestrome, soos die produksie van bagasse-byprodukte of die opwekking van elektrisiteit.

Aangesien die verwerking van ru suiker gekenmerk word deur 'n beduidende vraag na termiese energie, is hierdie studie uitgevoer om geleenthede te identifiseer vir die integrasie van sonenergie as 'n vorm van proseshitte. Potensiële integrasiepunte van sonenergie is geïdentifiseer deur alle hitte-verbruikers en insetstrome in 'n generiese ru suiker fabriek in ag te neem. Die geskiktheid van elk van hierdie integrasiepunte is beoordeel met betrekking tot die vraag na hitte en die verwagte impak wat die integrasie op die produksieproses sal hê. Voorkeur is verleen aan integrasiegeleenthede wat moontlik die verbruik van bagasse en steenkool kan verminder, of die potensiaal vir elektrisiteitopwekking verbeter.

Die produksieproses van ru suiker bestaan uit verskeie prosesse, soos die voorbereiding van die suikerriet en sap-onttrekking, suiwering, verdamping, kristallisering en droging. Alhoewel daar talle potensiële integrasiepunte vir sonenergie in hierdie prosesse is, blyk dit dat slegs ses hiervan potensieël lewensvatbaar mag wees. Die mees gepaste geleenthede vir die integrasie van sonenergie, is die gelyklopende produksie van hoë druk sowel as uitlaatstoom, die droging van bagasse en suiker, asook die voorverhitting van toevoerwater na die stoomketel en die verhitting van gemengde sap.

Basiese integrasie-konsepte is ontwikkel vir die bogenoemde integrasiepunte, om sodoende die potensiële energie-opbrengs te evalueer. Basiese energie-opbrengsimulasies is gebruik om die verwagte jaarlikse opwekking van die voorgestelde konsepte te bepaal, terwyl die versamelaarsvelde gegrond is op die gemiddelde termiese ladings van die prosesse. Die voorlopige ondersoek het getoon dat sonenergie as proseshitte potensieel tussen 10 en 27 % van die hitte-aanvraag in die onderskeie prosesse kan voorsien, sonder termiese stoorkapasiteit. Volgens 'n ekonomiese evaluasie is die gebalanseerde koste van die hitte van die betrokke integrasie-konsepte na verwagting tussen R 0.43 en R 1.72 / kWh[2].

Alhoewel hierdie studie slegs 'n voorlopige evaluasie van die potensiaal van die integrasie van sonhitte in die suikermeulbedryf is, is dit 'n bewys dat daar lewensvatbare moontlikhede bestaan. Daar behoort egter meer gedetailleerde studies uitgevoer word om die integrasie van sonenergie in die industrie te optimeer.

[2] 'n Wisselkoers van R 13: € 1 and R 12: $ 1 is aanvaar vir alle finansiële berekeninge.

Acknowledgements

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I am grateful to the Centre of Renewable and Sustainable Energy Studies (CRSES), the Solar Thermal Energy Research Group (STERG) for both the opportunity to participate in this project as well as for financial support.

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The contribution of the SMRI to this project is tremendous. I would like to commend Dr Katherine Foxon, Dr Paul Jensen, Dr Richard Loubser, Steve Davis and Prof Matthew Starzak for their input and support.

I would like to extend my gratitude to the supportive administrative staff at the Engineering Department of Stellenbosch University, especially Amelia Henning, Karina Smith and Janine Roussouw. Your kindness meant even more than your assistance.

Lastly, I would like to thank my wife, parents, family and friends, who supported me throughout my studies and shared in my struggles and my successes.

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Abbreviations

BRTEM	Biorefinery Techno-Economical Modeling
CAPEX	Capital Expenditure
CPC	Compound Parabolic Collector
DNI	Direct Normal Irradiance
ETC	Evacuated Tube Collector
FPC	Flat Plate Collector
GCV	Gross Calorific Value
GHI	Global Horisontal Irradiance
HEX	Heat Exchanger
HFC	Heliostat Field Collector
HTF	Heat Transfer Fluid
IEA	International Energy Association
IP	Solar Heat Integration Point
IPP	Independent Power Producer
IPPPP	Intepender Power Producer Procurement Programme
IRR	Internal Rate of Return
LCOH/E	Levelised Cost of Heat/Electricity
LFR	Linear Fresnel Reflector
NPV	Net Present Value
NREL	National Renewable Energy Laboratory
OTE	Overall Time Efficiency
PDR	Parabolic Dish Reflector
PTC-HT	Parabolic Trough Collector for High Temperature Applications
PTC-LT	Parabolic Trough Collector for Lower Temperature Applications
SHIP	Solar Heat for Industrial Processes
SMRI	Sugar Milling Research Institute
SPH	Solar Process Heat
Vn	Vapour from the n^{th} evaporator effect
VHP	Very High Pol Boiling House Configuration
WACC	Weighted Average Cost of Capital
W_{th}	Thermal Energy Demand

Definitions

Term	Definition
Bagasse	The fibrous sugarcane residue of the juice extraction process.
Brix	The concentration of solids in a liquid sugar solution.
Collector Field	An array of solar thermal collectors, usually expressed i.t.o. area.
Entry Barriers	Obstacles preventing the adoption of a specific technology or product.
Exhaust Steam	Desuperheated live steam supplying thermal energy to the plant.
Integration Concept	Hydraulic scheme of a solar thermal system and its connection to a thermal process.
Integration Point	Any heat demand within an industrial plant that can be supplemented with solar heat.
Levelised Cost of Heat	The discounted cost of the energy produced by a solar thermal system.
Live Steam	High pressure, superheated steam generated by bagasse and coal to generate electricity and perform mechanical work.
Overall Time Efficiency	The portion of operation time compared to the available time during the crushing season.
Pol	An estimation of the purity or sucrose content of sugar.
Raw Sugar	The output of the sugar production process prior to refining.
Solar Fraction	The portion of a process' thermal energy demand that can be substituted by solar heat.
Solar Gains	The annual energy yield of a solar thermal system.
Solar Heat Integration	The supply of solar heat to an industrial process.
Solar Resource	The average annual solar irradiation associated with a specific location.
Solar Thermal Process Heat	Process heat generated and supplied by a solar thermal system.
Solar Thermal System	A renewable energy technology that converts solar irradiance into usable heat.
System Efficiency	The output of a solar thermal system related to the irradiance exposed to the collectors.
Seasonal Utilisation Ratio	The portion of a solar thermal system's annual yield that is available during the crushing season.
Beam Irradiance	Irradiance onto a surface directly from the sun.
Diffuse Irradiance	Irradiance onto a surface from another direction than the sun due to reflection.
Global Irradiance	The annual sum of beam and diffuse irradiance received by a surface.

1. Introduction

The purpose of this dissertation is to report the results and findings of a research study aimed at highlighting the opportunities for solar thermal process heat integration in South African raw sugar factories. This chapter provides a broad overview of the background of the study, the motivation and objectives as well as the anticipated impact of the study. Furthermore, a basic overview of the layout of the dissertation is provided.

1.1 The Background of the Study

There has been an unprecedented interest in the integration of renewable energy in South Africa over the last few years. This can mostly be ascribed to the energy insecurity that have hampered the economy since 2008. Renewable energy alternatives are regarded as potential solutions to the prevailing energy crisis.

The South African government has shown great interest in the inclusion of renewable energy into the country's energy mix. The Department of Energy embarked on a programme[3] to allow Independent Power Producers (IPPs) to develop and operate renewable energy power plants in order to sell energy to the national grid operator. This programme has created an environment that fosters research in various renewable energy applications. Thus, numerous institutions are focusing on research projects aimed at evaluating and improving the potential for renewable energy integration.

Solar thermal technology is regarded as one of the most important renewable energy technologies in the South African context. Many IPPs have invested in utility-scale concentrating solar power (CSP) plants including parabolic trough and heliostat field technology, and stakeholders in the industrial sector are showing interest in solar thermal technology.

Due to economic pressure, the local sugar industry, under the leadership of the South African Sugar Milling Research Institute NPC (SMRI), has shown interest in incorporating solar thermal technology in order to reduce the running costs of sugar factories and expand additional income streams, thus ensuring sustained profitability of the industry.

Wienese & Purchase (2004) identified the potential of the sugar milling industry to export electricity by reducing the steam consumption of the mills by means of energy efficiency improvement. Ensinas et al. (2007a) also highlighted the fact that the production surplus electricity can be increased by reducing the demand for steam within the mill.

[3] https://www.ipp-cogen.co.za/

Participants of the International Energy Association's (IEA) Solar Heating and Cooling Programme have developed an integration guideline to assist solar planners, energy consultants and engineers to identify and rank potential solar heat integration points (Muster et al., 2015). This guideline can be used to identify and rank solar thermal integration opportunities within the sugar milling industry.

1.2 Research Motivation & Objectives

According to various previous studies, the potential of solar heat generation for industrial processes is immense, particularly in South Africa (Du Plessis, 2011). However, although solar thermal technology is relatively mature, the unrealised potential contribution of the technology greatly exceeds the current employment thereof, specifically in the industrial sector.

Although various studies have investigated the potential of solar process heat for industrial processes (Kalogirou, 2001; Schweiger et al., 2001; Vannoni, Battisti & Drigo, 2008; Lauterbach et al., 2012a), the potential of low-temperature solar heat integration in the South African industrial sector has not yet been investigated. No literature pertaining to solar heat integration opportunities in the sugar industry in particular have been found. This research seeks to address that dearth of research on solar heat integration in this particular industry.

This study forms part of a broader project launched by the SMRI to assess the energy use reduction and monitoring opportunities in sugar factories under the Sugarcane Technology Enabling Programme for Bio-Energy (STEP-Bio), which is aimed at enhancing the competitiveness of the sugarcane processing industry in South Africa.

In order to assess the potential of solar process heat integration in the sugar industry, this study's aim is to identify and evaluate the potential integration points within the raw sugar production process.

The primary objectives of the study are to:

- Identify the potential solar heat integration points;
- Pre-rank the integration points;
- Develop integration concepts for the most interesting integration points;
- Assess the potential solar gains;
- Assess the economic feasibility;
- Identify the most suitable integration points and
- Identify the barriers to entry.

This study is, therefore, expected to highlight the potential contribution of solar heat to a typical South African raw sugar factory. The study should, however, be regarded as a preliminary investigation with the goal of to establishing the framework and boundary conditions for further research in this field.

1.3 Significance of the Study

The abovementioned research problem has intrinsic value to stakeholders in the sugar milling industry and the solar energy industry in particular. The results of this study will aid practitioners in making informed decisions regarding the potential of solar process heat for the sugar milling industry, since it highlights some of the major opportunities and pitfalls.

Additionally, this research may provide manufacturers, distributors and project developers with an overview of the market potential of this technology in the sugar milling sector. It may also assist stakeholders in the industry to make informed decisions regarding the feasibility of solar thermal energy towards improved energy efficiency and cost saving.

The integration point identification and ranking methodology is relatively new and has not been applied in previous research projects. Therefore, this study may prove to be of value to other researchers interested in conducting similar studies for other industrial sectors.

The main contribution of this study to the existing body of knowledge is that it provides a framework and highlights the boundary conditions for further studies pertaining the integration of solar process heat into the sugar industry.

2. Research Methodology

In order to identify the opportunities for solar process heat integration in the sugar industry, a structured approach has been followed. The approach has been designed to identify and rank the potential integration points within the raw sugar production process. This section provides an overview of the research methods and instruments applied in this techno-economic feasibility study. A brief discussion of the limitations of the research design is also provided.

2.1 Research Strategy

The primary purpose of this study is to identify and assess the opportunities for solar heat integration in South African raw sugar factories. A structured quantitative evaluation approach has been followed to estimate the potential of solar process heat for this industry. The broad research approach is outlined in Figure 2-1. The structured evaluative research methodology is commonly applied in techno-economic feasibility studies (Hofstee, 2006).

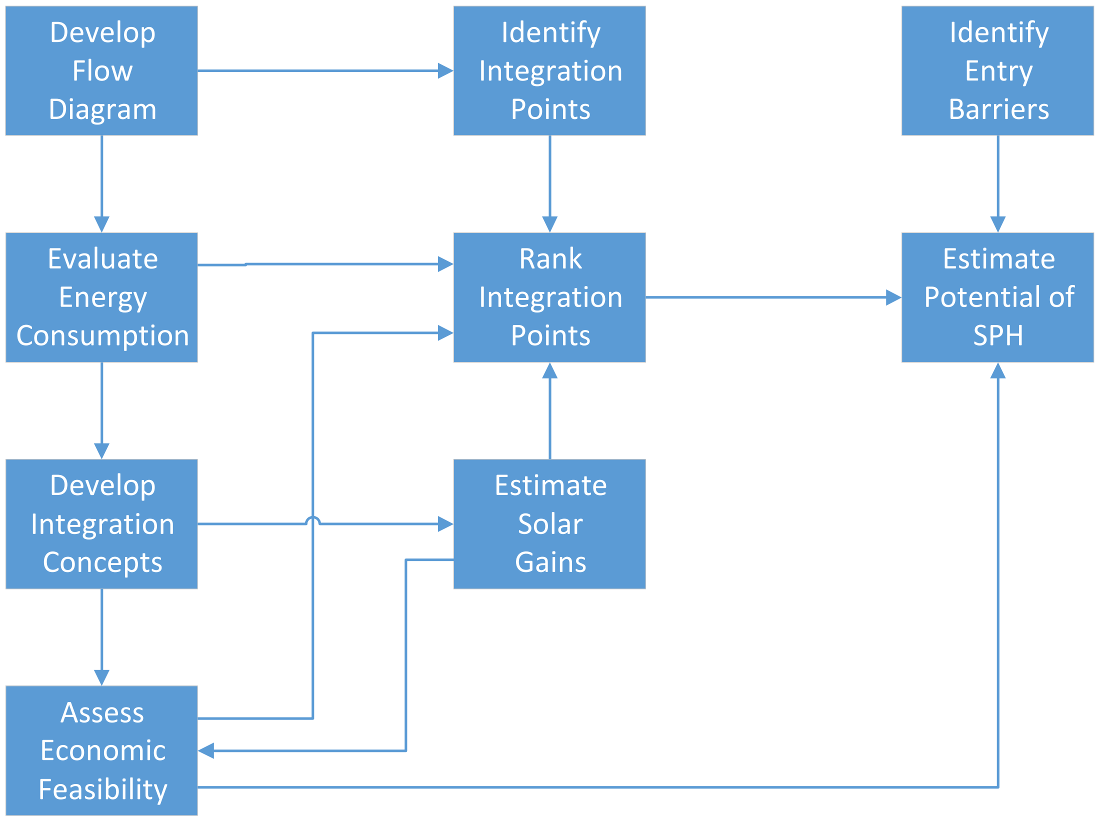

Figure 2-1: Research Approach

In order to provide a foundation for the analysis, flow diagrams of the raw sugar production process have been developed. The purpose of these process flow diagrams is to identify the relevant processes, input streams, outputs and flows within a typical sugar mill. These schemes are mostly based on textual sources and a site visit to an existing sugar mill.

A MATLAB model of a generic sugar mill has been developed by the SMRI as part of the Institute's Bio-Refinery Techno-Economic Modelling (BRTEM) project, which formed part of the Sugarcane Technology Enabling Programme for Bio-Energy (STEP-Bio). This process model consists of the typical processes within a raw sugar factory including a cogeneration utility plant. The model simulates the steady-state energy and mass flows of approximately 150 variable streams. As part of the output, the model returns the pressure, temperature, flow rate, composition and Brix[4] as well as the enthalpy of each of these variables. The output of the model has been validated and verified by the SMRI against similar models, and is regarded as representative of the typical South African mill.

The thermal energy consumption of the various processes has been assessed in order to identify the significant energy users within the production process. A steam balance has been developed in order to develop a Sankey diagram of the estimated thermal energy consumption of the various processes. The energy analysis is based on the BRTEM model and has been partially validated by related literature as part of this research project.

The process flow diagrams and the energy assessments were used to identify the potential solar process heat integration points. The integration points were pre-ranked according to criteria such as the energy consumption, energy source and temperature levels in the identification of the most suitable and valuable integration points. The analysis technique is based on a guideline for the integration of solar heat into industrial processes, which has been published by the IEA SHC Task 49 "Solar Process Heat for Production and Advanced Applications". The pre-ranking of the integration points has been verified by means of focus group discussions with a panel consisting of sugar production and solar heat experts.

Integration concepts have been developed for the most suitable integration points according to guidelines provided by textual sources. Similarly, suitable solar thermal concepts have been selected according to a literature review of the applicable technology. The collector field size of the proposed solar thermal systems were pre-dimensioned according to the mean thermal load of the integration points to avoid the production of surplus energy.

The potential solar gains estimations are based on preliminary unpublished results of yield simulation conducted by Hess (2015). These simulations are based on basic hydraulic schemes of each of the

[4] The sugar content of a liquid solution, usually expressed in terms of percentage.

integration concepts. Thermal storage has been excluded from the simulations considering that the energy consumption of the processes surpass the capability of the solar thermal systems significantly. The monthly yields for each of the integration concepts have been simulated, based on the expected inlet and outlet temperature levels and mass flows of the integration points and Durban's irradiation data. The resultant yield estimations have been related to monthly global horizontal irradiance (GHI) data of Durban, in estimating the monthly and annual system efficiencies. This was used to determine the expected seasonal yield for the maximum collector field size for each integration point. Unfortunately, the particular simulation software used does not include technologies to provide solar heat at temperatures higher than approximately 250 °C. The annual system efficiency of high temperature applications investigated in this study are based on relevant literature regarding the efficiency of the related technologies.

The levelised costs of heat (LCOH) associated with each of the integration concepts have been calculated by taking the expected capital and operational costs into account. The estimated capital cost of each concept is based on reported costs of existing solar thermal plants, while the operating costs are based on guidelines provided in literature. The sensitivity of the LCOH and the Internal Rate of Return (IRR) of solar thermal system have also been investigated by means of various single-variable sensitivity analyses. The results of the financial analysis have been verified by published results of similar studies. All of the financial calculations exclude debt amortisation and taxes.

The potential solar heat integration points have been ranked according to a structured ranking methodology in order to avoid biased results. The method is based on a multitude of preselected criteria prescribed in the IEA guidelines. Thus, the methodology is applied in order to highlight the most suitable integration points within a sugar factory.

Furthermore, various stakeholders in the sugar industry have been identified to comment on the perceived obstacles in an effort to identify some of the most significant entry barriers to the industry's adoption of solar process heat technology.

2.2 Delimitations & Critique

Although the investigation is based on the output of a simulation model and not a real case study or measured energy consumption data, the BRTEM model is regarded as representative of a typical South African sugar mill.

The steam balance is based on steady-state operating conditions, which does not represent the real-time steam consumption of a mill. However, the output of the model is based on the average throughput of the local sugar factories in the previous season and the steam consumption of a mill is relatively constant in relation to the throughput.

While there might be various alternative criteria to assess the potential for solar heat integration, the proposed procedure is expected to highlight the most suitable integration points. The results of this investigation are expected to be relatively universal and can be generalised. However, the integration concepts act only as guideline for further research and should be adapted for specific applications.

Financial indicators such as Net Present Value (NPV) and simple payback periods are commonly used in the economic appraisal of renewable energy technologies on the one hand (Short, Packey & Holt, 1995). On the other hand, the LCOH is regarded as a suitable measure to assess the feasibility of such technologies. While the investment window of 20 years exaggerates the merit of the investment opportunity, it portrays the benefit of solar thermal technology over the entire expected lifespan.

Furthermore, the study is focused on the costs and opportunities of solar thermal process heat generation and the feasibility does not include the details of integration with the existing energy network or the capital and operational costs that might be required to alter the existing infrastructure in a sugar mill to accommodate the integration of solar process heat.

The aim of this study is to identify the opportunities for solar heat integration. The yield estimations are based on simplified hydraulic integration concepts. Although the specific integration schemes can be investigated in much more detail, the purpose of this study is to highlight the most appropriate integration points based on first estimates and rules of thumb.

3. Solar Thermal Industrial Process Heat

Solar thermal technology is regarded as a relatively mature renewable energy technology. Almost 500 million square meters of solar thermal collectors have been installed across the world. The application of solar thermal technology for the production of heat for industrial processes has been gaining significant attention in recent years. This section provides an overview of the current developments in solar industrial process heat applications and reviews some of the most important solar thermal collectors. The integration of solar process heat and the generic entry barriers for the adoption of solar thermal technology are briefly discussed.

3.1 Solar Heat for Industrial Processes

Solar thermal systems can be used to harvest solar energy and convert it into heat, which can, in turn, be used to supply thermal energy to residential, commercial or industrial consumers at temperatures of up to 500 °C and beyond. More than 470 million square meters of non-concentrating collectors, amounting to almost 330 GW_{th} of installed capacity have been installed worldwide by 2014. The total installed capacity in Sub-Saharan Africa, of which South Africa is the most prominent participant, is approximately 1 GW_{th} (Mauthner & Weiss, 2014). Although the production of hot water for domestic use is a familiar practice, the generation of solar thermal process heat for industrial applications is still a relatively novel concept (Lauterbach, 2014), especially in South Africa.

Solar thermal process heat should be distinguished from the general term of solar process heat since the latter may include the employment of solar photovoltaic technology to provide electrical energy for heating purposes. Solar thermal systems, however, produce heat directly from the irradiance of the sun. Such a system typically consists of an array of collectors, storage tanks and heat exchangers (Muster et al., 2015). A graphical representation of the typical components of a solar thermal system is provided in Figure 3-1.

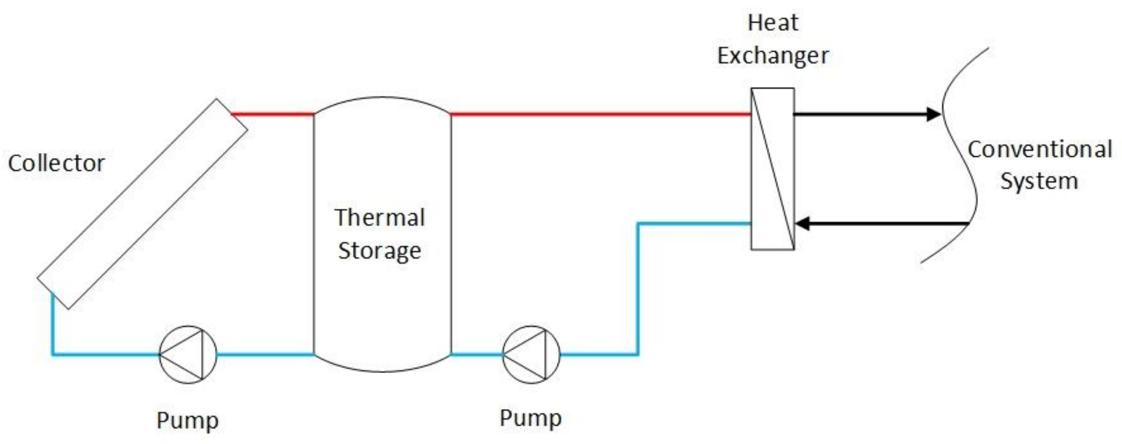

Figure 3-1: A Solar Thermal System

Various authors have identified the food processing industry as one of the industrial sectors that is most inclined towards the adoption of solar process heat (SPH). Industry reports by organisations such as the IEA's Energy Technology Systems Analysis Programme and the International Renewable Energy Agency (IEA-ETSAP & IRENA, 2015) as well as the German Association for International Collaboration (GIZ, 2011), conclude that solar thermal technology has the potential to supply a substantial portion of the heat required in this particular industry. Authors such as Vannoni, Battisti & Drigo (2008) ascribe this to the fact that most of the processes in the food industry require heat below 400 °C. According to Lauterbach et al. (2012), almost all of the process heat demand in Germany's food and beverages sector is below 200 °C.

Kalogirou (2004), as well as Werner, Gosselar & Johnson (2011), identified sterilisation, pasteurisation, evaporation, drying and cleaning as some of the industrial processes that are most suitable for solar heat integration since these processes typically require heat below 250 °C. Hess & Oliva (2010) identified the heating of hot water for cleaning purposes, the heating of boiler make-up water, the heating of baths or vessels and convective air drying as some of the most favourable applications of solar process heat.

Although there are no conclusive values on the heat consumption of South Africa's industrial sector, the potential for solar process heat is expected to be significant. This potential is reinforced by the favourable solar resource, considering that South Africa is exposed to some of the highest levels of solar radiation in the world (Du Plessis, 2011).

The potential for solar industrial process heat integration in the food processing industry has been recognised by various authors, but these studies mainly focus on the dairy and beer industries. Authors such as Du Plessis (2011), suggest that the sectorial heat demand and temperature range of South African industries should be investigated in greater detail. The integration of solar heat for industrial processes (SHIP) in the sugar industry has not been investigated.

3.2 Solar Thermal Collectors

The solar collector is the most important component of a solar thermal system, since it converts solar radiation into useful thermal energy. There is an assortment of approximately seven types of collectors that are most commonly used in practice. Each of these collectors has different characteristics in terms of design and operating temperature. Solar collectors can be divided into three primary classes according to their motion, namely stationary, single-axis and two-axes tracking collectors (Kalogirou, 2004). A list of the most common collectors is provided in Table 3-1.

Table 3-1: Solar Thermal Collectors (Kalogirou, 2003)

Motion Configuration	Collector Type		Temperature Range [°C]
Stationary	Flat Plate Collector	FPC	30 – 80
	Evacuated Tube Collector	ETC	50 – 200
	Compound Parabolic Collector	CPC	60 – 240
Single-Axes Tracking	Linear Fresnel Reflector	LFR	60 – 250
	Parabolic Trough Collector	PTC	60 – 300
Double-Axes Tracking	Parabolic Dish Reflector	PDR	100 – 500
	Heliostat Field Collector	HFC	150 – 2000

A comparison of the efficiency of flat plate, evacuated tube, parabolic trough and linear Fresnel collectors is illustrated in Figure 3-2. Although concentrating collectors can be used to supply higher temperature process heat, flat plate and evacuated tube collectors are most commonly employed to supply solar process heat in the medium and low range up to 200 °C. This is mainly due to the relatively low cost, ease of installation and low maintenance associated with this technology (Duffie & Beckman, 2013).

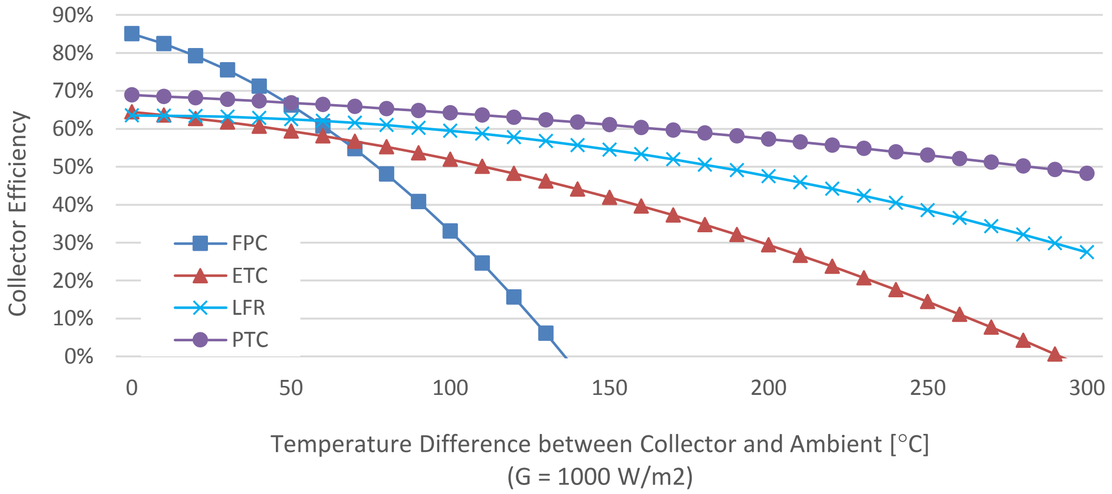

Figure 3-2: Collector Efficiency Curves (Adapted from Mauthner, 2014)

The annual yield of a solar thermal system is dependent on the collector efficiency, the irradiation and the inlet temperature, and can range from 100 to more than 1 000 kWh_{th}/m^2. In Spain, the annual yield of a FPC varies between 400 and 1200 kWh_{th}/m^2 (Lauterbach et al., 2011). As a rule of thumb, the lowest acceptable yield for a solar thermal system to be competitive is approximately 350 to 400 kWh_{th}/m^2 (Aidonis et al., 2002).

AEE INTEC (2015) maintains a database of existing industrial solar process heat plants. According to this database, more than 150 solar process heating systems have been installed worldwide, ranging from a few square meters to almost 40 000 m^2. As shown in Figure 3-3, flat plate and evacuated tube collectors are used in more than 70 % of the existing solar process heat applications across the world. In South Africa, at least 25 large-scale solar thermal systems have been commissioned between 2007 and 2015, contributing to more than 8 500 m^2 of installed collector area (Blackdot Energy, 2015). Most of the existing industrial solar process heat plants are integrated into processes with temperature levels of 60 to 100°C (Lauterbach et al., 2011).

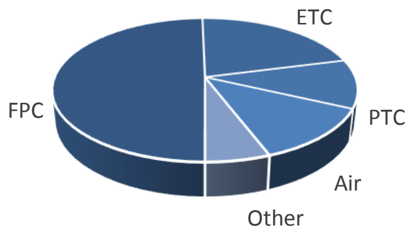

Figure 3-3: Collector Technology Distribution (Based on data of AEE INTEC, 2015)

3.2.1 Flat Plate Collectors

Flat plate collectors (FPC) are the most mature solar thermal technology and mainly consist of a glazed transparent cover and an absorber plate (Kalogirou, 2004). Such a collector absorbs beam and diffuse radiation and transfers it to the heat transfer medium, usually water or air. Flat plate collectors can be used to supply heat up to 100 °C above ambient temperature (Duffie & Beckman, 2013). The efficiency of flat plate collectors range between 60 and 25 % for operating temperatures between 80 and 120 °C (Weiss & Rommel, 2008). Flat plate collectors are the most economical solar thermal solution for processes with a heat demand below 120 °C, since it is a relatively cheap technology. This technology is mostly suitable for cleaning and drying process (Weiss & Rommel, 2008). The energy yield of a flat plate collector can be increased by means of a concentrating reflector (Kalogirou, 2004). AEE INTEC (2015) reported more than 75 industrial solar heat plants consisting of flat plate collectors, ranging from 20 to almost 40 000 m^2 of installed collectors per plant. In 2013, a FPC system with a gross collector area of 39 300 m^2 have been installed at a copper mine in Chile to supply heat at approximately 50 °C to an electro-winning process (AEE INTEC, 2015).

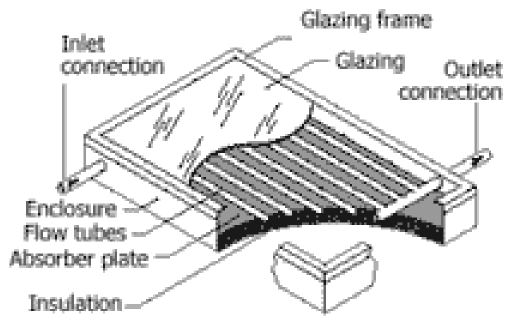

Figure 3-4: Flat Plate Collector (FlaSolar, 2008)

3.2.2 Evacuated Tube Collectors

An evacuated tube collector (ETC) typically consists of a row of vacuum-sealed glass tubes, each containing an absorber. Some collectors are also equipped with reflectors to enhance the yield. These collectors can supply heat up to 200 °C, although it is mostly employed for slightly lower temperature applications (Kalogirou, 2004). Evacuated tube collectors are more efficient than flat plate collectors because the vacuum pipes reduce the losses of such collectors. ETC can, therefore, be used to reduce the collector area of a solar thermal system (Weiss & Rommel, 2008). These collectors collect beam and diffuse irradiance and can reach efficiencies of 60% to 80% (Kalogirou, 2003). ETC is a relatively mature technology used for various industrial applications. More than 30 evacuated tube plants have been registered on the solar thermal plants database hosted by AEE INTEC (2015). The installed capacities of these systems range from a few to almost 9 000 m^2. The largest reported ETC system is used for preheating purposes in a textile factory in China and produces heat at approximately 50 °C (AEE INTEC, 2015).

3.2.3 Compound Parabolic Collectors

A compound parabolic collector (CPC) is a stationary concentrating collector that consists of an absorber and a trough that concentrates beam and diffuse radiation from a wide angle unto the absorber (Kalogirou, 2004). Stationary CPC systems can deliver heat in the range of 60 to more than 200 °C (Kalogirou, 2003). The efficiency of compound parabolic collectors typically ranges between 60 and 70 % at an irradiance of 1 000 W/m^2 (Kalogirou, 2003). The advantage of this technology is that it is relatively cheap compared to tracking collectors and can achieve much higher efficiencies than FPC's and ETC's, especially at higher temperatures. CPC technology, however, has not been widely implemented (SOLTRAIN, 2009).

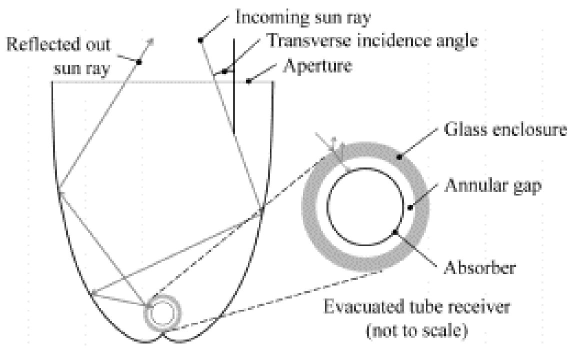

Figure 3-5: Compound Parabolic Collector (Gajic et al., 2015)

3.2.4 Parabolic Trough Collectors

Parabolic trough collectors (PTC) are line focusing concentrating collectors with single-axis tracking. The collector, consisting of a linear array of parabolic shaped mirrors, concentrates beam solar radiation onto a linear receiver tube. Synthetic thermal oil or water is usually used as heat transfer medium, which is circulated through the receiver tube (Weiss & Rommel, 2008). Parabolic trough technology is the most mature tracking and concentrating solar thermal technology and can be used to supply heat from 60 °C to even more than 500 °C (Sargent & Lundy Consulting Group, 2003). Throughout this study, a distinction has been made between high (PTC-HT) and low (PTC-LT) temperature parabolic trough technology. The former refers to the parabolic trough collectors

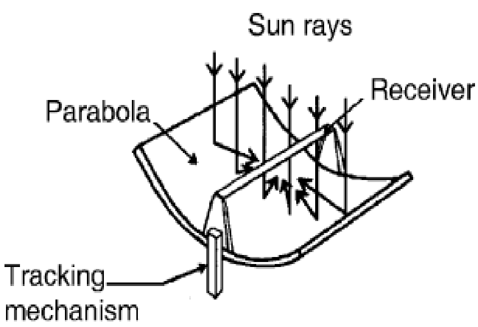

Figure 3-6: Parabolic Trough Collector (Kalogirou, 2004)

employed in large-scale concentrating solar power plants for the production of steam at temperatures beyond 250 °C, while the latter refers to smaller-scale collectors used mostly in process heat applications to supply heat below 250 °C. According to Silva et al. (2014), the average thermal efficiency of a PTC system is in the order of 40%, although this is a function of the mass flow of the heat medium and the temperature difference. This is also supported by Frank et al. (2014). Systems consisting of high temperature parabolic trough collectors are expected to attain annual system efficiencies of more than 50 % (Burns & McDonnell, 2009; Günther, Joemann & Csambor, 2012). Various authors have concluded that parabolic trough collectors are the most cost effective solar thermal solution to supply heat between 80 °C and 200 °C (Silva, Pérez & Fernández-Garcia, 2013). Approximately 17 PTC systems providing industrial process heat have been recorded on the AEE INTEC (2015) database. The sizes of these systems vary between 40 and 5 000 m^2. The largest reported industrial PTC has a gross area of approximately 5 000 m^2 to produce steam at a temperature of about 240 °C for the heating of oil in a potato chip factory in the United States of America (AEE INTEC, 2015).

3.2.5 Linear Fresnel Reflectors

A linear Fresnel reflector (LFR) is a line focusing collector and consists of an array of flat reflectors that track the movement of the sun on a single-axis and concentrate beam solar radiation onto a stationary linear receiver (Kalogirou, 2004). Pressurised water or synthetic oil is normally used as heat transfer medium or it can be used for direct steam production. Although a linear Fresnel system is relatively simple to construct, it requires a significant ground area. These collectors are typically used to supply process heat up to 250 °C, although temperatures up to 400 °C can be achieved. It is mostly suitable for systems larger than 50 kW (Weiss & Rommel, 2008; Du Plessis, 2011). The AEE INTEC (2015) database records only one LFR system of about 120 m^2 of gross collector area in Tunisia.

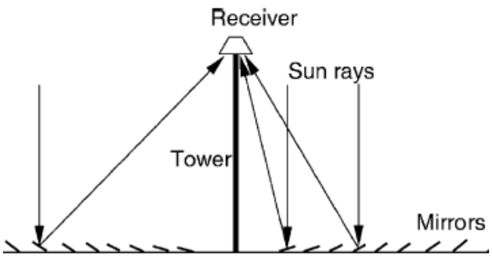

Figure 3-7: Linear Fresnel Reflector (Kalogirou, 2004)

3.2.6 Heliostat Field Collector

A heliostat field collector (HFC), or central receiver system, consists of a field of flat mirrors tracking the movement of the sun in order to reflect and concentrate beam solar irradiance onto a stationary receiver. A heliostat system can generate heat up to 2000 °C. This technology is mostly used to produce steam for utility-scale electricity production but commercial-scale systems are currently under development

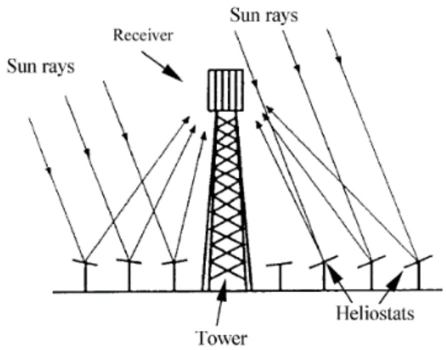

Figure 3-8: Heliostat Field Collector (Kalogirou, 2004)

(Helio100, 2014; AORA Solar, 2015). HFC technology is commonly combined with high temperature thermal storage facilities. Water, thermal oil or molten salt are typically used as heat transfer media (Kalogirou, 2004).

3.3 Integration of Solar Process Heat

In assessing the potential for solar heat integration into an industrial plant, it is important to identify the possible integration points in the processes. Furthermore, it is critical to identify the most suitable integration points. To address the lack of standardised procedures, various solar thermal experts collaborated to develop a guideline for the integration of solar heat for industrial processes (SHIP) as part of the International Energy Agency's (IEA) Solar Heating and Cooling Programme's Task 49 (Muster et al., 2015). The purpose of this guideline is to assist energy experts to identify potential solar heat integration points, develop integration concepts and to detect the most feasible integration opportunities by means of a ranking tool.

Solar thermal energy can be integrated into an industrial process at supply or process level in order to offset or supplement the heat demand of the processes. Although process level integration is often more suitable owing to the lower temperature levels, supply level integration is usually regarded as favourable due to the relatively constant load and added flexibility (Hess et al., 2011). Figure 3-9 provides a summary of the most common solar heat integration points.

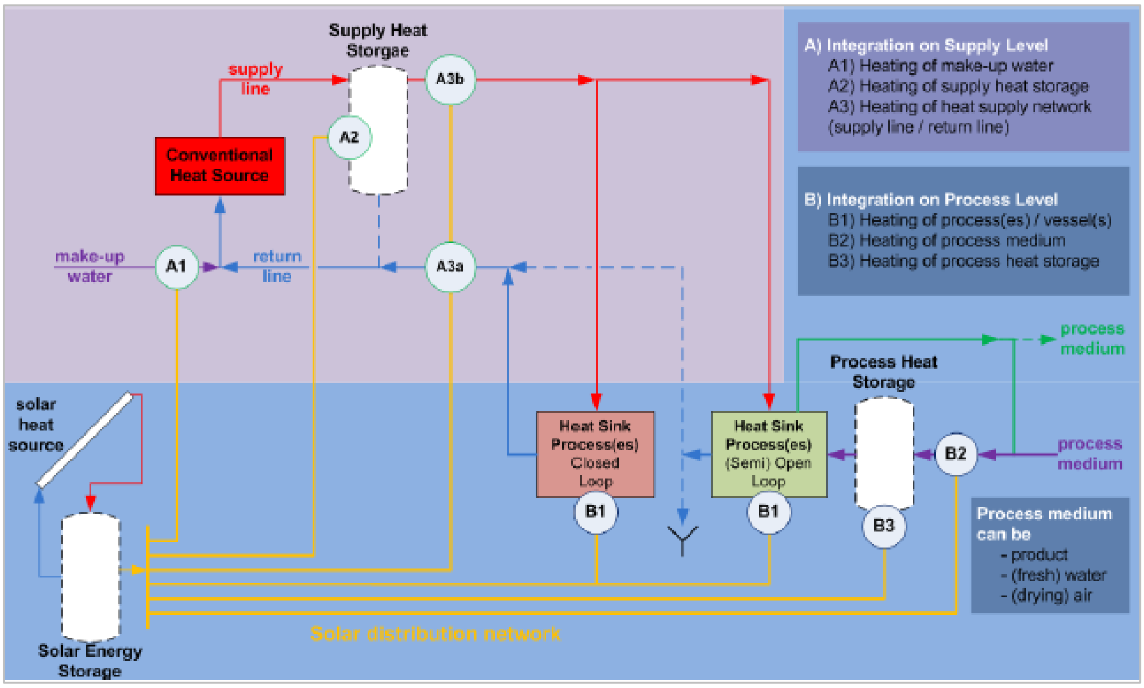

Figure 3-9: Solar Process Heat Integration (Muster, 2015)

On supply level, Schmitt, Lauterbach & Vajen (2011) identified three distinct solar heat integration concepts. The solar heat can be integrated in parallel with the conventional heat supply system to feed steam or hot water directly into the supply network, or to preheat the boiler feed and make-up water. The most common process level integration concepts include the heating of cleaning water, the heating of baths or vessels, and convective air drying (Hess & Oliva, 2010).

A preliminary assessment of the potential for industrial solar heat integration should be based primarily on the supply and return flow temperatures within the heat distribution network. The characteristics of the heating system, the type and cost of fuel, as well as the demand profile should also be taken into account (Hess & Oliva, 2010). Processes that have a heat demand for more than 75% of the year, especially during summer, and at least 5 days per week should be given preference for solar heat integration (Aidonis et al., 2002).

As part of the guideline, the participants of the IEA SHC Task 49 developed a classification method concerning the identification of generic integration concepts, both on supply and process level. Table 3-2 provides an overview of these concepts. Most integration concepts can be classified under one of these 13 concepts.

Table 3-2: Overview of the Generic Integration Concepts (Schmitt, 2015)

Integration Level	Heat Transfer Medium		Conventional Heating Method		Solar Heat Integration Concept	
Supply Level	S	Steam			PD/PI	Parallel Integration (Direct/Indirect)
					FW	Heating of Feed-Water
					MW	Heating of Make-Up Water
	L	Liquid			PD/PI	Parallel Integration (Direct/Indirect)
					RF	Return Flow Boost
					SC	Heating of Storage or Cascades
Process Level			E	External HEX	PM	Heating of Process Medium
					IC	Heating of Intermediate Circuit
					HB	Heating of Bath or Vessel
					IS	Heating of Input Streams
			I	Internal HEX		
			S	Steam Supply	V	Vacuum Steam
					LP	Low Pressure Steam

One of the crucial challenges of solar heat integration is the maximisation of the portion of heat supplied by the solar system (IEA-ETSAP & IRENA, 2015). Thus, solar thermal systems are most commonly used to supply a fraction of 10 to 50 % of a process' heat demand in conjunction with a conventional heat source, such as a boiler (Atkins, Walmsley & Morrison, 2010; Du Plessis, 2011). It is also the case that higher solar fractions are not practical given the intermittency of most industrial processes' heat demand and the availability of solar heat, whilst lower fractions usually result in insignificant savings (Aidonis et al., 2002).

Hess & Oliva (2010) suggests that assessment of the potential for solar thermal integration should be based on the operating temperature and demand profile of the processes, the heat supply system and the fuel, as well as the cost of the conventional energy. Hassine (2015) developed a two-staged ranking tool for the identification of the most suitable integration points in an industrial facility. Firstly, the thermal demand and load profile of the integration points, as well as the characteristics of the existing heat supply infrastructure are used to exclude some integration point to reduce the design effort. Thus, integration concepts should be developed for the remaining integration points where the most promising concepts are highlighted as part of the second phase of the ranking methodology. The integration assessment is, therefore, based on an assessment of the characteristics of each potential integration point and the characteristics of the integration concepts for the most promising integration points. Some of the integration assessment criteria are listed in Table 3-3.

Table 3-3: Integration Point Suitability Criteria (Adapted from Hassine, 2015)

Parameter	Description
Process Temperature	The temperature at which the process is operated.
Process Return Temperature	The temperature of the process medium at the inlet of the process.
Temperature Lift	The difference between the inlet and the process temperature.
Annual Heat Demand	The annual thermal energy requirement of the process.
Operation Time	The annual sum of operating hours.
Mean Load	The average thermal load of the process.
Demand Seasonality	The seasonality of the process.
Supply Quality	The sensitivity of the equipment and process medium to temperature fluctuation.

Heat sinks requiring lower temperature levels and significant temperature lifts are considered as more appropriate for solar thermal integration. Therefore, processes with a high annual heat demand should be given preference for SPH integration. A process' ability to deal with fluctuation in the demand and supply of process heat is described by its storage volume and charging capability. The recirculation parameter refers to the process' operational setup, which can be open, closed or semi-closed. Here, open loop processes are generally more inclined towards solar thermal integration.

Specific integration concepts should be developed for the most promising integration points according to the pre-ranking methodology. The feasibility of the integration concepts should be tested according to the criteria provided in Table 3-4. The viability of each of the integration concepts are subject to its expected reliability, cost and benefit.

Table 3-4: Integration Concept Suitability Criteria (Based on Hassine, 2015)

Parameter	Description
Process Continuity	The continuity of the process is not subject to the solar thermal system.
Control Hardware	No extension in supply equipment control hardware is required.
Control Software	No changes in supply equipment software required.
Fouling Risk	No fouling risk for the added HEX.
Heat Exchanger Sizing	Existing HEX can be used.
Storage Sizing	Addition of storage capacity can be avoided.
Distance to Solar	The solar plant is close to the supply line of the sink.
Auxiliary Energy	No significant pressure differential to be overcome.
Estimated Solar Yield	High solar estimated yield.
Multi-Supply	Other heat sinks can be easily co-assisted.
Modulation	The primary or back-up heat utility is modular.
Replacement of CHP	The utilisation of Combined Heat and Power will not be reduced.
Replacement of WH/HR	The use of waste heat or heat recovery will not be reduced.

The suitability of solar heat integration at each integration point can be assessed in a matrix whereby each integration point is assigned a score according to the abovementioned criteria. By means of the ranking tool, the integration points with the highest potential for solar heat integration can be highlighted.

3.4 Generic Entry Barriers

Entry barriers can be defined as obstacles that prevent the rapid adoption of a technology (Brown, 2001). Such barriers obstruct the achievement of a technology's potential. Most researchers agree that the high capital cost associated with renewable energy technologies and the seemingly unsatisfactory cost-effectiveness are the most prevalent barriers to renewable energy implementation. However, there are also technical and market related barriers. This section provides a chronological account of the most prominent entry barriers for renewable energy technologies since the 1980's to as recent as 2013 as explained by the most prominent researchers in the industry.

Even as early as the 1980's, it had been identified that cost considerations are not the primary entry barriers for the implementation of solar thermal technology. Rather, it is rather hampered by ignorance or scepticism regarding the advantages and opportunities of this technology. Tax incentives are, therefore, not sufficient to drive the adoption of solar thermal technology or to overcome the entry barriers. Risk, which can be defined as the anticipated likelihood of problems arising due to the implementation of a certain technology, is also suggested as a major entry barrier. These risks can be economic, social or personal (Guagnano et al., 1986).

Painuly (2001) provided a list of possible barriers that hinder the adoption of renewable energy technologies. These general barriers are listed in Table 3-5.

Table 3-5: Generic Entry Barriers for Renewable Energy Adoption (Adapted from Painuly, 2001)

Category	Barrier
Market Barriers	Stringent Energy Regulations
	Ignorance regarding Technology
	Constrained Access to Technology
	Absence of Competition
Financial Barriers	Economic Infeasibility
	High Discount Rates
	Long Payback Period
	Small Market
	High Cost of Capital
	Insufficient Access to Capital
	Insufficient Access to Credit
	High Capital Expenditure
	Insufficient Institutional Support

Institutional Barriers	Lack of Information Sharing
	Lack of Regulatory Framework
	Volatile Macro-Economic Environment
Technical Barriers	Insufficient Codes and Standards
	Skills Shortage
	Inadequate Entrepreneurship
	System Barriers
	Unreliable Products
Perception Barriers	Unsatisfactory Consumer Acceptance
	Inflated Risk Perception
	Inadequate Infrastructure

Brown (2001) discussed the barriers to the implementation of clean energy programmes and highlighted an interesting phenomenon. Although economic factors play a role in the adoption of energy efficient technologies, the lack of reward within an organization for energy managers who reduce energy costs regularly discourages investment in such technologies. Furthermore, the relatively low cost of energy resulted in a low drive towards the reduction of energy costs. However, this has changed in the South African context in the last few years. Brown also identified uncertainty of future energy prices and high perceived risk as further obstacles.

Owens (2002) highlighted the high development costs and the erroneous risk perception of potential investors due to the lack of information as some of the greatest barriers to the adoption of renewable energy technologies. Similarly, Menenteau, Finon & Lamy (2003) identified high capital expenditure and the non-continuous energy generation associated with renewable energy technologies as significant barriers.

Reddy & Painuly (2004) took a step further to break the barriers down into various groups according to the stakeholders. Stakeholders from the residential, industrial and commercial sectors, renewable energy developers, as well as policy makers were engaged in the identification of barriers. The study showed that although the various stakeholders were in accord as to what the barriers are, their perceptions regarding the importance of these barriers vary. Stakeholders from the industrial sector regard technical barriers as most important.

A report compiled by Philibert (2006) regarding the barriers to the diffusion of solar thermal technology described the lack of skilled installers as one of the most important technical barriers.

Furthermore, the integration of this technology with existing industrial systems posed another threat. Economic barriers include suboptimal efficiencies and unreliable output. A list of behavioural barriers were also provided, of which consumer ignorance and the reluctance to operate more complicated systems were the most prevalent.

Margolis & Zuboy (2006) led an investigation on behalf of National Renewable Energy Laboratory (NREL) to assess literature regarding the non-technical barriers to the adoption of solar energy technologies. According to their study, the following barriers were the most frequently highlighted:

- Insufficient governmental support
- Consumer ignorance
- High cost of renewable energy compared to conventional energy
- Lack of financing instruments for renewable energy projects
- Ignorance regarding costs and benefits of energy systems
- Lack of skilled installers
- Inadequate codes and standards

In Verbruggen et al.'s (2010) discussion regarding the costs, potential and barriers of renewable energy, the authors make an important distinction between cost and price. The price of a product is defined as the total of all costs of that product, including personal costs, social costs as well as opportunity costs[5]. According to them, the total price of a renewable energy project is often misrepresented and can be described as a significant barrier to the successful adoption of industrial-scale renewable energy projects.

Fernández-García et al. (2010) identified the availability and cost of land and the long payback periods associated with SHIP plants as some of the primary entry barriers for this technology. The potential for energy efficiency and waste heat recovery is also regarded as an obstacle since these measures usually supersedes the potential for solar thermal integration.

Hess et al. (2011) identified the priority that an enterprise assign to energy efficiency measures as one of the barriers to solar thermal adoption. The complexity of solar heat system design and integration is also listed as potential entry barriers.

Additionally, Viardot (2013) argued that renewable energy adoption is firstly subject to the perceived usefulness of the technology, which is closely associated with the perceived reliability of the technology. Secondly, the apparent ease of use (or lack thereof) of renewable energy technologies also plays an important role. Thirdly, the familiarity of renewable energy technologies also drives the

[5] Opportunity cost is the inevitable loss of results of a project due to the unavailability of resources spent on another project.

adoption, while the lack of knowledge can be a barrier. Furthermore, solar thermal technology competes with various other heat sources and the adoption thereof is primarily dependent on its financial competitiveness (IEA-ETSAP & IRENA, 2015).

It is apparent that there are various economic, technical and market related obstacles that are expected to hamper the dissemination of solar thermal technology in the sugar milling industry. These entry barriers are to be addressed in order to ensure that stakeholders in the industry accept the integration of solar thermal process heat as a feasible opportunity.

4. The South African Sugar Milling Industry

The production of raw sugar is one of the most significant sectors in the South African agro-processing industry. This chapter provides some background of the local sugar industry and describes the raw sugar production process in detail. An outline of the heat supply and distribution network within a typical sugar factory is also provided. Furthermore, the challenges and opportunities associated with the industry are also briefly discussed, as are the solar resource of the sugar producing regions.

4.1 Overview of the Sugar Milling Industry

The sugar industry is an important sector within the South African economy and certainly one of the most important sectors in the KwaZulu-Natal and Mpumalanga provinces. This agricultural and agro-processing industry is concerned with the cultivation of sugarcane and the production of raw and refined sugar, as well as a wide spectrum of by-products. The average direct income of the sector is approximately R 12 billion per year realised from the average production of more than 2 million tonnes of sugar. Almost 80 000 people are directly involved in the production of raw sugar, of which more than 12 750 are employed in the sugar milling sector. South Africa is one of the leading exporters of sugar, competing with countries such as Brazil, Australia and India (DAFF, 2013).

The South African sugar milling industry consists of 6 milling companies that operate 14 sugar mills. Figure 4-1 provides an overview of the locality of the sugar mills in South Africa. Although two of the mills are situated in the Mpumalanga province, most are located in KwaZulu-Natal.

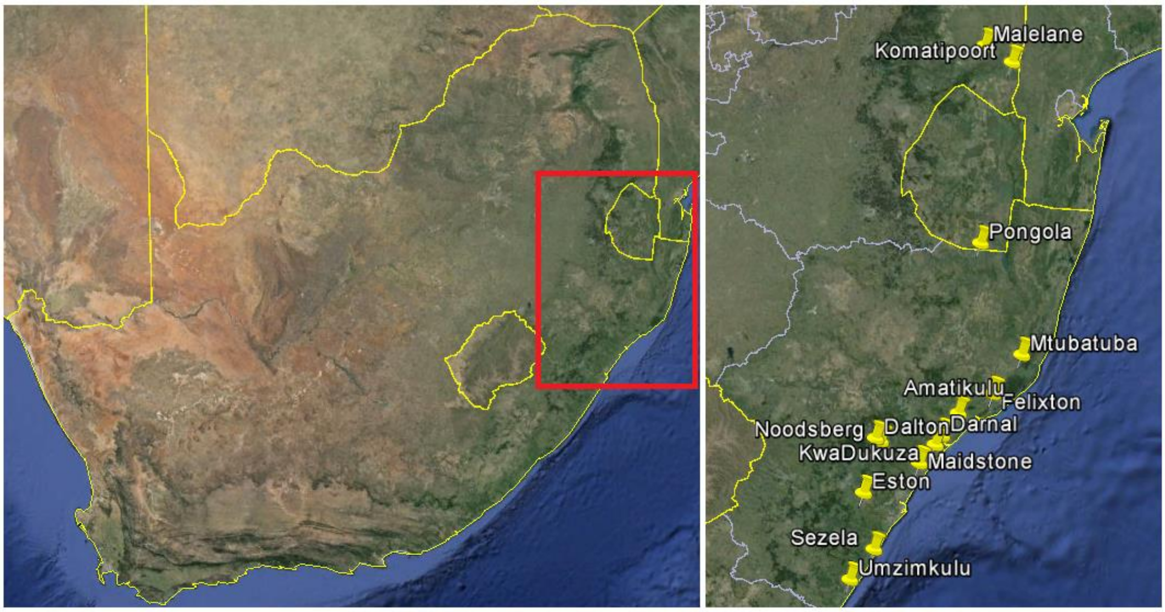

Figure 4-1: Locality of the Sugar Industry (Based on SASA (2013))

The milling season normally stretches from March until December (Foxon, 2015a), during which an average of almost 22 million tonnes of sugarcane is processed in total (Wienese & Purchase, 2004). In the 2012/2013 season, approximately 17.3 million tonnes of sugarcane were harvested and processed (DAFF, 2013). The capacity of these factories vary between 90 and 550 tonnes of cane per hour, with an average of about 300 tonnes per hour (Smithers, 2014). The average throughput of the mills in the 2012/13 season was approximately 270 tonnes per hour (Smith et al., 2013).

The average length of the 2012/13 crushing season was 254 days and the overall time efficiency (OTE)[6] was about 76 % (Smith et al., 2013). Therefore, the annual operating time of a typical South African mill is approximately 4 615 hours per season.

4.2 Raw Sugar Production

The raw sugar production process primarily consists of five stages, namely juice extraction, clarification, evaporation, crystallization and sugar drying. Figure 4-2 provides an overview of the raw sugar production process and some of the most prominent product streams. Detailed process flow diagrams, indicating all of the input and output streams, are provided in this section. The flow rates of the streams and the operating temperatures and pressures of the operations are based on the output of the BRTEM model (Starzak & Zizhou, 2015).

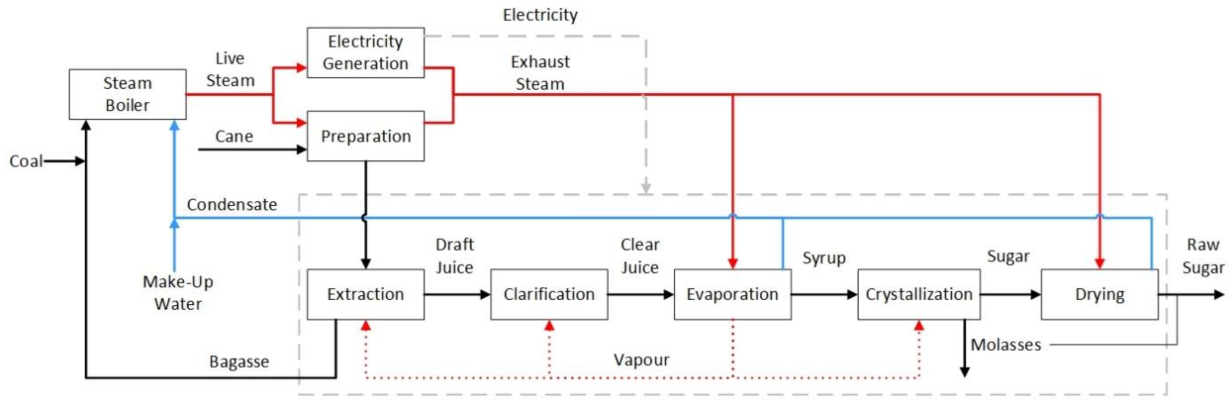

Figure 4-2: Raw Sugar Production Process

The process description provided in this section is directly based on the works of Rein (2007), unless otherwise stated.

4.2.1 Cane Delivery & Preparation

Sugarcane is normally burned in the field to remove the leaves and harvested manually in most parts of South Africa. Bundles of cane stalks are delivered to the sugar factories by truck and unloaded at the cane yard where it is stored until the cane enters the factory. Due to risk of sucrose losses and quality deterioration, the cane is to be processed as soon as possible after the harvest.

[6] The operational hours of the factory as a percentage of the total available hours during the season.

Excess dirt and rocks are removed from the cane before it is cut by rotating knives. The purpose of the cane knives, rotating at about 500 to 600 revolutions per minute and usually driven by steam, is to reduce the size of the cane stalks. Once reduced, the cane is fiberized by means of steam-driven shredders.

The cane knives and shredders are commonly referred to as prime movers. Although they are usually steam-driven, electric drives can also be used in more energy efficient mills. According to Rein (2007), the prime movers can account for more than a quarter of a factory's total power requirements. Some of the more energy efficient sugar factories are equipped with electric mill drives.

4.2.2 Juice Extraction

Although raw sugar factories are commonly referred to as sugar mills, few factories still employ milling for sucrose extraction. Most modern sugar factories use moving bed or chain diffusers for the extraction process. Almost all of the sugarcane processed in Southern Africa is extracted by means of diffusion. The primary function of the juice extraction unit is to extract the maximum amount of sucrose from the available sugarcane. The cane preparation and juice extraction process is illustrated in Figure 4-3.

A diffuser typically consists of 10 to 18 stages (Rein, 1995). The sucrose is leached from the cane by spraying heated juice onto a moving bed of cane fibre in a counter flow direction. Diffusers normally operate at a temperature of more than 80 °C throughout the diffuser to maximise the extraction of sucrose (Reid & Rein, 1983). The temperature within the diffuser is maintained by injecting bleed vapour from the second evaporation effect[7] (V2) directly into the diffuser. Some factories also use vapour from later effects, especially if there are 5 evaporator effects.

The scalding juice at the cane entry side of the diffuser is heated through heat exchangers with vapour from the third evaporation effect (V3), often to temperatures close to 100 °C, in order to increase the temperature of the incoming cane. Most of the heat requirements of the diffuser is supplied by the scalding juice heat exchangers (Reid & Rein, 1983; Munsamy, 2008).

Condensate from the final effect of the evaporation unit is normally used as imbibition water within the diffuser to enhance the sucrose extraction. The temperature of the imbibition water is normally 50 to 60 °C or more and the imbibition rate in South African mills is in the order of 333 % on fibre (Smith et al., 2013).

[7] See section 0

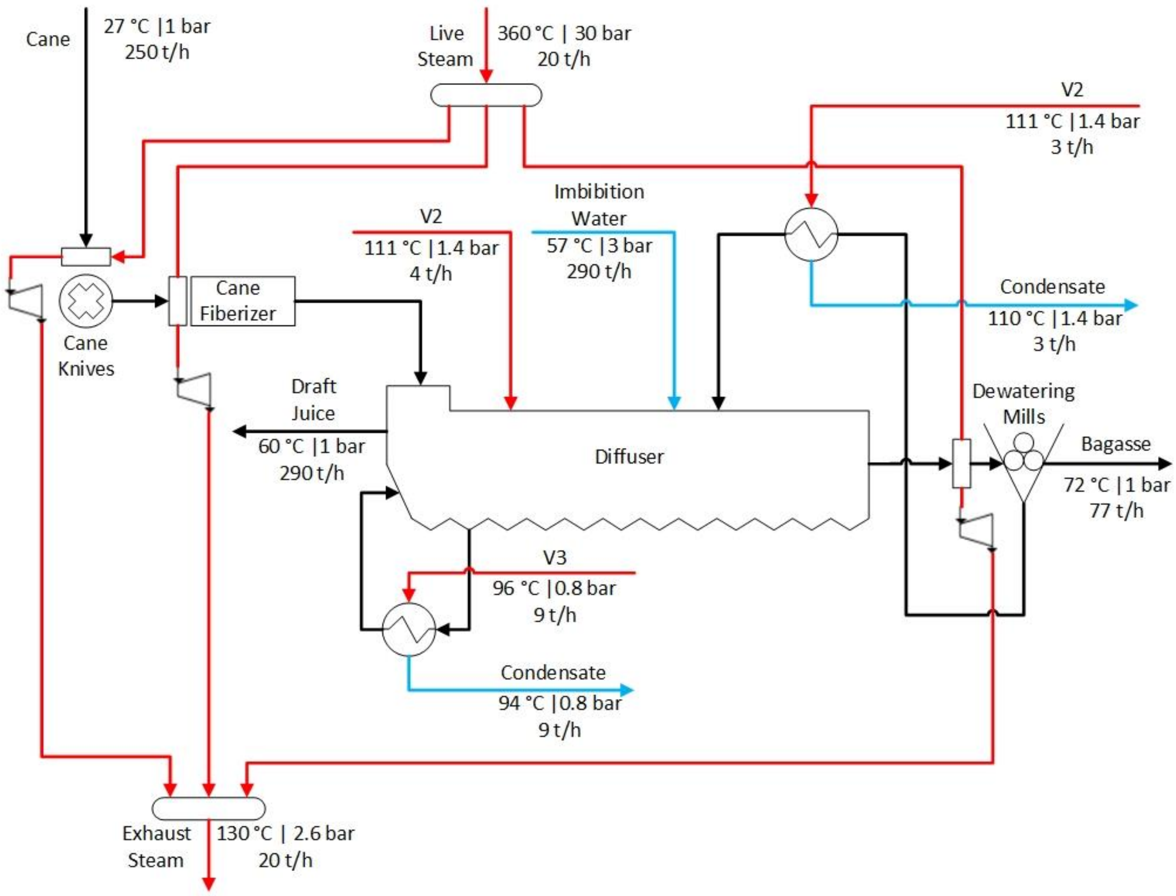

Figure 4-3: Cane Preparation & Juice Extraction (Based on Starzak & Zizhou, 2015)

The bagasse exiting the diffuser is pressed in roller mills to reduce the moisture content and to extract the maximum amount of sucrose. The press water is heated to approximately 80 °C with vapour bled from the third evaporation effect before it is reintroduced to the diffuser. In some factories even higher grade vapour is used to heat the press water. The dewatering mills are predominantly driven by high-pressure steam and are also classified as prime movers.

The draft juice leaves the diffuser at a temperature of about 60 to 65 °C.

4.2.3 Clarification

The draft juice exits the diffuser at roughly 60 °C and is stored in a buffer tank before the clarification process, where the impurities in the juice are removed in clarifiers. The juice is heated in a train of plate or shell-and-tube heat exchangers to a few degrees above 100 °C by means of vapour bled from the first three evaporation effects, prior to clarification. Chemicals, such as milk of lime, are added to the juice to enhance the clarification process. Figure 4-4 provides and overview of the clarification process.

The heated juice is flashed in a flash tank to ensure a constant temperature of 100 °C within the clarifiers and to remove the air present in the juice. In order to ensure the efficiency of the flash tank and to minimise the steam consumption, the temperature of the juice should be regulated within 1 to 2 °C of the desired temperature.

The suspended solids in the juice flocculates and is separated from the juice in the clarifiers, where it settles as mud. The clarifier mud is usually filtered, after which the filtrate can be returned to the mixed juice tank. Some factories reintroduce the mud to the diffuser instead of using a filter.

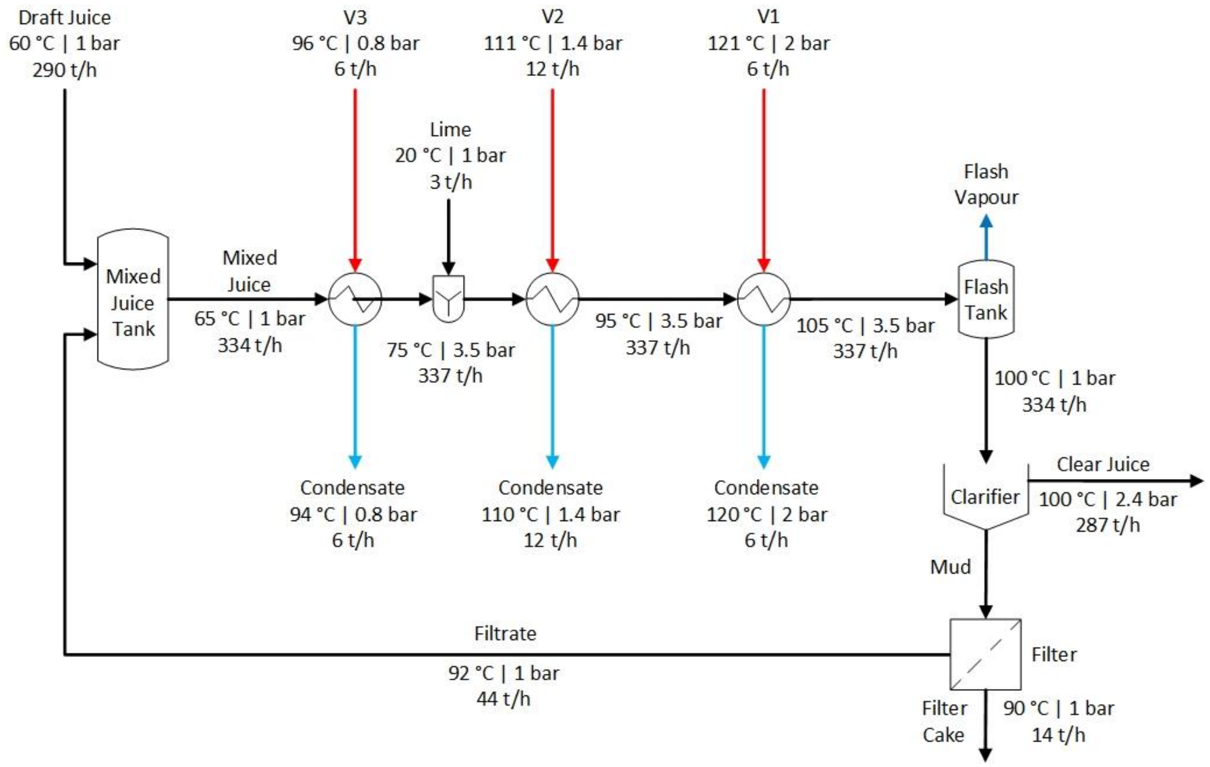

Figure 4-4: Clarification (Based on Starzak & Zizhou, 2015)

The clear juice leaves the clarifier at approximately 100 °C. If the factory makes use of a filter, the filter cake is used for the production of by-products such as fertiliser and/or animal feed.

4.2.4 Evaporation

The primary purpose of the evaporation process is to concentrate the sucrose content of the clear juice from about 15 to approximately 65 % Brix. Most of the exhaust steam is consumed in this process. To prevent spontaneous crystallization, the syrup should not be concentrated to more than 65 % Brix.

The boiling point of the clear juice is about 110 °C. Thus, most factories heat the clear juice to or above boiling point prior to the first evaporation effect by means of exhaust steam to improve the capacity of the evaporators.

The juice is concentrated in multiple effect evaporators, which consist of a train of four or five heat exchangers that utilise low-pressure steam as a heating medium. The first effect consumes exhaust steam, after which each successive effect consumes vapour bled from the preceding effect. The operating pressure is reduced in each consecutive effect to lower the saturation temperature of the vapour and the boiling point of the syrup. A schematic representation of a quadruple effect evaporation process is provided in Figure 4-5.

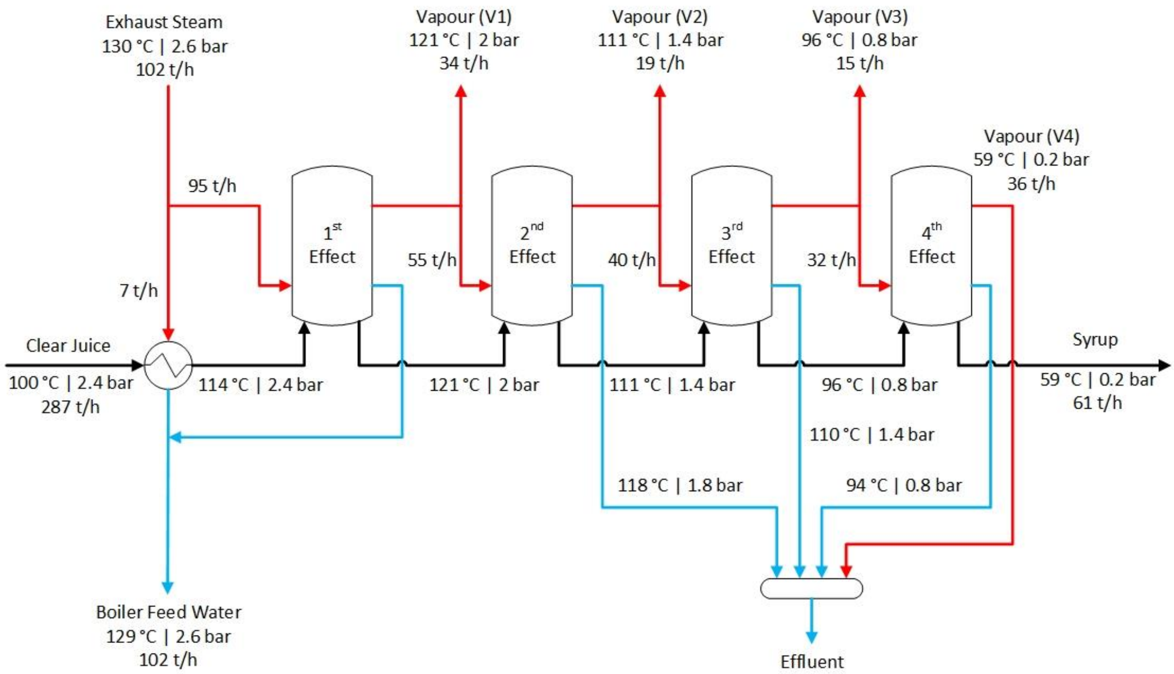

Figure 4-5: Evaporation (Based on Starzak & Zizhou, 2015)

According to Rillieux's principles, a multi-effect evaporator of N effects can achieve the evaporation of N kg of water with 1 kg of steam. Furthermore, bleeding vapour from the i^{th} effect as heating medium for external processes will result in a saving of i/N the amount of steam for the same duty. Therefore, vapour is bled from the evaporators to serve as heating medium for most of the other processes within the factory to improve the overall steam economy. According to Rein (2007), the throughput of the evaporators can be improved by increasing the amount of vapour bleeding.

The condensate of 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 heat for the next effect. The vapour from the final effect is mostly used as imbibition water for the diffuser.

4.2.5 Crystallization

The syrup is boiled under vacuum in batch or continuous boiling pans in order to concentrate it to saturation. The primary aim of the boiling house is to crystallize the maximum amount of sugar from the available syrup. The crystallization is enhanced by the addition of seed grains or magma to the massecuite, referring to the semi-crystallized syrup or slurry. In order to minimise the sucrose content of the final residue of the process, referred to as molasses, the crystallization process is usually divided into three stages. The syrup and magma solution in the boiling pans, also referred to as massecuite, boils at temperatures between 60 and 70 °C, depending on the pressure of the vacuum pans.

The Very High Pol (VHP) boiling scheme is most commonly applied in South African factories for the crystallization of the sugar. In this three stage boiling scheme the syrup is boiled in the "A" pan at a vacuum to produce "A" sugar and "A" molasses, which are separated in centrifuges. The "A" sugar is the purest sugar and is the primary product of the factory. The "A" molasses usually contains a noteworthy amount of sucrose and is further boiled in the "B" and "C" pans to extract more sucrose. The "B" sugar is sent to the mingler, where water and syrup is added to it. A share of the mixture is fed to the "A" pan as footing, while the rest is dissolved in the remelter. The footing serves as seed crystals for the deposition of "A" sugar. The "B" molasses are further boiled in the "C" pan. The "C" sugar is completely dissolved in the remelter and the remelt it used as footing for the "A" pan. Most of the sucrose are extracted from the "C" molasses, which is discarded from the process as a secondary product. A simplified llustration of a VHP boiling scheme is provided in Figure 4-6.

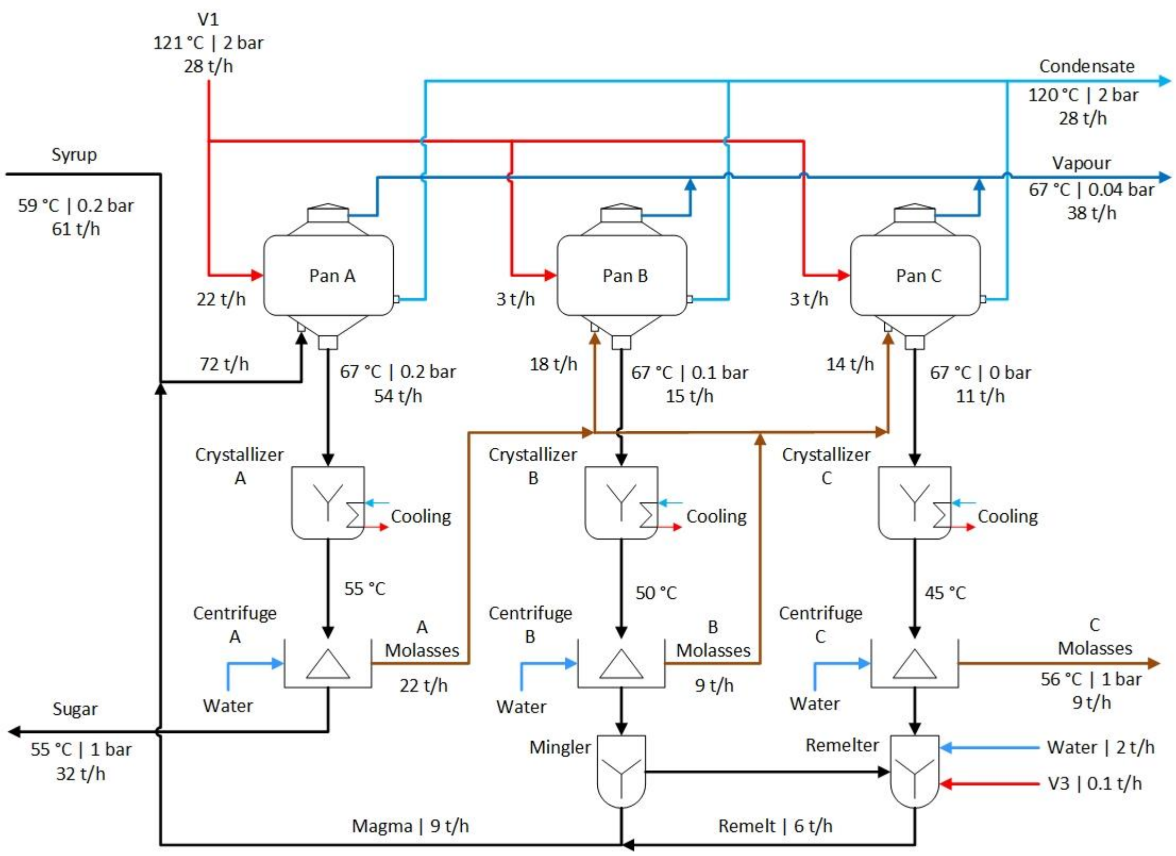

Figure 4-6: Crystallization (Based on Starzak & Zizhou, 2015)

Rein (2007) provides an overview of the operation of a conventional batch pan in the boiling house. The footing or seed grain is added to the pan under vacuum. The syrup or molasses is fed from tanks to the pan until it is filled to the strike level. The massecuite is boiled to the desired concentration, after which the steam flow is interrupted and the massecuite is discharged from the pan. The residence time of the “A”, “B” and “C” massecuite in the boiling pans is approximately 4.5 h, 6 h and 9 h respectively.

The residual molasses is used to produce by-products such as ethanol, yeast, fertiliser and animal feeds.

4.2.6 Sugar Drying

Drying is the last procedure in the raw sugar production process. The purpose of the drying process is to reduce the surface moisture content of the final sugar by means of evaporation. The sugar is mostly dried in rotary cascade drums with hot air flowing in a counter current direction. The air is heated by means of exhaust steam or V1. The sugar moves through the rotating drum under gravitation and is tumbled continuously throughout the drum by means of lifters within the drum. The drying process is illustrated in Figure 4-7.

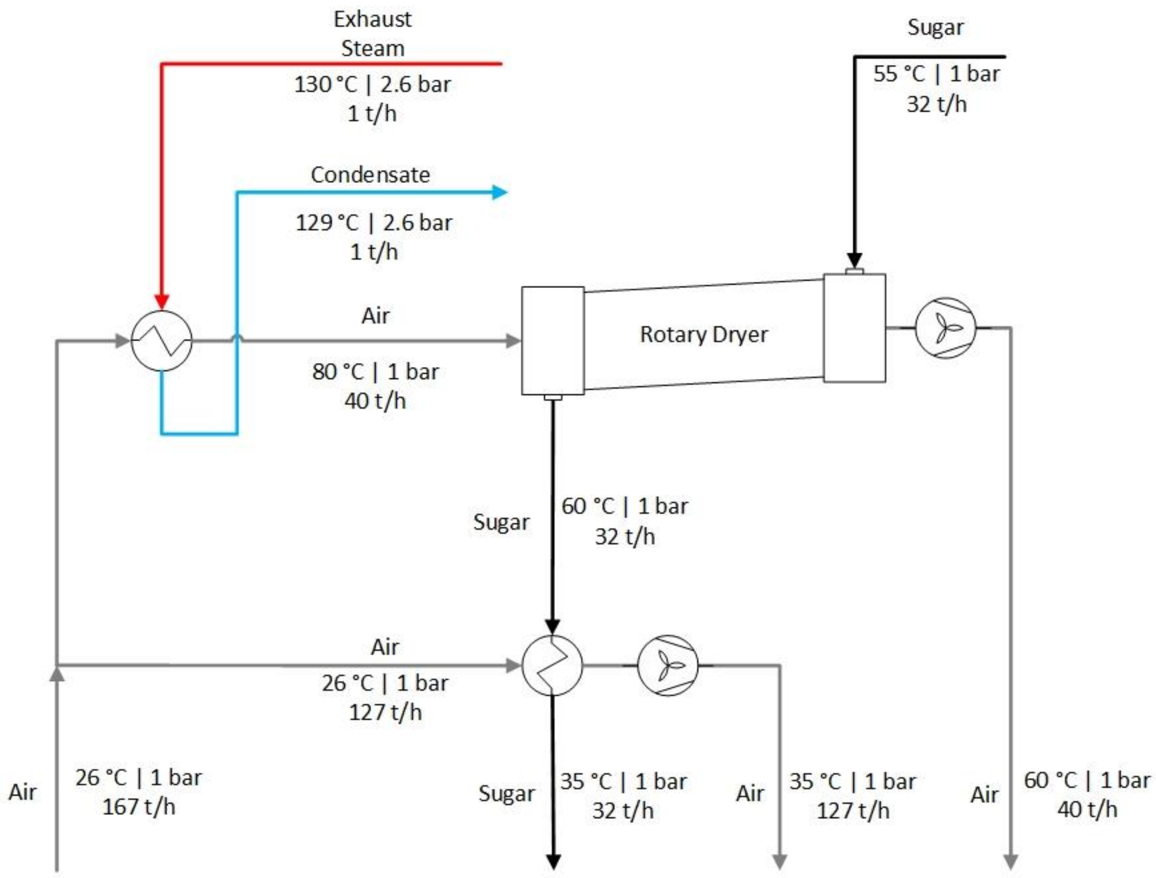

Figure 4-7: Drying (Based on Starzak & Zizhou, 2015)

After the sugar is dried, it is cooled by means of cool air. The raw sugar can be sold directly or refined at a refinery.

4.3 Heat Supply and Distribution Network

Sugar production is a relatively energy intensive industry and requires vast amounts of steam. In order to perform mechanical work, generate electricity and supply heat to the processes within the factory, high pressure steam, referred to as live steam, is produced by means of the incineration of bagasse. Figure 4-8 provides an overview of the heat supply and distribution network of a typical sugar mill.

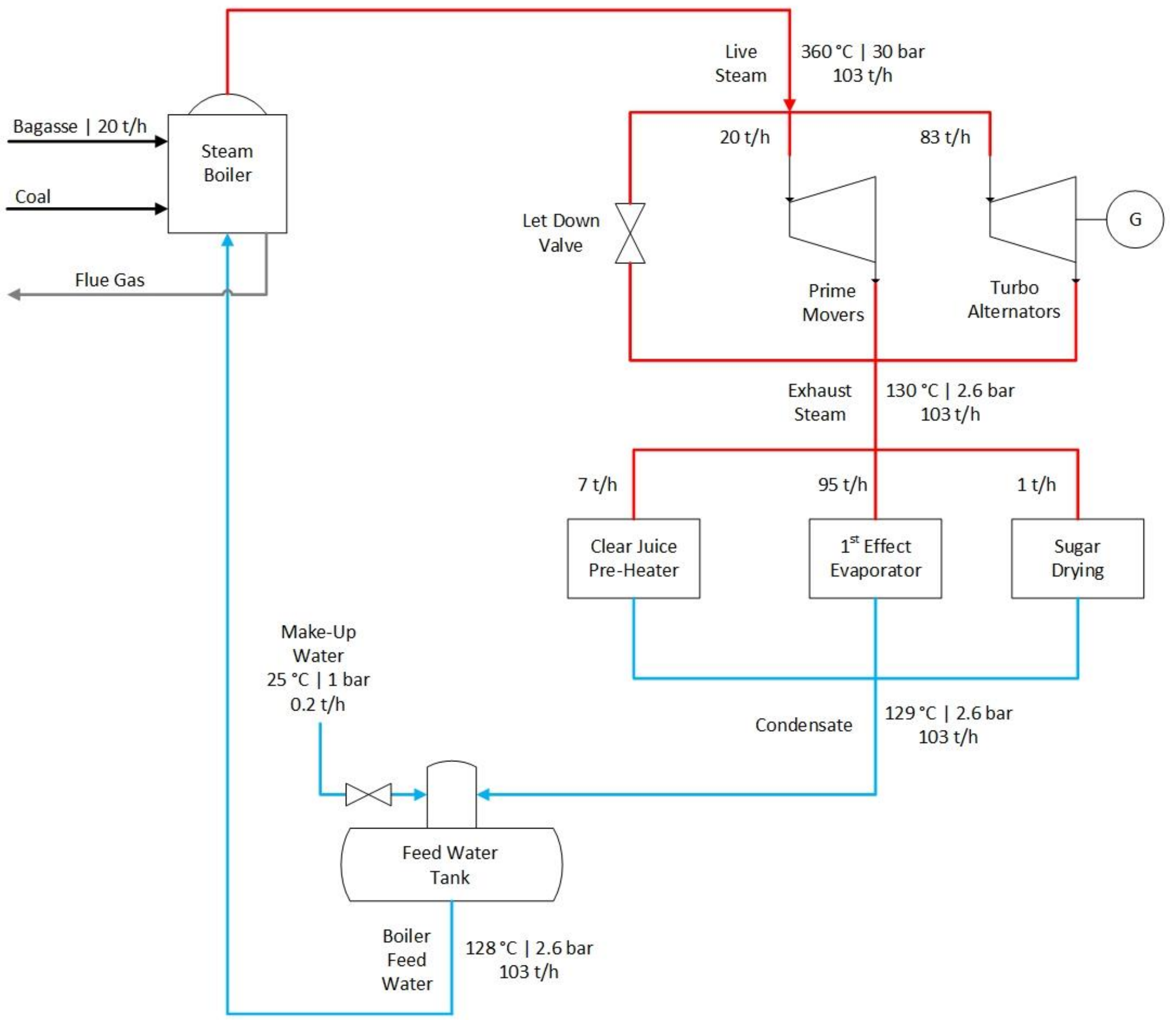

Figure 4-8: Heat Supply & Distribution Network

An overview of the steam balance of a generic raw sugar factory with a quadruple effect evaporator is provided in Addendum A. The steam balance is based on the output of the BRTEM model (Starzak & Zizhou, 2015).

Theoretically, a raw sugar factory should generate enough bagasse to be self-sufficient in terms of its energy requirements. However, coal is used as an auxiliary fuel to supplement the bagasse in most local factories. The average coal consumption in the South African sugar industry in the 2012/13 season was approximately 11 tonnes per 1 000 tonnes of sugarcane. However, in some factories, it was even as high as 32.5 tonnes coal per 1 000 tonnes of cane (Smith et al., 2013). Therefore, approximately 4 to 13 % of the thermal energy demand of the sugar milling industry is supplied by coal. The industry consumes roughly 200 000 tonnes or more of coal per season (Reid, 2006; Smith et al., 2013). Most of the factories that are consuming high amounts of coal, however, have an alternative use for bagasse or additional on-site energy demands, such a back-end refineries.

The steam consumption of a typical sugar mill is related to the average cane throughput. The estimated steam requirement is approximately 0.5 tonnes of steam for every tonne of sugarcane. High pressure superheated live steam, in the order of 400 °C and 30 bar, is produced to perform mechanical work and to generate electricity. In most cases, inefficient turbines are used and boilers are operated at efficiencies of about 65 % to balance the energy supply and demand of the factory in order to prevent the costly accumulation of surplus bagasse. The temperature of the boiler’s flue gas is in the range of 160 to 280 °C, depending on the presence of waste heat recovery equipment such as economisers and combustion air heaters (Rein, 2007).

The live steam is exhausted to approximately 130 °C and 2 bar in the turbo-alternators and the prime movers, consisting of the cane knives, shredders and press mills (Wienese & Purchase, 2004). The exhaust steam is used to provide process heat to the factory. Approximately 85 % of the exhaust steam is used to supply heat to the first evaporation effect. The balance thereof is used as heating medium for the clear juice preheater, the drying process and the deaerator.

If the exhaust steam is not sufficient to fulfil the process heat requirements of the factory, live steam is directly exhausted by means of a let-down and desuperheating station. According to Reid & Rein (1983), most South African factories have an exhaust steam shortage. In a typical factory, almost 30 % of the exhaust steam is exhausted directly from live steam (Rein, 2007). The exhaust steam is desuperheated and used to supply the bulk of the process heat required within the production process.

The exhaust steam condensate is returned to the boiler as feed water. According to Rein (2007), heat losses and steam leaks over all steam ranges within the factory result in an estimated average loss of approximately 3 %. The condensate is supplemented by fresh make-up water to account for the steam losses and blow-down. The deaerated feed water is supplied to the boiler.

The water vapour evaporated from the juice in each evaporation effect is reused as heating medium in the following effect at reduced pressure, while the partially concentrated product of each effect is the feedstock for the next effect (Singh & Heldman, 2001). The surplus vapour resulting from the first three effects is used to supply thermal energy for other processes within the factory. Most of the condensate from the last three evaporation effects is used as imbibition water in the diffuser, although a portion thereof is used as coolant in the crystallisation process.

The vapour from the first evaporation effect, V1, is primarily used as heating medium in the second effect, although some of it is bled for the boiling pans in the crystallization process and the tertiary heater in the clarification process. The bulk of the vapour resulting from the second evaporation effect, V2, is used as heating medium for the third effect. The rest is used to heat the mixed juice in the secondary heater as part of the clarification process.

Moreover, V3, the vapour of the third evaporation effect is employed to supply the thermal energy required in the fourth evaporation effect, the scalding juice heat exchangers within the diffuser and the primary heater in the clarification process.

Due to the low temperature and pressure of the vapour of the final effect, it is considered as waste heat. Waste heat, consisting of mostly of V4 and vapour from the boiling pans, in the order of 40 to 60 °C is cooled down in cooling towers to about 25 °C to supply cooling in the factory.

Although the bleeding of vapour is not indicated in Figure 4-8, the details thereof are provided in section 0 and Addendum A. There are multiple potential bleed vapour use arrangements for supplying process heat to the various processes. The description provided in this report is mostly based on the generic model provided by Starzak & Zizhou (2015).

4.4 Challenges and Innovation Opportunities

The South African sugar industry is exposed to various risks, such as environmental risks and currency fluctuation. Climatic conditions are also imposing risk on the sugar milling industry. One of the mills in South Africa was completely out of production during the 2011/12 as well as the 2015/16 season due to a drought and the resulting low crop estimate. The low rainfall experienced during this time also had a negative effect on the cane quality. The annual throughputs of the local sugar factories are declining rapidly, seeing that the annual amount of cane harvested has declined consistently over the past 10 seasons (Smith et al., 2013).

The profitability and economic sustainability of the South African sugar industry is, thus, under pressure, even though the operating efficiencies are relatively high. This phenomenon can be ascribed to the effect of the overproduction of some of the leading sugar-producing countries on the sugar price due to subsidies (SASA, 2013). Furthermore, the input costs of the mills, such as the cane price, have risen significantly over the past 10 years (DAFF, 2013). The average South African sugar production costs are significantly higher than in the USA, Brazil and Thailand (Tongaat Hulett, 2013).

In order to address these pressing issues, stakeholders in the sugar industry are exploring alternatives for sustaining the profitability of the industry and gain competitive advantage. The most noteworthy tactics towards this goal include the production of by-products and the cogeneration of electricity. Tongaat Hulett (2013), one of South Africa's major sugar enterprises, estimated the potential contribution of the local industry to renewable energy to be approximately 1 000 MW of electrical power and about 600 to 1 100 million litres of ethanol per year. However, this would require the installation of additional generation capacity or ethanol distilleries.

4.4.1 Bagasse By-Products

The sugar industry recognises the potential of by-products to increase the turnover of the industry and thereby improve profitability (Wienese & Purchase, 2004). Except for the production of steam in the factory, bagasse can be used for the production of a wide range of by-products. As the value of these by-products increase, the need to reduce the bagasse consumption of the factory intensifies. Bagasse can be used to produce products such as pulp and paper, animal feeds, as well as charcoal (Rein, 2007). Bagasse can also be used as a supplementary feedstock for the production of bio-ethanol.

By-products such as fuel-grade ethanol, are regarded as potential supplementary revenue streams for the sugar industry (Wienese & Purchase, 2004). Even though potable, pharmaceutical and industrial ethanol are already downstream products of the sugar industry, the production of fuel grade ethanol is also an opportunity on the horizon (SASA, 2013). This is already an established practice in some sugar-producing countries, such as Brazil (Ensinas et al., 2007a).

Ethanol can be produced from a variety of substrates such as sugar syrup, molasses and bagasse (Van Der Westhuizen, 2013). Most of the ethanol-producing sugar mills in Brazil use molasses as feedstock for the ethanol distilleries, although some use a portion of the cane juice at the expense of the mills' sugar production. In such a plant, the molasses and juice mixture are fermented and distilled to produce ethanol (Ensinas et al., 2007b). Bagasse can be transformed into bio-ethanol by means of acid hydrolysis, which produces approximately 186 kg per tonne of dry bagasse (Botha & Von Blottnitz, 2006).

The increase in demand for bagasse for the production of downstream products is a driver for the reduction of steam consumption within a sugar mill (Reid & Rein, 1983). As such, on-site sugar refining or by-products production increase the steam requirements of the plant.

4.4.2 Renewable Energy Co-Generation

Bagasse is the world's most abundant crop residue (Smithers, 2014). Many sugar factories worldwide use this residue to produce electricity. By 2012, India already had a total capacity of approximately 5 GW_e of bagasse-fuelled power stations (Tongaat Hulett, 2013). It is also the case that approximately 90 % of the sugar factories in Mauritius produce electricity for the grid (Smithers, 2014).

According to Botha & Von Blottnitz (2006) a typical utility plant in a South African mill converts approximately 30 % of the fuel energy to electricity. Thus, the total installed electrical capacity of the local milling industry is estimated to be approximately 240 MW (Wienese & Purchase, 2004).

Stakeholders in the South African sugar industry are aware of the potential contribution that the industry can make to relieve the pressure on the electrical grid, ensure energy security and contribute to the government's objectives regarding renewable energy (SASA, 2013). By improving the operating efficiency within the plants, the sugar mills would be able to sell surplus electricity to Eskom, the national energy provider. A study conducted by Conningarth Economists (2013) also concluded that the generation of electricity from bagasse is profitable in the South African context and should be considered by the industry as a feasible additional income stream.

Cogeneration is a term used for the concurrent generation of electricity and useful heat. According to Saha (1998), bagasse is one of the cheapest fuels for the generation of cogenerated electricity.

The South African Department of Energy is planning to launch a cogeneration bidding process to procure a total capacity of 1.8 GW_e. Illovo and Tongaat Hulett, two of the major stakeholders in South Africa's sugar industry, both regard the production of renewable energy as a strategic opportunity for sugar mills to diversify their sources of income (Creamer, 2015; Hancock, 2015).

The South African Department of Energy's Independent Power Producers (IPP) Projects Office issued a request for bids (RFB) for cogeneration projects under the Cogeneration Independent Power Producers Procurement Programme (IPPPP) in June 2015. The programme caters for a maximum of 800 MW in the first bidding round, which might be increased in the future. This program allows three distinct cogeneration technologies and allocated approximately 25% of the capacity towards combined heat and power projects, 31% to waste-to-energy projects and the balance of 44% to industrial biomass projects. Priority will be ascribed to projects where energy output can be augmented by upgrading existing equipment or improving operating efficiencies.

Additionally, the Department indicated that the maximum selling price of electricity under this programme varies between R0.90/kWh_e and R1.20/kWh_e, depending on the technology. A premium has been assigned to energy produced during peak hours (Norton Rose Fulbright, 2015). Since bagasse is a by-product of the sugar production process, sugar factories are able to sell surplus electricity to the grid operator at a price of up to R 1.20 /kWh_e (Department of Energy, 2015).

Although most sugar factories are geared to produce cogenerated heat and electricity for own use, many authors have investigated alternative boiler and turbine configurations to maximise the potential of exporting surplus electricity to the grid. Most existing factories are equipped with backpressure steam turbines (BPST). Some authors, such as Saha (1998) and Pellegrini & de Oliveira Junior (2011), propose the use of condensing extraction steam turbines (CEST) to enhance the facility's electricity output. This configuration enables the factory to extract steam at the appropriate pressure and temperature and allows for the production of electricity during off-season periods, since superfluous steam is condensed. Other configurations, such as supercritical steam systems (SuSC) or biomass integrated gasification combined cycles (BIGCC) can also be considered (Pellegrini & de Oliveira Junior, 2011).

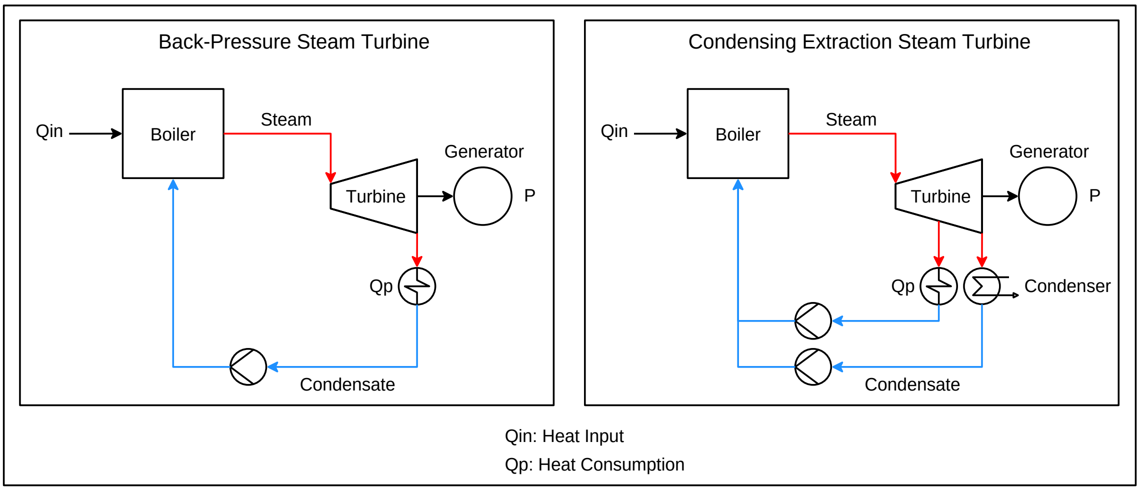

Figure 4-9: Steam Turbine Configurations (Adapted from Paula, 2002)

By 2014, at least three of the South African sugar factories had already been involved in cogeneration for electricity export (Smithers, 2014). Smithers (2014) estimated that the South African sugar industry could potentially produce a total of 600 MW of electricity by 2016, accounting for approximately 1.5 % of the country's total generating capacity. This would, however, require significant investment for the additional generating capacity.

4.5 Solar Resource

The solar resource associated with the sugar producing regions in South Africa refers to the sum of solar irradiation available throughout the year for the production of solar process heat. The solar irradiance primarily comprises of two portions, namely beam and diffuse irradiance. Beam irradiance can be defined as the radiation received directly from the sun. Diffuse irradiance consists of radiation that has been scattered or reflected by particles or objects in the atmosphere. Global horizontal irradiance (GHI) is the sum of diffuse and beam irradiance on a horizontal surface. Direct normal irradiance (DNI) is the radiation received by a surface that is always perpendicular to the sun's incoming rays (3TIER, 2015).

While non-concentrating solar thermal collectors, such as FPC and ETC, can convert beam and diffuse irradiation into heat, concentrating collectors, such as PTC and LFR, can only make use of beam irradiance (Fernández-García et al., 2010). Figure 4-10 provides a graphical representation of the annual sum of the global horizontal and direct normal irradiation in KwaZulu-Natal, the major sugar producing region in South Africa. The GHI in this region ranges from approximately 1 500 to about 2 000 kWh_{th}/m^2, while the DNI varies between 1 250 and 2 000 kWh_{th}/m^2. The difference can be attributed to the significant portion of diffuse irradiation that characterises the solar irradiation of the area.

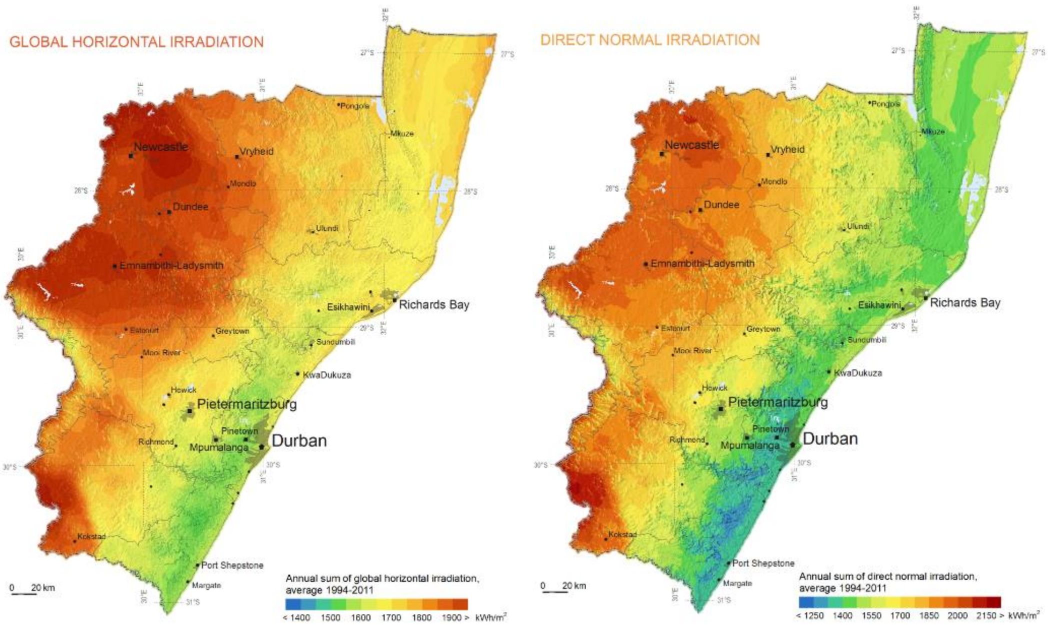

Figure 4-10: Solar Resource Map of KwaZulu-Natal (SolarGIS, 2012)

The solar resource is similar to that of the sugar producing regions in Brazil and India (SolarGIS, 2015). The annual sum of GHI in Durban is approximately 1 825 kWh/m^2, while the DNI is about 2020 kWh/m^2 (PVGIS, 2012). The monthly sum of global horizontal irradiation for Durban is illustrated in Figure 4-11, which also illustrates the relationship between beam and diffuse irradiance. Diffuse irradiance contributes approximately 34 % to the annual global irradiance in Durban.

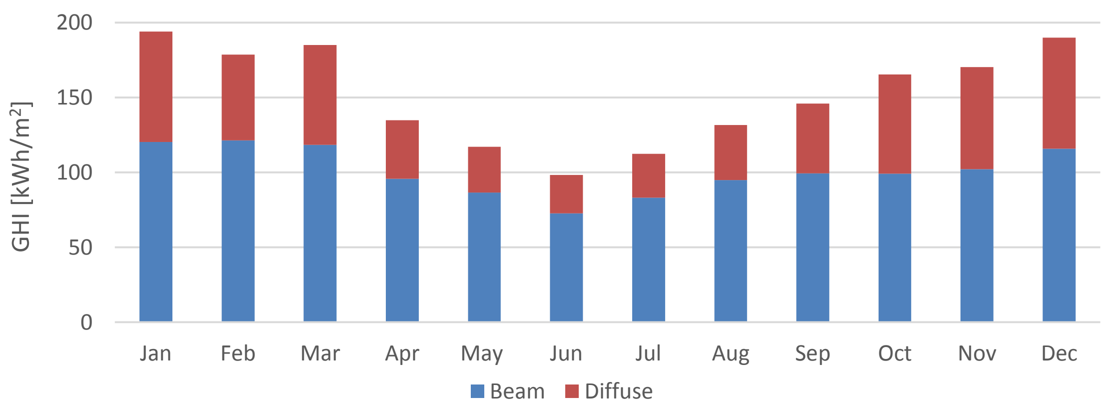

Figure 4-11: Global Horizontal Beam and Diffuse Irradiation of Durban (Based on values from PVGIS, 2012)

Although Durban has been selected as the point of reference for the yield assessments in this study, the correlation between the GHI of Durban and that of Dalton, Felixton and Malelane is illustrated in Figure 4-12. Dalton, Felixton and Malelane are representative of the three sugar-producing regions in

South Africa, namely the KwaZulu-Natal Coastal region, the KwaZulu-Natal Midlands and Mpumalanga.

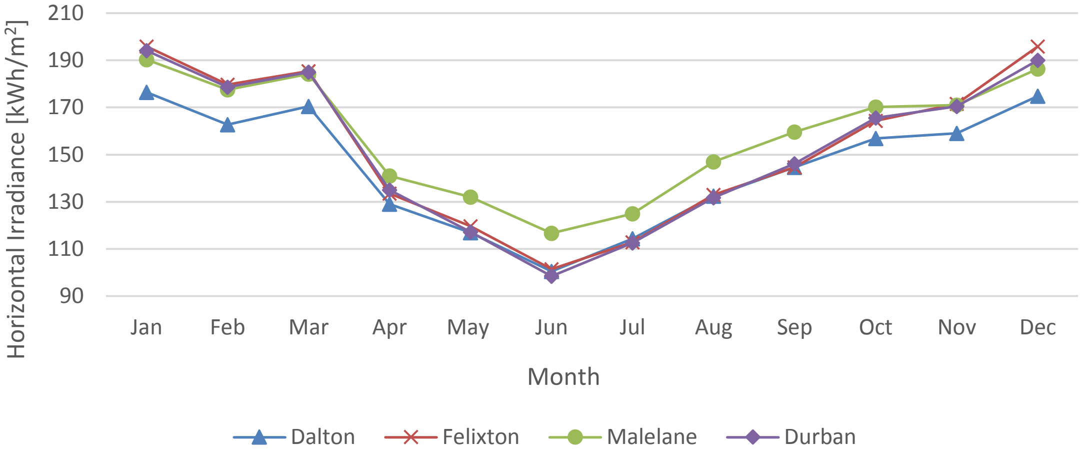

Figure 4-12: Global Horizontal Irradiance (Based on values from PVGIS, 2012)

The monthly sum of the global irradiance on a tilted plane at an angle of 30 ° at the various locations are also provided in Figure 4-13. The irradiance on a tilted plane is more or less constant throughout the year.

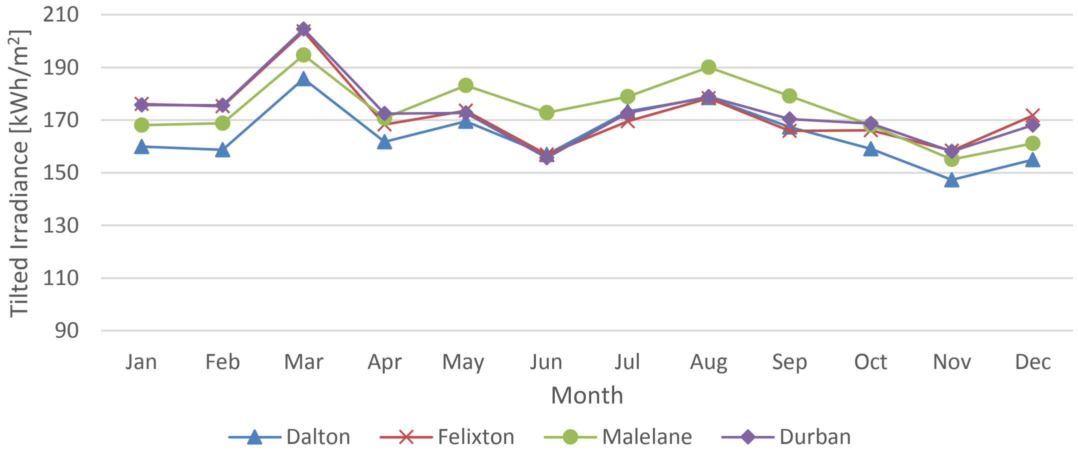

Figure 4-13: Global Irradiance on a Plane at a Tilt Angle of 30 ° (Based on values from PVGIS, 2012)

It is evident, from the above figures, that the annual global irradiance associated with the respective sugar-producing areas is relatively equal. Although the solar resource associated with the sugar production regions is not as high as other parts of South Africa, it is still relatively high in relation to other countries, such as Germany and other European countries, which have adopted solar thermal technology.

5. Potential Solar Heat Integration Points

Most of the processes associated with the production of raw sugar require substantial quantities of thermal energy. The heat requirements for the evaporation and juice heating processes are supplied by means of exhaust steam from the turbines, while the heat for the pan floors and diffusers are generally provided with bleed vapour from the multi-effect evaporator. Each heat sink and input stream within the supply- and process-level of this heat distribution network is considered a potential integration point for solar process heat. The suitability of each of these integration points is considered according to the demand, schedule and technology as prescribed by the IEA's guideline for solar heat integration. The demand data is sourced from the SMRI's BRTEM model, which is based on a throughput of 250 tonnes of cane per hour.

5.1 Assessment of Integration Points

Each heat sink and input stream has been considered a potential integration point for solar heat. These integration points have been assessed as a first order according to some of the most applicable integration assessment criteria[8]. The IP's have been evaluated according to the benefit in terms of the conservation of the heating medium or fuel. Therefore, IP's conserving bagasse or coal have been prioritised over those offsetting bleeding vapour.

The inlet or process return temperature of the process medium of each IP is also considered. A lower process temperature is beneficial towards the integration of SPH. The final temperature and resultant temperature lift are also considered as important criteria, since the contribution of solar heat is more significant for process with a high temperature lift. Considering the efficiency curve of a solar thermal collector, the integration of solar heat into processes with a low return temperature and a high temperature lift is expected to attain higher annual yields.

Additionally, the mean thermal load is used to pre-dimension the solar field size of the proposed integration concepts. The thermal load of the integration points are based on the BRTEM model provided by the SMRI (Starzak & Zizhou, 2015).

The annual heat demand of the process determines the potential impact of solar heat integration, considering that SPH is expected to be more beneficial for processes with a high demand for thermal energy. Thus, the annual heat demand is the product of the mean thermal load and the annual operating hours associated with each of the processes. The average annual operating time of a South African sugar mill is approximately 4 615 hours per year, based on an average season length of 254 days and an OTE of 75.7 %. This particular operation time has been applied to all of the integration points to approximate the heat demand of the processes. Although not all of the processes are

[8] See Chapter 3, Section 3.3 and Table 3-3.

continuous in reality, this provides a good estimation of the extent of the heat demand for the preliminary calculations of this study.

The potential integration concept for each IP has also been considered[9], although this does not have a significant impact on the feasibility of the integration opportunity. Some of the most relevant characteristics of the integration points are tabulated in Addendum B.

5.2 Supply-Level Integration Opportunities

5.2.1 Live Steam Generation

Superheated live steam is produced by the combustion of bagasse and coal, and is used for mechanical work and electricity generation. The cane knives, shredders and bagasse mills within the juice extraction unit are often referred to as the prime movers. These prime movers consume high-pressure live steam for the mechanical work, although the prime movers are electrically driven in some of the more energy efficient mills.

A kilogram of bagasse can produce approximately 2 kWh_{th} of heat, whilst 3 to 5 kilograms are required for the generation of 1 kWh_{th} of electricity (Bhattacharyya & Thang, 2004; Mashoko, Mbohwa & Thomas, 2013). Due to the efficiencies associated with typical sugar factories, the energy content per tonne of coal is roughly equivalent to 4 tonnes of bagasse (Smith et al., 2013). Therefore, it is assumed that coal can produce approximately 8 kWh_{th} of thermal energy per kilogram.

A typical sugar factory requires about 40 to 60 tonnes of steam for every 100 tonnes of cane. Although the fuel consumption of the boiler is dependent on the boiler's efficiency and the calorific value of the fuel, a bagasse boiler typically consumes about 0.4 to 0.5 tonnes of bagasse to produce a ton of steam at 400 °C and 30 bar (Rein, 2007). As mentioned in Chapter 0, some local sugar factories consume vast amounts of coal to meet the steam requirements of the plant.

Solar thermal technology can be applied to support the boiler in the production of live steam in order to reduce the consumption of bagasse and coal. Therefore, the integration concept can be classified as indirect production of steam in parallel with the existing steam generation plant. Every tonne of solar generated live steam has the potential to offset approximately 0.5 tonnes of bagasse or about 0.125 tonnes of coal (Smith et al., 2013).

The injection of solar generated live steam may also assist in the generation of electricity in a factory that exports electricity generated by means of a pass-out condensing cogeneration turbine. In this case, the introduction of solar steam is expected to increase the annual electricity production of the cogeneration plant.

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[9] Based on Table 3-2.

In order to produce live steam, a solar thermal system would be required to raise the temperature of the feed water from approximately 130 °C to about 360 °C. Although the temperature lift of more than 200 °C is favourable towards solar integration, the high inlet temperature is expected to result in a relatively inefficient solar thermal system. The mean load of the boiler, which is equivalent to the total power demand of the factory, is approximately 74 MW_{th} and the annual heat demand is about 340 000 MWh. The factory, therefore, requires approximately 100 tonnes of steam per hour of operation at a throughput of 250 tonnes of cane per hour. Most South African sugar factories actually require more steam per tonne cane, due to the lack of energy efficiency.

5.2.2 Boiler Feed Water Preheating

The feed water introduced to the boiler for the production of live steam primarily consists of condensate returned from the first evaporation effect, the clear juice preheater and the drying process. The condensate is supplemented to a small degree by make-up water. The feed water is deaerated in the feed water tank before it is introduced to the boiler. The final temperature of the feed water is in the order of 105 to 130 °C (Foxon, 2015b).

The potential for solar assistance in the preheating of boiler feed water and combustion air has been investigated as early as the 1970's (Zoschak & Wu, 1975). Such a solar thermal system would be able to save fuel by heating the feed water to about 240 °C. Although the optimal temperature of the feed water is the temperature of the steam drum, it is usually not heated to more than 250 °C (Pierce, 2013).

Approximately 66 % of the boilers installed in the South African sugar factories are equipped with economisers, which typically raises the temperature of the feed water from approximately 105 °C to about 150 to 180 °C with flue gas (Rein, 2007; Foxon, 2015b). This intervention should enjoy preference over the adoption of solar thermal process heat, since it is a cheaper solution.

Solar thermal collectors can, however, be used in conjunction with the economiser to increase the temperature of the feed water from approximately 150 to 250 °C. Based on the values provided by Starzak & Zizhou (2015), an average thermal capacity of about 14 MW_{th}, or 65 000 MWh per year, would be required to heat the boiler feed water from 130 to 240 °C.

5.2.3 Make-Up Water Preheating

Make-up water is added to the exhaust steam condensate as boiler feed water to compensate for the losses within the return flow loop. The low temperature, of about ambient, of the make-up water results in a decrease in feed water temperature. The feed water is heated with exhaust steam to boiling point in the feed water tank to facilitate deaeration. The preheating of make-up water is, therefore, expected to result in a decrease of exhaust steam consumption. Rein (2007) states that typical deaerators consume about 2 tonnes of exhaust steam per 100 tonnes of feed water, depending on the temperature of the feed water in the feed water tank.

Therefore, exhaust steam consumption can be reduced by preheating the make-up water from ambient to between 100 and 130 °C with a solar thermal system. However, since the make-up water accounts for less than 0.5% of the boiler feed water, the contribution thereof is expected to be fairly insignificant, especially considering that the make-up water can be preheated by means of waste heat recovery.

5.2.4 Combustion Air Preheating

The combustion air can be preheated by means of air collectors. According to Kakaç (1991), the maximum temperature of the combustion air is dependent on the fuel type and typically ranges between 200 and 400 °C. However, the combustion air is heated in most local sugar mills by means of waste recovery from the flue gas exhaust of the boilers. According to Foxon (2015b), all of the boilers installed in South African sugar factories are equipped with flue gas air heaters that preheat the air from ambient to a maximum of 260 °C. Thus, since all of the boilers in the local industry recover waste heat to preheat the combustion air, the adoption of solar thermal technology for this purpose does not seem to be a viable alternative.

5.2.5 Bagasse Drying

The typical moisture content of the 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). The bagasse is used to raise steam in the boilers and is supplemented with coal. Various authors, such as Smithers (2014), highlight the moisture content of bagasse as one of the primary bottlenecks of energy generation, since the moisture content affects the calorific value of the bagasse. Alena & Sahu (2013) also emphasise the impact of bagasse drying on the potential for electricity production, owing to its influence on the performance of the boiler. According to Rein (2007), bagasse drying increases the boiler efficiency and flame temperature and reduces the additional air requirements of the boiler. Therefore, the moisture content has a significant impact on the fuel consumption and output of the boiler. The advantages of bagasse drying include improved boiler efficiency, reduced fuel consumption, higher flame temperature and reduced excess air requirements. The greatest rewards for the sugar industry include reduced coal consumption or higher potential for cogeneration of electricity.

The higher heating value, or gross calorific value (GCV), of bagasse is dependent on its moisture content (M), ash content (A) and Brix (B), as shown in Equation 5-1. The typical ash and brix content in South Africa is approximately 3.15 % and 1.19 % respectively (Smith et al., 2013).

$$GCV = 19\,605 - 196.05 \cdot M - 196.05 \cdot A - 31.14 \cdot B \;\; [kJ.kg^{-1}] \qquad \text{5-1}$$

The effect of the moisture content of bagasse on its energy content is illustrated in Figure 5-1. The GCV can be increased by approximately 20 % by means of reducing the moisture content of the bagasse from 50 to 40 %.

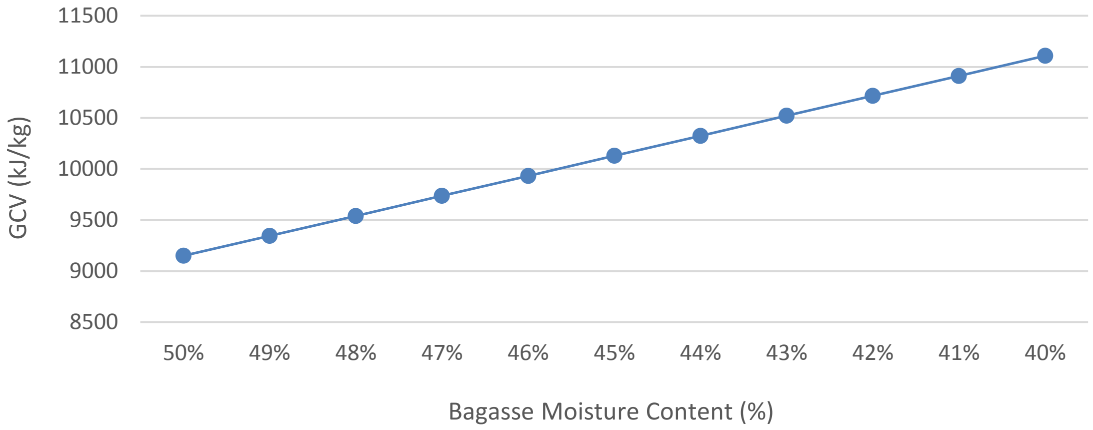

Figure 5-1: Gross Calorific Value of Bagasse

Rein (2007) 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 of the bagasse should not be reduced to less than 40 %, due to the risk of spontaneous combustion.

The efficiency of a bagasse boiler is in the order of 65 % based on the GCV (John Thompson, n.d.). Most of the boilers in the industry have been designed to be inefficient to avoid the accumulation of bagasse. The fuel consumption of the boiler can be reduced significantly by reducing the moisture content. Figure 5-2 illustrates the potential reduction in boiler fuel consumption by reducing the moisture content of the bagasse based on a boiler efficiency of 65 % on GCV.

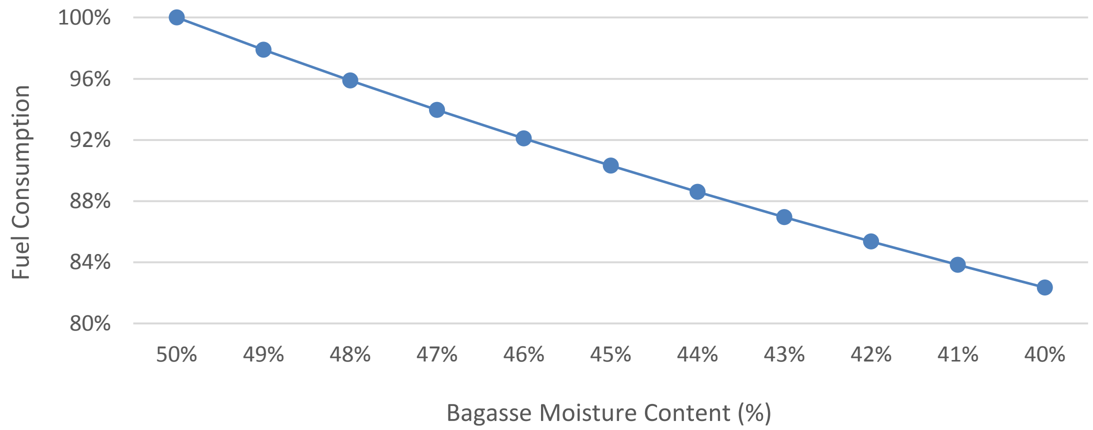

Figure 5-2: Boiler Fuel Consumption Related to Bagasse Moisture Content

Conventional bagasse dryers, especially rotary drum or pneumatic flash dryers, have been installed in various other sugar producing countries such as Brazil, India and the USA. These dryers usually make use of boiler flue gas to dry the bagasse. In South Africa, however, bagasse drying is not a common practice.

Solar thermal process heat can assist the drying of bagasse by heating the input stream of air for the drying process. In order to reduce the moisture content of the bagasse from 50 to 40 % at a mass flow rate of 20 tonnes per hour, the dryer should be designed to accommodate the evaporation of at least 2 tonnes of water per hour. According to the characteristics of bagasse dryers, as shown in Table 5-1, approximately 6 GJ/h of thermal energy would be required to achieve such an evaporation rate. Therefore, the mean load of the dryer would be about 1.67 MW_{th} to heat the air from ambient to approximately 200 °C. The annual heat demand of the dryer is expected to be in the order of 8 000 MWh.

Table 5-1: Bagasse Dryer Characteristics (Based on Bruce & Sinclair, 1996)

Dryer Type	Evaporative Capacity [t/h]	Operating Temperature [°C]	Thermal Requirements [GJ/t_{evap}]
Rotary Type	3 – 23	120 – 320	3 – 4
Cascade Type	2 – 41	120 – 320	2.7
Flash Type	5 – 17	200 – 400	2.7 – 2.8

Although the drying of bagasse would be advantageous to the sugar industry, it is expected to be a costly retrofit since no South African raw sugar factories are currently equipped with bagasse dryers. The solar thermal system will not be able to supply 100 % of the energy required for the drying process and it would have to be supplemented by flue gas or steam. According to Rein (2007), the use of flue gas for bagasse drying is more beneficial than feed water preheating. Solar thermal technology is, therefore, expected to compete against waste heat recovery for the heating of bagasse.

5.2.6 Exhaust Steam Production

The total thermal energy demand of a typical raw sugar factory is satisfied by exhaust steam from the turbo alternator, prime movers and let-down station. The theoretical demand for exhaust steam in a factory operating at 250 tonnes of cane per hour, is approximately 103 tonnes per hour at 130 °C and 2.6 bar, based on the model provided by Starzak & Zizhou (2015). In most cases, the realistic steam consumption is even higher. Approximately 85 % or more of the exhaust steam is dedicated to evaporation in the first effect. The balance is used to preheat the clear juice before the evaporation unit and for sugar drying. The cumulative thermal load of these processes is approximately 63 MW_{th}, or almost 290 000 MWh per season. The condensate of these closed-loop processes is recycled to the boiler as feed water.

The adoption of solar thermal technology for the indirect production of exhaust steam in parallel with the conventional system is expected to be particularly feasible due to the relatively low temperature of the steam. The boiler feed water is close to the exhaust steam temperature and the solar thermal system would only be required to provide the energy required for evaporation with an expected temperature lift of 2 °C.

There are various scenarios to justify or promote the reduction of exhaust steam consumption in a raw sugar factory. At some of the local factories, a significant amount of the exhaust steam demand is met by expanding live steam directly. Therefore, a reduction in exhaust steam demand is expected to have a direct impact on the bagasse and coal consumption of the boiler if the let-down is reduced. However, the benefit of exhaust steam reduction would be maximised in a factory that generates electricity for export in a pass-out condensing turbine configuration. This is because such an intervention is expected to increase the annual electricity production. By reducing the exhaust steam consumption of the factory, up to 80 kWh_e/tc of surplus electricity can be generated for export (Pellegrini & de Oliveira Junior, 2011).

5.3 Process-Level Integration Opportunities

5.3.1 Diffuser

Diffusers normally operate at temperature of more than 80 °C throughout the diffuser to maximise the extraction of sucrose (Reid & Rein, 1983). Due to the significant heat losses within the diffuser, the juice is only heated from ambient temperature to approximately 60 to 65 °C by the diffusion process.

Maintaining a constant temperature of about 80 °C within the diffuser requires direct injection of vapour from the second evaporation effect (V2) unto the diffuser bed. Approximately 4 tonnes of V2 at 111 °C is injected to the diffuser on an hourly basis to account for the mean thermal demand of approximately 3 MW_{th}. This amounts to an annual demand of almost 14 000 MWh for an average throughput of 250 tonnes cane per hour.

Although solar thermal technology can be applied for supplying low pressure steam so as to maintain the temperature of the diffuser, this intervention would offset the consumption of bleed vapour from the second evaporation effect (V2). Since the multiple-effect evaporation concept is fairly energy efficient and designed according to the evaporation and throughput requirements of the factory, the reduction of bleed vapour consumption by means of solar thermal process heat is not regarded as a feasible solution. A reduction in vapour bleeding is expected to have a negative impact on the throughput of the evaporation process. The value of bleeding vapour, especially the value of V2 and V3, is then considered as insignificant. Thus, the production of solar-generated V2 is not considered as feasible.

5.3.2 Scalding Juice Heaters

The extraction of sucrose is aided by heating the scalding juice at the cane entry side of the diffuser often to temperatures close to 100°C (Munsamy, 2008). The scalding juice is heated through heat exchangers with vapour from the third evaporation effect (V3). These heat exchangers supply most of the heat requirements within the diffuser (Reid & Rein, 1983).

The scalding juice heat exchangers consume 9 t/h of V3, which is supplied at approximately 96 °C. The mean load of the heat exchangers is 6 MW_{th} and the annual heat demand is in the order of 28 000 MWh.

Solar thermal process heat can be used to heat the process medium within external heat exchangers of the diffuser. This is not regarded, however, as a feasible option since it would offset the consumption of V3, which is a waste heat stream.

5.3.3 Imbibition Water

Condensate from the last effect of the evaporation unit is reintroduced to the diffuser as imbibition water to aid the extraction process. The temperature of the imbibition water is normally 50 to 60 °C and the flow rate is in the order of 110 t/h.

Solar thermal integration can be considered to heat the input stream of imbibition water from 50 to 80 °C. However, there is no existing heat exchanger to heat the imbibition water and this intervention is expected to save only V2 and V3. In view of this, the intervention is not justifiable.

5.3.4 Press Water Heater

The bagasse exiting the diffuser is pressed in roller mills to reduce the moisture content and extract the maximum amount of sucrose. Approximately 230 tonnes of press water is heated per hour from 70 °C to approximately 80 °C with vapour bled from the second evaporation effect (V2) before it is reintroduced to the diffuser.

The press water heaters' mean load is about 2 MW_{th} and consumes approximately 9 000 MWh of V2 per annum. The mass flow rate of the V2 is about 3 t/h at a temperature of nearly 110 °C through the heat exchanger.

Although the low process return temperature and the temperature lift of 10 to 20 °C is favourable towards the integration of solar thermal process heat, it is not feasible to reduce the V2 used for heating the input stream.

5.3.5 *Mixed Juice Heating Train*

Before clarification, the mixed juice is heated by means of a series of heat exchangers from 65 °C to 75°C, 95°C and 105°C. The juice is not sensitive to temperature, as long as it is heated to more than 100 °C before it is flashed to 100 °C prior to the clarifier. The mixed juice, flowing at approximately 330 t/h, is heated in the primary heat exchanger from about 65 to 75 °C by means of V3, at about 96 °C and flowing at roughly 6 t/h. The secondary heat exchanger consumes V2 to heat the juice from 75 to 95 °C. The juice is heated to about 105 °C in the tertiary heater with V1.

The primary and tertiary heaters' mean thermal load is 4 MW_{th} each, consuming roughly 18 500 MWh per season. The mean load of the secondary heater is about 8 MW_{th} and requires more than 35 000 MWh per year.

Although V1 is not considered as particularly valuable, it is considered as more valuable than V2 and V3, since it is a higher grade steam. Therefore, it might be worthy to investigate the potential for solar heat integration at the tertiary heater, although it should not be regarded as a high priority integration point. The primary and secondary heaters can be disregarded as solar integration points.

Therefore, a solar thermal system can be used to supply a portion of the tertiary heater's demand of 4 MW_{th} in order to heat the juice from 95 to 105 °C, even though the relatively low temperature lift of 10 °C is not necessarily favourable towards solar integration.

5.3.6 *Lime Milk*

Before clarification, lime milk and other chemicals are added to the mixed juice to aid the purification process. This mixture of chemicals can be preheated from ambient to approximately 100 °C, in order to reduce the load of the secondary and tertiary heaters. Although the low process return temperature and high temperature lift is susceptible for solar heat integration, the flow rate of the lime milk is relatively low compared to that of the mixed juice. The contribution thereof is therefore expected to be very low.

5.3.7 *Clear Juice Heater & Evaporation Train*

Before the clear juice is concentrated to 65 % Brix in the multi-effect evaporators, it is normally preheated with exhaust steam from 100 °C to slightly more than 110 °C. The flow rate of the clear juice is almost 290 t/h. Roughly 7 t/h of exhaust steam at 130 °C is used to add the temperature difference. The heat exchanger's mean load is about 4 MW_{th} to supply the 18 500 MWh per annum.

Most of the exhaust steam in the factory is condensed in the first effect of the evaporation process. Exhaust steam is used to evaporate the clear juice in the first effect. Thereafter, the vapour of each effect is used as heating medium in the successive effect. The surplus vapour of the first three effects is also used as heating medium in most of the other processes within the factory.

The first effect of the evaporator has a mean load of approximately 58 MW_{th} and consumes about 270 000 MWh of heat during a season. Approximately 95 t/h of exhaust steam is required to attain the evaporation rate.

The clear juice heater and the first effect of the evaporation train can be assisted with solar heat. The parallel production of solar generated exhaust steam has already been under scrutiny in this section.

The thermal load of the second, third and fourth effects are estimated to be approximately 34, 25 and 20 MW_{th} respectively, which accounts for almost 365 000 MWh per year. This energy demand is supplied in the form of V1, V2 and V3. The system is designed to cater for a certain evaporation rate, temperature, pressure and amount of vapour bleeding of each effect. A reduction in the demand for bleed vapour is not expected to have a positive impact on the exhaust steam, live steam or boiler fuel consumption and is therefore regarded as a fruitless endeavour.

5.3.8 Boiling House

The syrup is further concentrated in batch boiling pans in the boiling house. In a VHP[10] boiling house configuration, most of the boiling occurs in the "A" pan. The "A" pan, therefore, has the highest heat load. Nearly 72 t/h of syrup is boiled in the "A" pan at 67 °C and 0.179 bar. An estimated 18 t/h of massecuite is boiled in the "B" pan and 14 t/h in the "C" pan at 67 °C at 0.119 and 0.04 bar, respectively. The 16 MW_{th} required for the boiling operation is supplied by bleed vapour from the first evaporation effect (V1). The boiling house consumes an estimated 74 000 MWh per season.

The low boiling temperature of the syrup is favourable for solar heat integration. However, the heat is supplied by low grade steam and solar integration is disregarded as a feasible substitute.

The potential for the preheating of syrup has been investigated. However, the technical upper limit of the syrup temperature is 60 °C, since a heat difference of 45 to 50 °C between the massecuite and the heating medium is required in unstirred boiling pans and the temperature of the V1 is approximately 110 °C (Rein, 2007). Therefore, the sensible temperature lift is only 1 °C and the contribution of solar heat is expected to be insignificant.

5.3.9 Remelter

The purpose of the remelter is to dissolve a portion of the "B" and all "C" sugar with the aim of reintroducing the solution to the "A" pan as footing. To assist the dissolution, the solution of water and sugar is heated by means of the direct injection of V3. The average thermal load of the remelter is about 25 kW_{th} while the annual heating requirement is 115 MWh. This is fairly insignificant compared to the total energy consumption of the factory.

[10] Very High Pol

5.3.10 Raw Sugar Drying

Reducing the moisture content of the final raw sugar requires that most sugar mills employ rotary drum air dryers. This is a continuous process in which the sugar pass through the rotating drum counter to the direction of the air flow (Savaresi, Bitmead & Peirce, 2001). The sugar is heated with air from approximately 55°C to about 60°C. The air is heated from ambient to 80 °C by means of exhaust steam, although some mills use lower grade steam.

Approximately 40 tonnes of air is used to dry the 32 tonnes of sugar per hour. The mean load of the air heater is about 0.6 MW_{th} and the annual heat demand of 2 800 MWh consumes roughly 1 tonne of exhaust steam per hour.

In order to reduce the demand for exhaust steam, the input stream of air can be preheated with solar heat. The relatively low process return temperature is inclined towards solar heat integration. Furthermore, the high temperature lift of more than 50 °C improves the feasibility of solar heat integration.

This integration point seems as a particularly favourable option. However, there is an opportunity for waste heat recovery that is expected to supersede the potential for solar integration. Although it is not implemented in most factories, the wet air leaving the dryer at approximately 60 °C or other waste heat streams can be used to preheat the incoming dry air. However, there would still be a potential for solar heat integration to heat the dry air from a maximum of 60 to 80 °C.

5.4 Apparent Integration Potential

If viewed individually, most of the processes associated with the production of raw sugar can be regarded as favourable towards the integration of solar thermal process heat. Most of the processes are characterised by process temperatures below 100 °C and the heat consumption of these processes are relatively high and constant relative to the throughput. However, the processes are interlinked in a delicately balanced heat distribution network with very little waste heat. The available waste heat is below 60 °C and cannot be used for heating purposes within the factory except for the preheating of drying air. The apparent energy efficiency of modern raw sugar factories is regarded as one of the primary obstacles for solar thermal integration due to the recycling of waste heat. Most of the heat requirements within a sugar mill are satisfied with steam or vapour that already performed work in previous processes. Therefore, the offsetting of lower grade steam will not necessarily reduce the fuel consumption of the boiler. In order to maximise the contribution of solar thermal process heat, it should be integrated at the highest possible level of heat supply.

Although solar industrial process heat can be successfully integrated into most of the processes within the production plant, only a few of these interventions would have a significantly beneficial impact.

The production of live steam would significantly reduce the coal and bagasse consumption of the boiler or increase the electricity output of the turbo-alternator. The preheating of boiler feed water and the drying of bagasse are also expected to have a positive impact on the efficiency of the boiler and the fuel consumption. Furthermore, the production of exhaust steam can be regarded as a potential intervention, since it might reduce the let-down requirements or increase the electricity output of a condensing turbine. The preheating of air for the sugar drying process is also an alternative to reduce the demand for exhaust steam, although it is not expected to have a significant impact on the energy consumption of the factory in total. Although it is not expected to have a particularly significant impact on the process, the heating of mixed juice in the tertiary heat exchanger may also be considered as a potentially feasible integration point, since it consumes the highest grade of bleed vapour. The potentially significant integration points are listed in Table 5-2.

IP	Heat Sink	Process Medium	Mass Flow [t/h]	Fuel Offset	Inlet Temp [°C]	Final Temp [°C]	Temp Lift [°C]	Mean Load [MW_{th}]
1	Live Steam	Live Steam	103	Bagasse /Coal	128	360	232	74
2	Feed Water Preheater	Feed Water	103	Bagasse /Coal	129	240	111	14
3	Bagasse Drying	Bagasse	21	Bagasse /Coal	75	N/A	N/A	1,67
4	Tertiary HEX	Mixed Juice	337	Vapour 1	95	105	10	4
5	Dryer	Sugar / Air	32	Exhaust Steam	25	80	55	0,6
6	CJ HEX, 1st Effect, Dryer	Exhaust Steam	103	Bagasse /Coal	128	130	2	63

Table 5-2: Potentially Viable Integration Points

Most of the remaining integration points have been excluded on the basis that the integration of solar heat at these points would have an insignificant impact on the consumption of bagasse and coal as well as the cogeneration of electricity.

6. Solar Heating of Selected Integration Points

Based on the characteristics of the heat supply and distribution network, there are only a few processes within a typical raw sugar factory that are inclined towards the integration of solar thermal process heat. Based on the first order integration assessment, the integration points that are regarded as the most susceptible to SPH include the production of live steam, the preheating of boiler feed water and the drying of bagasse and sugar, as well as the production of exhaust steam. In addition, the heating of mixed juice might be considered as a potential integration point, although it is not regarded as a high priority. This chapter revolves around the basic integration concept and potential solar gains associated with each of the abovementioned integration points.

6.1 Assessment of Integration Concepts

The assessment of the six potentially feasible integration points is based on some of the most important post-integration assessment criteria prescribed by the integration guideline[11]. An overview of the assessment of these integration concepts is provided in Addendum D.

The size of the solar field of each integration concept is pre-dimensioned according to the mean load of the integration point. Although the collector field size does not have a direct impact on the integration potential, it affects the required capital expenditure.

The annual yield of the solar thermal system is an estimation of the contribution of solar thermal energy to the process. This is dictated by the total installed capacity and the annual efficiency of the solar thermal system, as well as the solar resource associated with the location. The yield of the proposed solar thermal systems are based on unpublished simulation results conducted by Hess (2015). These simulations are based on the inlet and desired outlet temperatures specified for each integration point and excludes any thermal storage. The annual system efficiency is based on the specific yield of each solar thermal system related to the global horizontal irradiance of Durban.

The seasonal utilisation ratio is an estimation of the portion of the annual yield of the solar system that is available for use during the crushing season.

The solar fraction is one of the most important criteria for the feasibility of the integration concept, because it is an estimation of the portion of the processes' energy demand that can be supplied by the proposed solar thermal system.

The utilisation of waste heat or heat recovery should not be reduced. Instead, energy efficiency should enjoy preference over solar process heat integration, since it is usually a more cost effective intervention.

[11] See Chapter 3, Section 3.3 and Table 3-4.

6.2 Parallel Production of Live Steam

The production of live steam in parallel with the existing boiler has the potential to maximise the contribution of solar heat to the sugar milling process. This intervention would have a direct impact on the fuel consumption of the boiler due to the reduction of the demand for conventional live steam. The live steam, at 400 °C and 30 bar, can only be produced by concentrating solar collectors, such as parabolic trough, linear Fresnel or heliostat field collectors. Considering the relative maturity of the technology, utility-scale parabolic trough collectors are expected to be the most suitable technology.

Solar steam can either be produced directly, by evaporating feed water within the collector field, or indirectly, by means of a heat transfer fluid such as thermal oil. Indirect solar steam generation (SL_S_PI), where the feed water is evaporated by the heat transfer medium in a heat exchanger such as a kettle type reboiler, is preferred. Here, the solar steam is introduced to the heat supply network at the same temperature and pressure as the conventional boiler system. The injection valve that controls the feed of the solar steam into the supply network is regarded as the integration point, as illustrated in Figure 6-1.

In order to reach temperatures in the range of 400 °C, utility-scale concentrating solar thermal technology, such as parabolic trough collectors, would be expected to be the most efficient application. Since the solar gains of such high temperature applications could not be simulated, the expected solar gains are based on related literature. According to different experts such as Geyer et al. (2002), Sargent & Lundy Consulting Group (2003), Burns & McDonnell (2009) and Günther, Joemann & Csambor (2012), the average solar field efficiency of a large scale PTC system is in the order of 50 to 60 % in relation to DNI. The gains for this integration concept are based on a conservatively estimated annual system efficiency of 55 % related to DNI. Since the system efficiency in this section is related to GHI for the other integration concepts, the system efficiency of this concept can be stated as 61 % related to GHI. Therefore, such a system is expected to yield approximately 1 110 kWh/m^2a. Considering the seasonal utilisation factor of 69 %, a 74 MW_{th} system of roughly 105 000 m^2 is expected to yield approximately 81 400 MWh_{th} during the season. Such a system is, therefore, expected to be capable of supplying up to 24 % of the seasonal live steam demand of the factory.

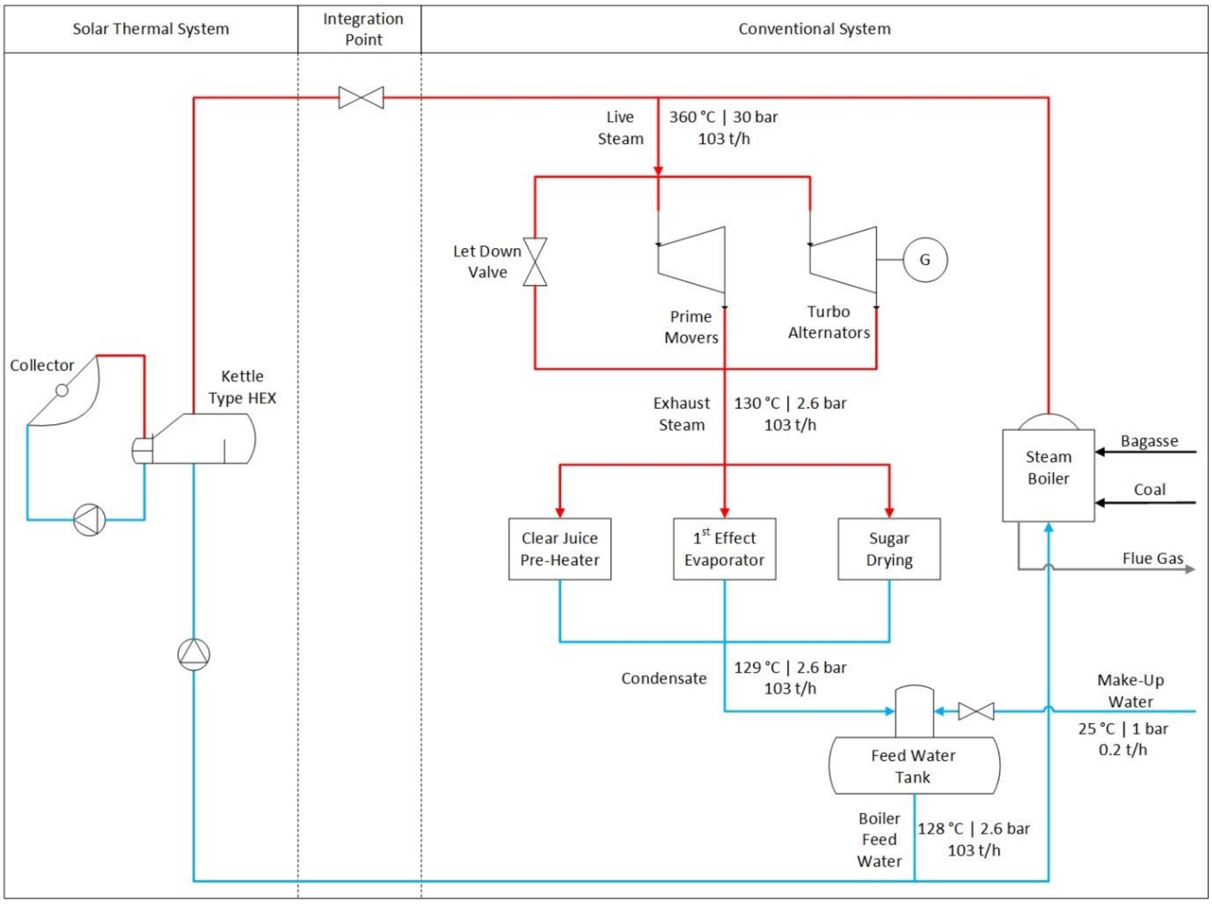

Figure 6-1: Indirect Live Steam Production (SL_S_PI)

In the case of parallel production of live steam, the range of modulation of the conventional boiler dictates the upper limit of the solar steam fraction with regard to the total steam demand. This is because the output of the boiler is expected to vary according to the production of the solar field, while the fuel consumption of the boiler is expected to decrease accordingly.

6.3 Preheating of Boiler Feed Water

Solar collectors can be used to preheat the boiler feed water to improve the efficiency of the boiler, thereby reducing the fuel consumption. However, the boiler feed water should not be heated to more than 240 to 250 °C[12].

However, waste heat recovery can be employed to preheat the feed water to approximately 180 °C. The impact of solar integration can therefore be maximised at boilers without economisers, owing to the larger temperature lift. In this case, concentrating solar collectors (SL_S_FW) can be used to heat the feed water from 130 to 240 °C at a pressure of about 40 bar, which is the discharge pressure of the feed water pump. Figure 6-2 provides a graphical representation of the suggested integration concept.

[12] See Chapter 5, Section 5.2.2.

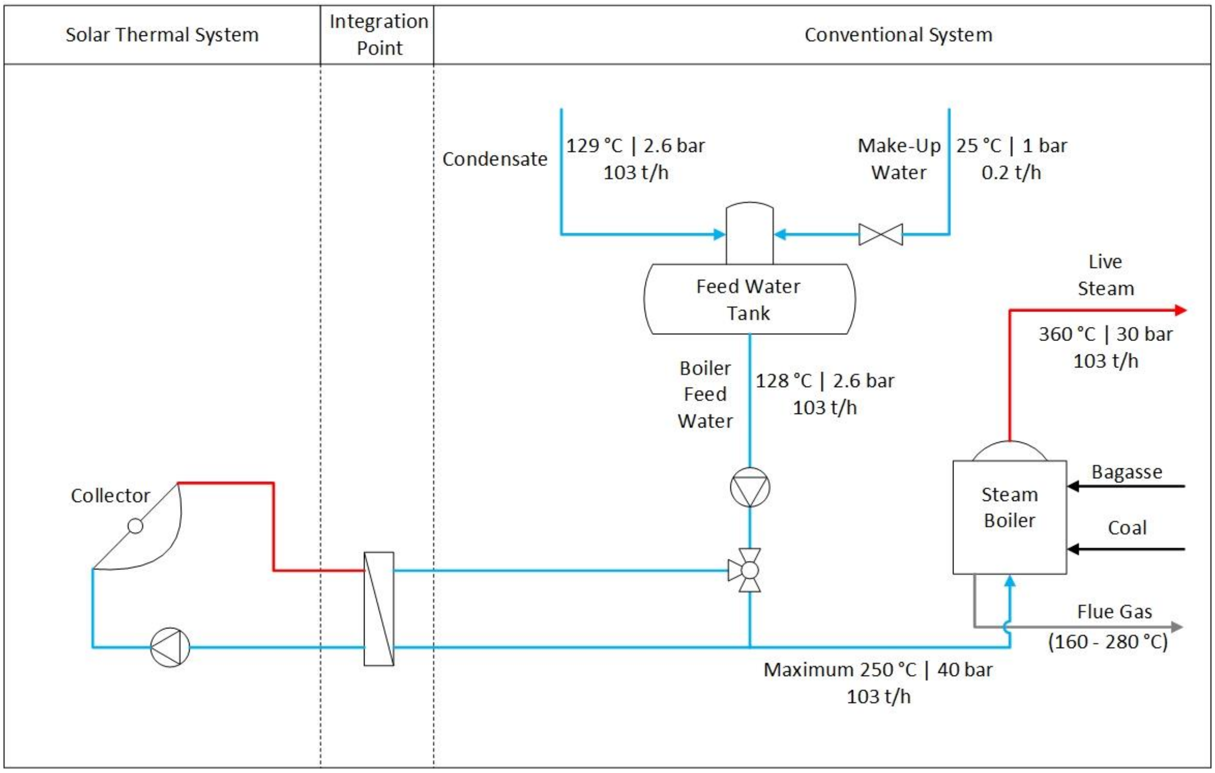

Figure 6-2: Preheating of Boiler Feed Water (SL_S_FW)

Concentrating solar collectors are used to heat the heat transfer medium. A valve is to be used to direct the feed water through a heat exchanger as soon as the temperature of the HTF exceeds the temperature of the feed water in the feed water tank. Thereby the solar system can add heat to the feed water and improve the efficiency of the boiler.

Approximately 14 MW_{th} is required to heat the feed water from 130 to 240 °C. Therefore, a solar field with a maximum gross collector area of 20 000 m^2 can be considered to offset a portion of the seasonal demand of nearly 65 000 MWh. Such a field of parabolic trough system is expected to have an annual efficiency of 26 %, with an annual yield of approximately 9 000 MWh_{th}. However, nearly 6 500 MWh can be produced during the crushing season, which accounts for 10 % of the seasonal heat demand for the preheating of the boiler feed water.

6.4 Drying of Bagasse

In order to reduce the fuel consumption of the boiler, air dryers can be used to reduce the moisture content of the bagasse to a minimum of 40 %. A typical bagasse dryer requires air at approximately 200 °C to ensure an evaporation rate of at least 2 t/h. Solar thermal technology can be used to supply hot air to the dryers to enhance the drying process. A graphical representation of the proposed integration concept for bagasse drying is provided in Figure 6-3.

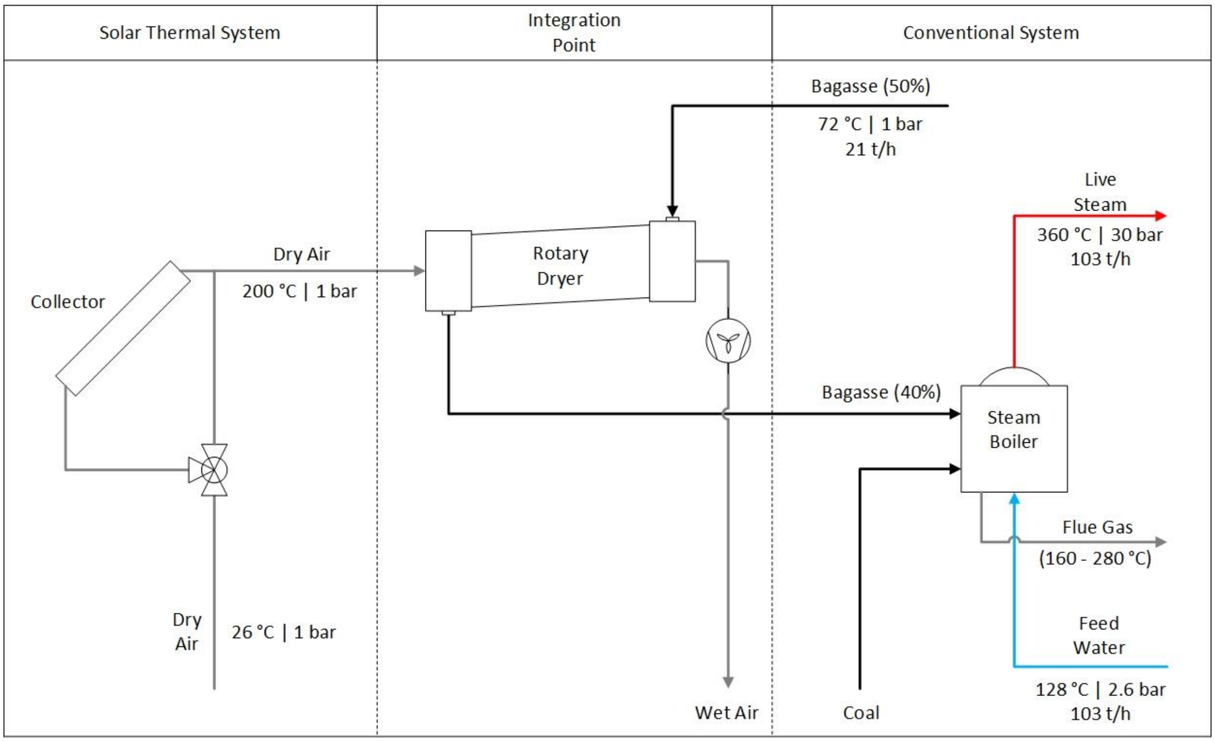

Figure 6-3: Air Heating for Bagasse Drying (PL_E_IS)

Flat plate air collectors can be applied to heat the incoming air when there is sufficient solar radiation. Alternatively, conventional flat plate collectors can be used to heat a HTF such as water. In such a configuration, the air would be heated indirectly by means of a heat exchanger between the incoming air and the HTF. The collectors can then be by-passed if no solar heat is available.

The input stream of dry air should be heated from ambient to approximately 200 °C before the dryer. However, the solar field should be assisted by either exhaust gas or steam to ensure a constant air temperature. Otherwise the bagasse dryer should only be operated when solar heat is available.

The average thermal load of the dryer is assumed to be approximately 1.67 MW_{th} and the process is expected to consume about 7 700 MWh/a. A field of flat plate air collectors of less than 2 400 m^2 in total could be considered to supply heat to the bagasse drying process. The annual system efficiency is expected to be about 60 %. Therefore, a maximum of 2 500 MWh of heat can be supplied during the course of a year. However, only about 1 850 MWh, or roughly 74 % of the annual potential yield, can be produced during the crushing season. Thus, approximately 24 % of the annul heat demand of the bagasse drying operation can be provided by the proposed collector field.

6.5 Parallel Production of Exhaust Steam

As with the production of live steam, exhaust steam can be produced in parallel with the conventional heat supply system in order to reduce the amount of let-down or to increase the electricity production of a cogeneration system. An overview of the integration concept is provided in Figure 6-4. Although Figure 6-4 depicts the status quo of most of the South African mills, whereby electricity is generated for own consumption by means of turbo alternators, this integration concept is expected to be most valuable if condensing pass-out turbines are employed for the generation of electricity for export.

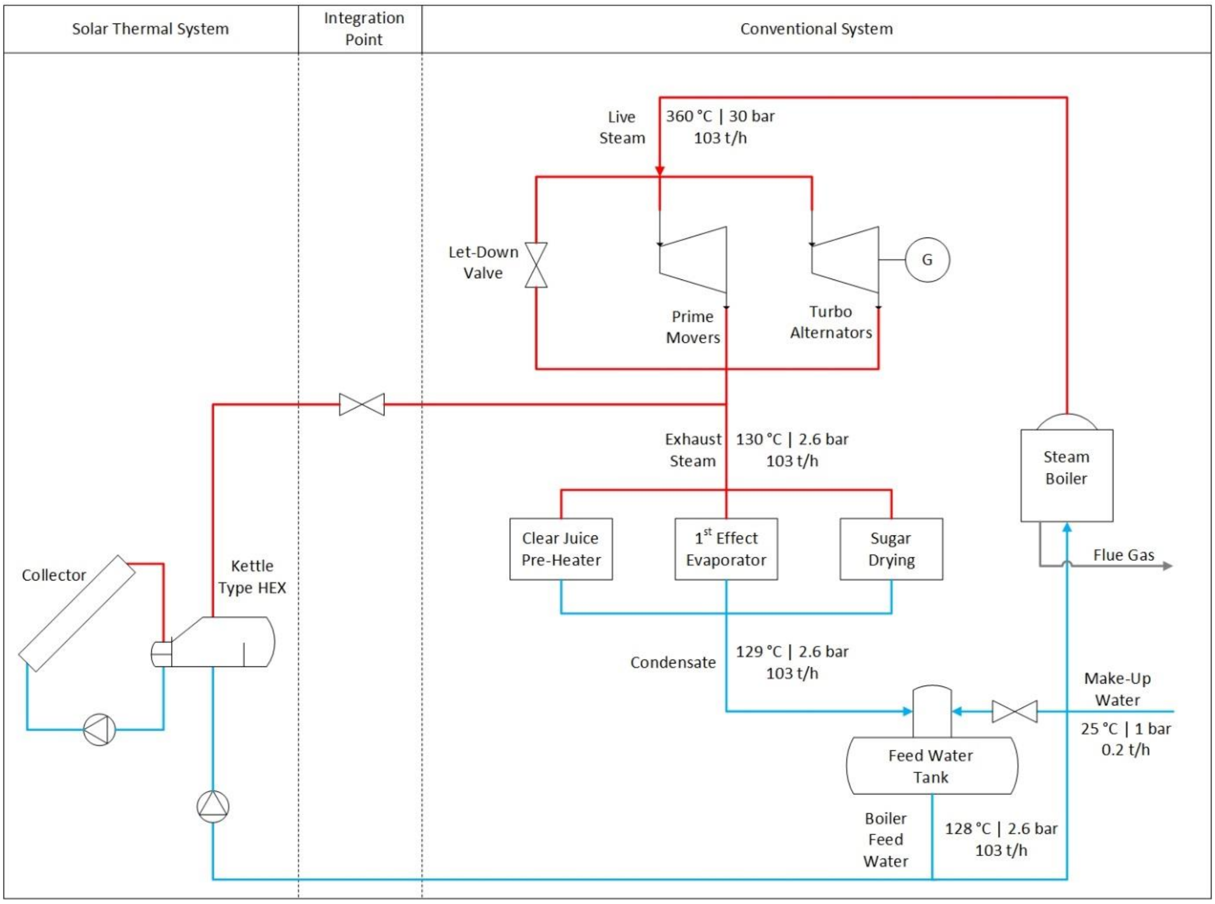

Figure 6-4: Parallel Production of Exhaust Steam (SL_S_PI)

Concentrating solar collectors, such as parabolic trough collectors, can be used to heat a heat transfer fluid in order to evaporate the boiler feed water indirectly by means of a kettle-type reboiler. However, since the solar collectors are only required to add sufficient energy to evaporate the boiler feed water at 130 °C, evacuated tube collectors can also be considered. A pump can be used to direct a portion of the boiler feed water to the heat exchanger if the solar heat is sufficient to evaporate the water. The steam is then injected to the exhaust steam manifold at the required temperature and pressure by means of a two-way valve, which can be regarded as the integration point. This is expected to reduce the amount of let-down steam, thereby reducing the bagasse and coal consumption of the boiler. In the best case scenario, the production of solar generated exhaust steam is expected to increase the electricity production of a pass-out turbine.

The exhaust steam provides approximately 550 000 MWh of heat to the factory over the course of the crushing season. In order to meet the mean load of 63 MW_{th}, a collector field of approximately 90 000 m^2 can be considered to offset a portion of the exhaust steam heat demand.

Although concentrating collectors, such as parabolic trough collectors, would generally be expected to be the most suitable technology for this application, advanced evacuated tube collectors can also be considered to produce the exhaust steam at 130 °C and 2.6 bar. According to the collector simulation results, the annual efficiency of advanced evacuated tube collectors is expected to be approximately 40 %. Thus, the expected yield of the evacuated tube collectors exceeds the yield of parabolic trough collectors by more than 30 %. A comparison of the specific monthly gains of the evacuated tube and the parabolic trough collectors for the production of exhaust steam is illustrated in Figure 6-5. This phenomenon can primarily be ascribed to the high portion of diffuse radiation associated with the location.

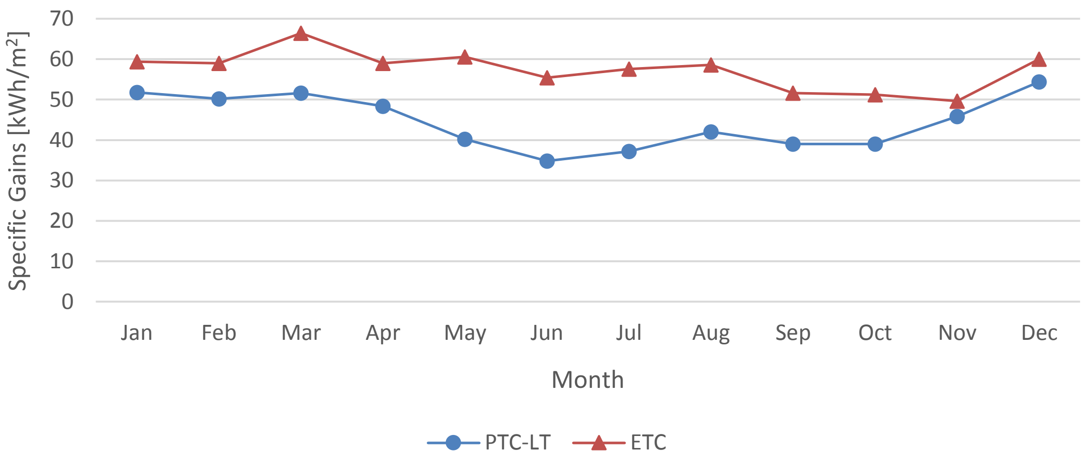

Figure 6-5: System Efficiency for Exhaust Steam Production (Related to GHI)

A solar collector field of 90 000 m^2 is expected to produce more than 60 000 MWh of heat per annum. Approximately 74 % of the annual yield, or 46 000 MWh, can be supplied in the crushing season. Therefore, nearly 16 % of the heat demand of the clear juice heater, first effect evaporator and the sugar drying process can be satisfied by the abovementioned solar field.

6.6 Drying of Final Raw Sugar

The final raw sugar is dried by means of hot air after the crystallization process. The air is normally heated with exhaust steam. To reduce the demand for exhaust steam, solar air collectors can be used to preheat the input stream of air prior to the exhaust steam heat exchanger, as illustrated in Figure 6-6. Alternatively, conventional flat plate collectors can be applied to heat the incoming air indirectly by means of a heat exchanger between the air and the HTF. In this case, the purpose of the solar thermal system is to heat the incoming air from ambient temperature to 80 °C. If the solar heat is sufficient to heat the air, a valve can be used to direct the air through the collectors or through the heat exchanger. The solar heat is to be supplemented with exhaust steam to ensure a constant air temperature within the dryer by means of the conventional heat exchanger.

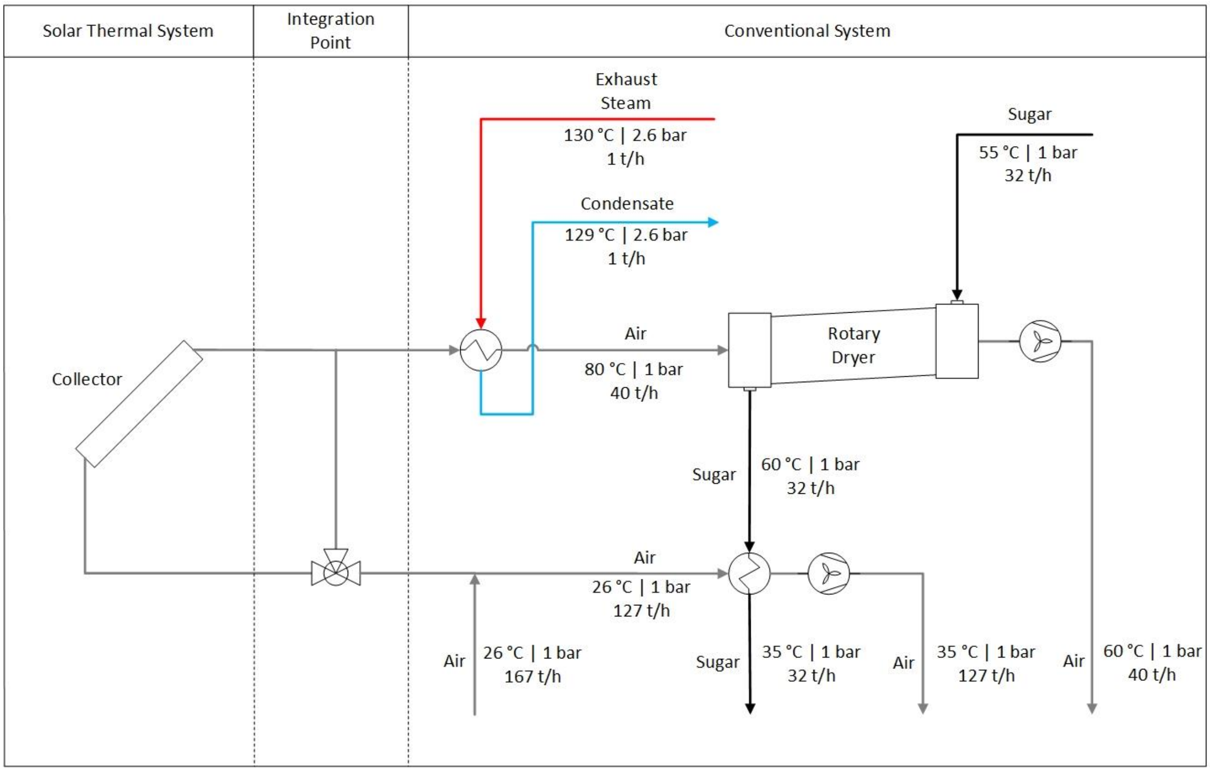

Figure 6-6: Air Heating for Sugar Drying (PL_E_IS)

The mean load of the air heat exchanger is 0.63 MW_{th} and the annual heat consumption is almost 3 000 MWh during the crushing season. Thus, to meet the thermal requirements of the heat exchanger, a solar collector field of 900 m^2 can be considered. An average system efficiency of 69 % can be achieved by flat plate collectors for the heating of drying air. Therefore, the solar field is expected to yield a total of 1 083 MWh per year. However, approximately 795 MWh, or 73%, thereof is expected to be produced during the crushing season. Consequently, a solar fraction of 27 % can be achieved for the sugar drying process.

6.7 Heating of Mixed Juice

In order to reduce the consumption of bleed vapour, solar heat can be integrated into the mixed juice heating train. Non-concentrating collectors can be used to heat the process medium from 95 to 105 °C before the tertiary heat exchanger. As illustrated in Figure 6-7, the heat transfer fluid (HTF) is heated in the solar collectors, which, in turn, heats the mixed juice via an external heat exchanger. The HTF is then circulated through the collector field and the heat is accumulated in the storage tank. The circulation pump is activated as soon as the temperature within the storage vessel is sufficient to heat the process medium.

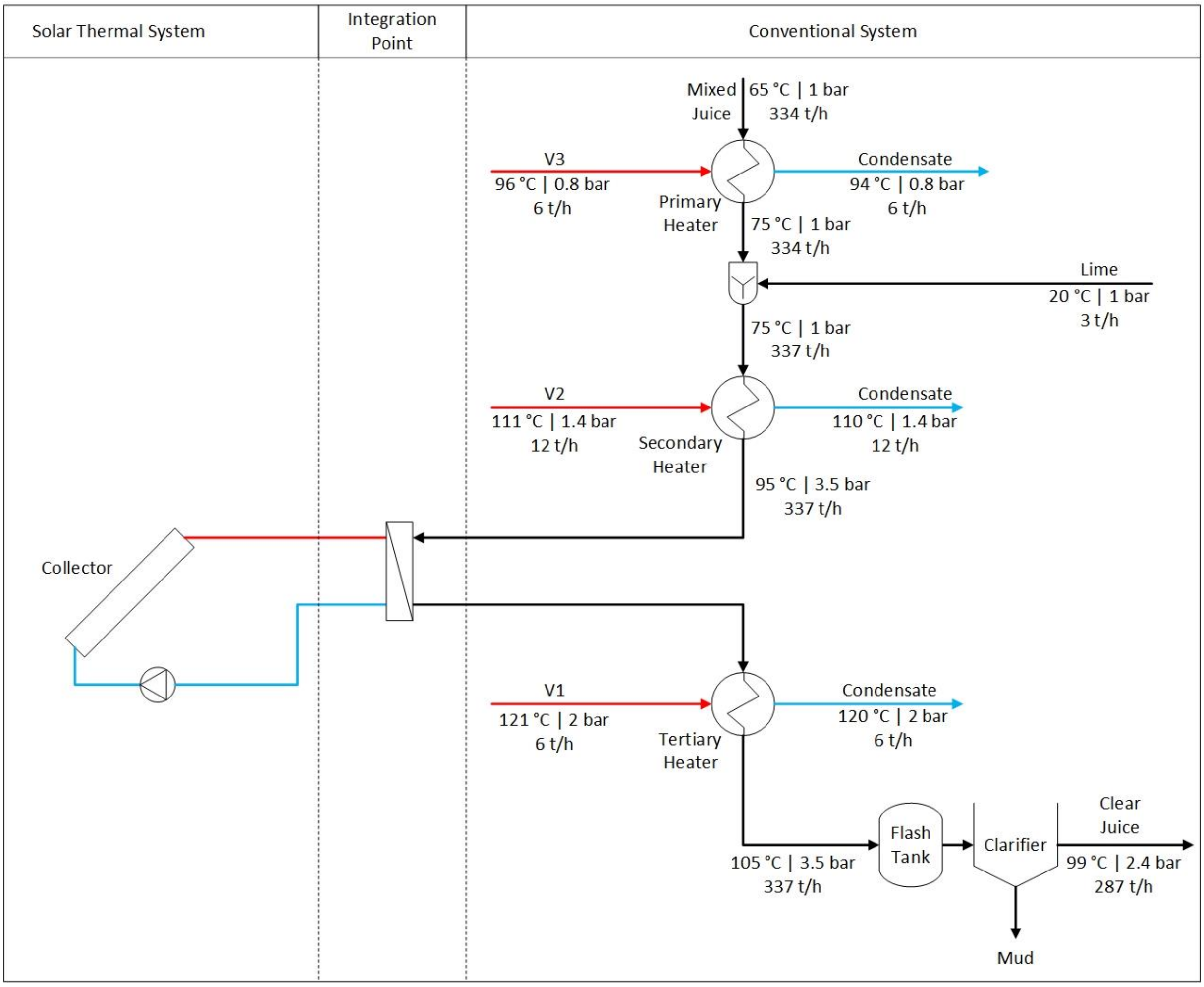

Figure 6-7: Heating of Mixed Juice (PL_E_PM)

The power requirement for the tertiary heater is 4 MW_{th} and it consumes roughly 18 500 MWh of thermal energy per season. Therefore, the maximum solar collector field is projected to be 5 700 m^2. Due to the relatively low process return temperature, either flat plate or evacuated tubes collectors can be considered to heat the mixed juice to 105 °C. According to the simulation results, the efficiency of the evacuated tubes is expected to exceed that of flat plate collectors by more than 25 %. The specific monthly yield of these collectors are compared in Figure 6-8.

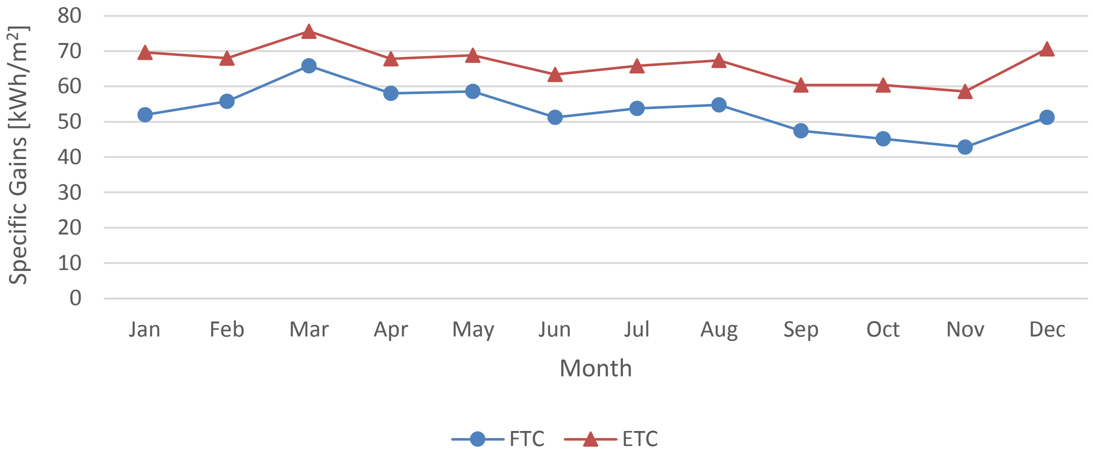

Figure 6-8: System Efficiency for Mixed Juice Heating (Related to GHI)

The evacuated tube collector field is expected to produce approximately 4 550 MWh of heat per year. It is anticipated that 74 % of the annual yield, or 3 360 MWh, will be supplied during the season. This would account for 18 % of the thermal energy requirements of the tertiary heater.

6.8 Potential Solar Gains

The expected solar gains for the selected integration points are tabulated in Table 6-1. The detailed results of the solar yield estimations are provided in Addendum C.

Table 6-1: Potential Solar Gains

Integration Point	Collector Type	Maximum Collector Field Size [m^2]	Rated Capacity [MW_{th}]	Annual System Efficiency [%]	Annual Solar Gains [kWh/m^2]	Seasonal Utilisation Rate [%]	Solar Fraction [%]
Live Steam	PTC-HT	105 000	74	61	1 110	69	24
Feed Water	PTC-LT	20 000	14	26	455	71	10
Bagasse Drying	FPC	2 400	1.67	60	1 058	74	24
Exhaust Steam	ETC	90 000	63	40	688	74	16
Sugar Drying	FPC	900	0.63	69	1 203	73	27
Mixed Juice	ETC	5 700	4	46	796	74	18

Large solar fields are required for the generation of live steam and exhaust steam. However, these systems are expected to offset approximately 24 and 16 % of the seasonal demand respectively. The anticipated annual system efficiency of these systems is relatively high, resulting in an expected annual yield of 1 001 and 688 kWh/m^2 per year. These interventions are expected to have a significant impact on the annual coal and bagasse consumption of the boilers. Furthermore, the introduction of solar generated live and exhaust steam can increase the electricity cogeneration capacity of a sugar factory significantly, especially in a pass-out turbine configuration.

The annual system efficiency of the solar feed water preheater is expected to be relatively low and would have a fairly insignificant impact, since a solar field of 20 000 m^2 is expected to provide a maximum solar fraction of 10 %.

The annual system efficiency of the sugar and bagasse drying solar systems are expected to be relatively high and could offset more than 20 % of the conventional energy demand of these processes. However, the annual yield is relatively low in relation to the total thermal energy demand of the factory.

From a solar gains perspective, the heating of mixed juice is not expected to be a feasible opportunity, since the maximum solar fraction of a solar field of a solar collector field of approximately 5 700 m^2 is less than 20 %.

Based on the solar gains estimations and the integration concept assessment, the production of live and exhaust steam, as well as the drying of bagasse and sugar can be regarded as the highest priority integration concepts.

6.9 Entry Barriers

The enormous capital requirements of such a project are also expected to prevent the implementation of solar thermal technology. A 105 000 m^2 field of parabolic trough collectors for the production of live steam is expected to incur installation costs of more than R 500 million in total. This amounts to more than 10 % of the total capital requirements of a typical raw sugar factory. Apart from the economic factors, there are various obstacles hampering the adoption of solar thermal technology by the sugar milling industry. Some of the most critical entry barriers for solar process heat integration in this industry are discussed in this section, as highlighted by Foxon (2015c).

A sugar factory's heat supply and distribution network design is based on established design philosophies. Therefore, the optimisation of solar process heat integration into the intricate system is expected to be a complex and iterative process. The engineering time required for this process, as well as the inertia of the industry to adopt a new design philosophy are expected to be some of the most significant obstacles.

Sugar factories should be energy net positive, since the bagasse should theoretically be sufficient to produce more energy than the factory consumes (Saha, 1998). However, most South African factories consume a significant amount of coal to balance the energy needs. Therefore, there is an apparent opportunity for energy efficiency improvement. Energy efficiency measures should enjoy precedence over investment in solar thermal technology, considering that these measures generally offer more favourable return on investment.

A major obstacle for the adoption of solar heat is the large ground area required for the substitution of only a small portion of the annual heat demand. Since the required ground area for a solar thermal system is approximately 2.5 times the gross area of the collector field, approximately 2 250 m^2 would be required for the drying of the final sugar, while more than 25 hectares of ground area would be required for the production of live steam. In order to accommodate the installation of a solar thermal system, it would be necessary to sacrifice land that is currently used for the production of sugarcane because the roof space of a typical sugar factory would not be sufficient.

Furthermore, a typical sugar factory can exploit less than 75 % of the potential annual energy yield owing to the limited duration of the crushing season. This arises from the short crushing season and the low overall time efficiency of the factories. These limitations are expected to have a negative impact on the cost of the energy and the return on investment.

Similarly, the shortage of local expertise regarding the design, installation, operation and maintenance of such large-scale solar thermal systems for the production of process heat is also expected to be a perceived risk. The largest SPH system in the world is approximately 40 000 m^2, which is less than 40 % of the solar field required for the production of live steam. The lack of demonstration plants in South Africa is also expected to hamper the adoption of the technology.

7. Economic Assessment & Sensitivity

The feasibility of solar process heat for the sugar industry is inevitably dependent on the cost and benefit of the energy. In order to assess the financial feasibility of solar process heat integration, the levelised cost of the solar thermal energy, as well as the expected return on investment are considered in this chapter. The sensitivities of these indicators are also evaluated. All of the financial calculations are based on current Rand values and are, therefore, calculated in nominal terms[13].

7.1 Levelised Cost of Heat

The levelised cost of electricity (LCOE) is a common measure to assess the financial feasibility of renewable energy projects. The LCOE can be defined as the discounted cost of the energy produced over the lifespan of the energy system, or the cost per unit of energy produced. For solar thermal energy, the same method is applied to determine the levelised cost of heat (LCOH). The LCOH incorporates the capital expenditure, operation and maintenance costs, fuel costs, annual energy generation and the discount rate (Orbaiz & Brear, 2014). Equation 7-1 provides the formula for the calculation of the LCOE or LCOH (NREL, 2014).

$$LCOH = \sum_{n=0}^{N} \frac{C_n}{(1+d)^n} \Bigg/ \sum_{n=1}^{N} \frac{Q_n}{(1+d)^n} \quad [R.kWh^{-1}] \qquad \text{7-1}$$

The LCOH is dependent on the annual costs (C_n) and the yield (Q_n) for each year (n) over the lifespan of the system (N). The annual costs and yields should be discounted to real terms at an appropriate rate (d).

According to Tchanche (2011), the costs of solar process heat in Europe typically range from R 0.25 to R 1.04 /kWh$_{th}$. A previous study, investigating the optimization of an industrial process heat PTC system, reported an expected LCOH of roughly R 0.70 /kWh$_{th}$ and a payback period of 8 years (Silva et al., 2014). Gabbrielli et al. (2014) estimated the LCOH of a linear Fresnel reflector system to be in the range of R 0.40 to about R 1.30 /kWh$_{th}$. Similar results have been published by Hummel et al. (2013), who reported that the LCOH of a flat plate industrial solar process heat system is about R 1.00 to R 2.47 /kWh$_{th}$. However, the LCOH of solar thermal systems in South Africa is expected to be significantly lower, considering the renowned local solar resource.

[13] An exchange rate of R 13: € 1 and R 12: $ 1 has been used for all the financial calculations in this study.

The costs associated with the generation of solar process heat include the capital expenditure, as well as the operation and maintenance costs. As with most renewable energy technologies, solar thermal projects are characterised by large capital requirements, low operation and maintenance costs and stable annual income streams. The annual revenue of the project rises according to the escalation of the value of the heat.

The capital cost of a solar thermal process heat project, including the engineering, procurement and construction, is mainly dependent on the collector type and the size of the system. Table 7-1 provides an overview of the reported system costs of existing solar thermal plants. These costs have been derived from AEE INTEC's (2015) database, which reports the capital cost of some of the existing solar process heat systems. This correlates with the expected cost of R 1 800 to R 2 700 /m^2 for flat plate and evacuated tube collectors as estimated by the IEA (IEA-ETSAP & IRENA, 2015).

Table 7-1: System Costs of Existing SPH Plants (Adapted from AEE INTEC, 2015)

Collector Type		Capital Cost Range [R/m^2]	Median [R/m^2]
Flat Plate Collectors	[FPC]	750 – 6 850	3 000
Evacuated Tube Collectors	[ETC]	1 400 – 3 300	2 350
Parabolic Trough Collectors	[PTC-LT]	2 900 – 28 500	4 500
Air Collectors	[FPC]	1 000 – 6 000	5 700

Although these reported costs exclude grants or financial incentives, the costs are relatively low. This can be ascribed to the fact that the disclosure of the installation costs of the existing plants is voluntary. Therefore, it is possible that only the participants who considered the actual project costs as competitive disclosed these cost on the database.

According to Geyer et al. (2002), the installed solar field costs of a large-scale parabolic trough collectors to be used for the production of high temperature steam, such as live steam, is expected to be roughly R 2 600 /m^2. According to Turchi (2010), the estimated installation cost, including site preparation, the solar collector field and the heat transfer fluid system, of a such large-scale PTC system can approach R 5 000 /m^2.

The operational costs include the cost of auxiliary energy consumption as well as replacement and maintenance costs. A good estimate of the annual operational expenditure of a solar thermal plant is about 1 to 2 % of the capital cost of the system. The typical annual auxiliary energy consumption of such a plant is in the range of 2 to 5 % of the yearly energy yield (VDI, 2004). Silva et al. (2014) also estimated the annual operation and maintenance costs of a PTC system roughly 2% of the capital cost.

The input parameters that have been considered for the economic assessment of the various integration concepts are listed in Table 7-2. The global horizontal irradiation of Durban, retrieved from PVGIS (2012), was used for the annual yield calculations. A nominal discount rate of 10 % has been selected for all the financial calculations, since it correlates with the typical weighted average cost of capital (WACC) expected for the South African sugar industry for a gearing ratio of 70 % and an interest rate of 8 %.

Table 7-2: Parameter Values for the Financial Model

Parameter	Value
GHI	1 820 kWh_{th}/m^2a
Auxiliary Energy Consumption	2 % of Annual Yield
Auxiliary Energy Tariff	R 0.50 /kWh_{th}
O&M Expenditure	1 % of Capex
Discount Rate	10 %
Project Life	20 years

The expected capital cost of each of the proposed integration concepts are provided in Table 7-3. The CAPEX, ranging from R 2.7 million to more than R 500 million, represents the total cost of the maximum installed capacity for each of the integration concepts, based on the mean thermal load of the integration points.

Table 7-3: Capital Expenditure

Integration Point	Collector Type	System Cost [R/m^2]	Rated Capacity [MW_{th}]	Installed Capacity [m^2]	Capital Expenditure [Rm]
Live Steam	PTC-HT	5 000	74	105 700	529
Feed Water	PTC-LT	4 500	14	20 000	90
Bagasse Drying	Air	5 700	1.67	2 400	13.7
Exhaust Steam	ETC	2 350	63	90 000	211.5
Sugar Drying	FPC	3 000	0.63	900	2.7
Mixed Juice	ETC	2 350	4	5 700	13.4

The LCOH have been calculated over a project lifespan of 20 years, accounting for the capital expenditure, O&M costs and the auxiliary energy consumption. The resulting LCOH for each of the potential integration points are reported in Figure 7-1. As shown, the LCOH varies between R 0.43 and R 1.72 /kWh. The lowest heating costs are associated with the heating of mixed juice and the production of exhaust steam, whilst the production of live steam and boiler feed water preheating is expected to be the most expensive.

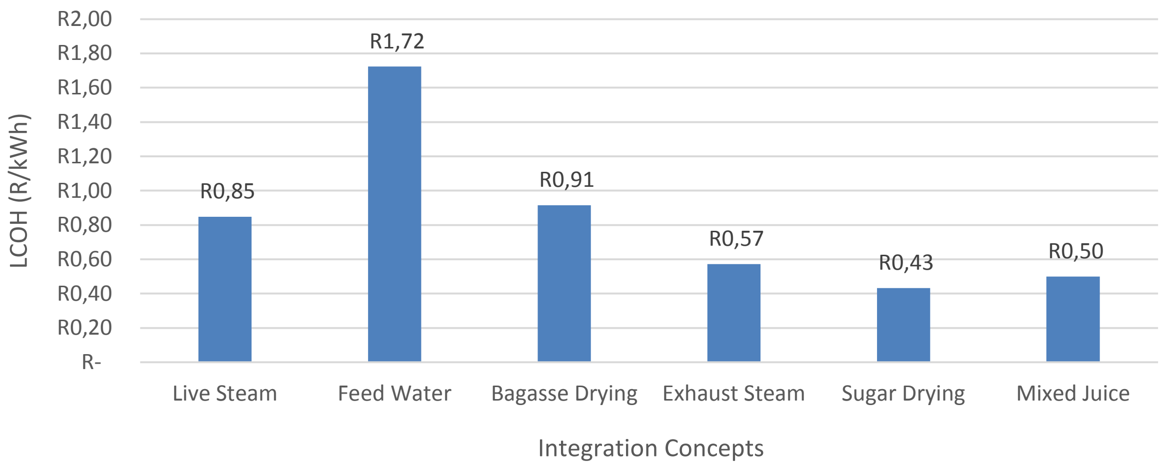

Figure 7-1: Levelised Cost of Heat

A sensitivity analysis has been performed in order to highlight the effect of the most important parameters on the LCOH. The sensitivity of the LCOH has been tested against the variation of the irradiance, system efficiency, capital expenditure and discount rate, as well as the seasonal utilisation ratio. Realistic arbitrary values have been assigned to these input parameters. Each input variable has been varied by 40 % in intervals of 10 % in each direction. The starting values for the sensitivity analysis are listed in Table 7-4.

Table 7-4: Parameter Values for the LCOH Sensitivity Analysis

Parameter	GHI [kWh_{th}/m^2a]	Annual System Efficiency [%]	Capital Expenditure [R/m^2]	Seasonal Utilisation Ratio [%]	Discount Rate [%]
Starting Value	2 000	40	3 000	74	10
Minimum	1 200	24	1 800	44	6
Maximum	2800	56	4 200	100	14

The results of the sensitivity analysis are illustrated in Figure 7-2.

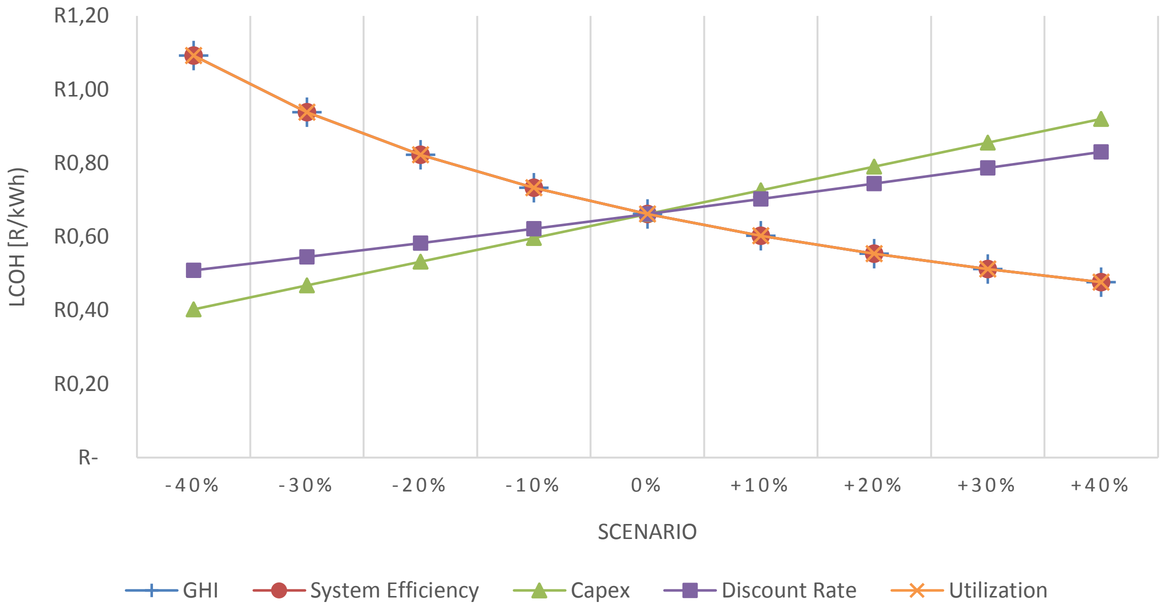

Figure 7-2: Sensitivity of the LCOH

From the sensitivity analysis, it is clear that the LCOH is equally sensitive to variation of the irradiance, the system efficiency and the seasonal utilisation ratio. However, these variables are expected to be fairly stable and can be predicted with relative accuracy. In practice, the variability of the annual sum of irradiation is relatively low. The annual GHI in KwaZulu-Natal only varies between 1 550 and 2 000 kWh_{th}/m^2. According to the solar gains simulations, the seasonal utilisation rate of the potential annual solar yield is between 69 and 74 % for all of the proposed solar thermal systems. The LCOH is inversely proportional to the capital cost of the project. Access to grant funding can, therefore, reduce the LCOH significantly.

7.2 Return on Investment

The return on investment of the proposed solar thermal projects is primarily dictated by the project costs, the energy yield of the collector field, as well as the value of the energy, and, therefore, the fuel, which is offset by the solar energy. The simple payback period of the solar thermal system for each of the integration concepts under scrutiny is expected to be in the range of 7 to 15 years. In order to investigate the influence of some of the most important variables on the return on investment of the solar project, a sensitivity analysis has been performed on the Internal Rate of Return (IRR).

The IRR is an accepted project finance criterion for expressing the merit of a renewable energy investment opportunity, based on the assumed cash flows associated with the investment. The IRR is usually compared to a predetermined hurdle rate in order to estimate the feasibility of a prospective project (Short, Packey & Holt, 1995). As such, the IRR is an estimation of the discount rate that would result in a zero net present value (NPV), which is the discounted sum of the annual cash flows over the lifespan of the project (NREL, 2014). A higher IRR is expected to result in a higher return on investment. The formula for the calculation of the NPV is provided in Equation 7-2.

$$NPV = \sum_{n=0}^{N} \frac{C_n}{(1+d)^n} \quad [R] \tag{7-2}$$

The NPV is dependent on the net cash flow (C_n) of each year (n) over the lifespan of the system (N). The annual cash flows are discounted to real terms at an appropriate rate (d).

The IRR, calculated by means of the built-in Microsoft Excel function, is based on the expected annual cash flow of a hypothetical solar thermal system. The assumed starting values for the IRR's sensitivity analysis are provided in Table 7-5. These parameters have been varied up to 40 % of the starting values in both directions. The influence of the irradiation, system efficiency, capital expenditure, seasonal utilisation ratio and the value of the conserved energy has been evaluated.

Table 7-5: Parameter Values for the IRR Sensitivity Analysis

Parameter	**GHI [kWh/m^{2}a]**	**System Efficiency [%]**	**Capital Expenditure [R/m^2]**	**Seasonal Utilisation Ratio [%]**	**Energy Value [R/kWh$_{th}$]**
Starting Value	2 000	40	3 000	74	0.65
Minimum	1 200	24	1 800	44	0.39
Maximum	2800	56	4 200	100	0.91

The result of the IRR sensitivity analysis is illustrated in Figure 7-3. The resultant 20 year IRR of a typical solar thermal investment is in the order of 15 %, although it can vary significantly. This correlates with similar studies conducted by the GIZ (2011).

As expected, the return on investment is highly sensitive to the initial cost of the system. A reduction in the capital cost of the plant is expected to result in a significant improvement of the IRR. The IRR is equally proportional to the irradiance, collector efficiency, discount and seasonal utilisation rate, as well as the value of the energy.

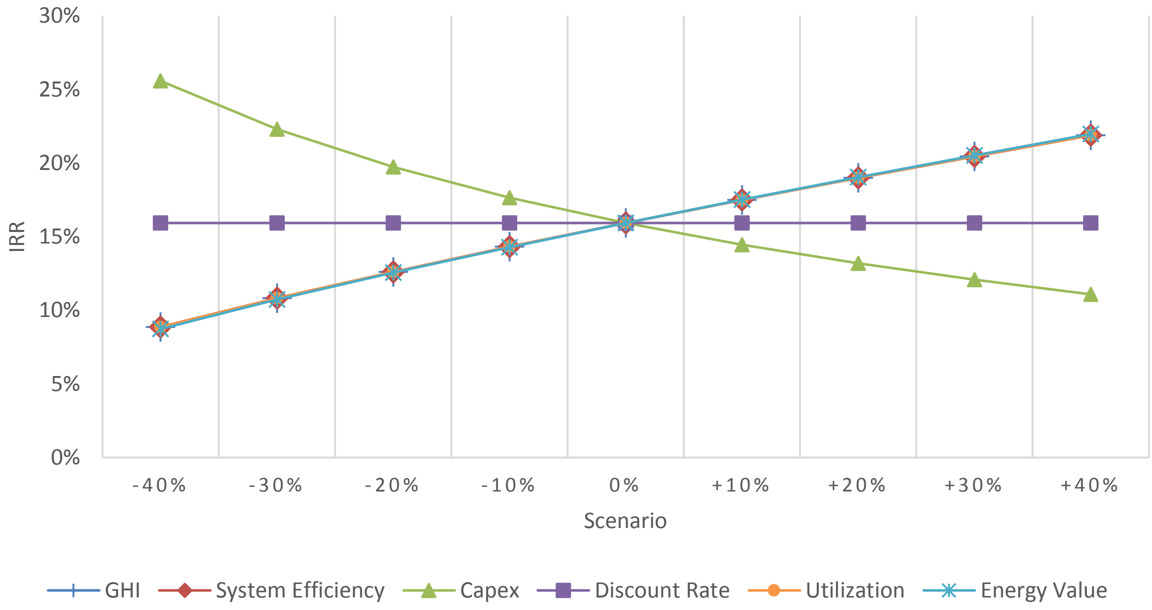

Figure 7-3: Sensitivity of the IRR

As indicated in the sensitivity analysis, the IRR is significantly influenced by the value of the energy that is offset by solar heat. The value of the energy is mostly based on the cost of the energy source or the fuel. The cost of bagasse is fairly insignificant since it is a residue of the sugar production process. Conningarth Economists (2013) estimated the cost of energy produced by bagasse to be approximately R 0.30 /kWh. However, due to the potential production of various bagasse by-products, the true value of bagasse is dictated by the opportunity cost. This cost is dependent on the economic value of the by-product.

The cost of the energy consumed in the factory is further inflated by the coal consumption because coal is relatively expensive compared to the bagasse. The cost of thermal coal over the last five years varied between R 400 and R 700 /tonne (InfoMine, 2015). Furthermore, local sugar factories can export cogenerated electricity at R 1.20 /kWh. Therefore, the value of live and exhaust steam is also inflated by the opportunity cost of electricity generation. Therefore, the value of the energy is expected to be between R 0.30 and R 1.20 /kWh. According to the result of the sensitivity analysis, the IRR is expected to exceed 10 % even if the value of the energy is as low as R 0.45 /kWh.

The hurdle rate for projects or investments in the sugar milling industry is typically expected to be 10 to 15 % (Foxon, 2015d). Since the IRR is expected to exceed the hurdle rate, integration of solar thermal process heat could be justified as a feasible investment opportunity according to the return on investment expected by investors in the industry.

8. Conclusion & Recommendations

This final chapter of the dissertation provides an overview of the research problem and the objectives of the study, as well as the methods that have been applied. Furthermore, a summary of the key findings is provided and recommendations for future research are made.

8.1 Project Review

Stakeholders in the South African sugar milling industry are exploring alternatives to improve the profitability of the industry. This can be achieved by the reduction of operating costs, the production of by-products and the export of electricity by means of cogeneration. The adoption of solar thermal technology is gaining momentum across the world and is regarded as a possible solution for the local sugar industry to establish a competitive advantage in the market.

This research study was aimed at performing a first investigation of the feasibility of solar thermal process heat integration in the South African sugar milling industry. In order to identify the opportunities for solar heat integration, the objective was to detect the prospective integration points in a typical sugar mill by identifying the primary processes within such a factory and evaluating the heat demand characteristics of these processes. The energy consumption assessment is based on the results of a simulation model of a generic raw sugar factory with a throughput of 250 tonnes of cane per hour.

The thermal demand and schedule of the potential integration points have been assessed in order to highlight the most significant integration points. Basic integration concepts have been developed for the six highest priority integration points in order to estimate the potential solar gains.

The financial feasibility of solar thermal energy has been assessed in terms of the levelised cost of heat and the internal rate of return expected for this technology. Sensitivity analyses have also been performed in order to investigate the vulnerability of these financial indicators to the fluctuation of some of the key variables.

The integration concepts have been assessed according to the costs and benefits related to each in an effort to identify the most appropriate integration points within a typical South African raw sugar factory.

8.2 Results and Findings

8.2.1 Overview

Raw sugar production is characterised by significant thermal energy requirements. Heat is required in almost all of the six distinct processes at temperature levels below 130 °C, which is seemingly favourable towards the adoption of solar thermal technology.

The heat demand is fairly constant over most of the operating season, although it only stretches over approximately three quarters of the year. Unfortunately, the crushing season extends over the winter months, which are characterised by lower solar irradiance. In addition, the South African sugar industry is not located in an area known for extremely favourable solar resource, even though the annual sum of GHI exceeds 1 800 kWh/m^2.

The heat demand of a raw sugar factory is primarily fulfilled by the combustion of bagasse. Since this feedstock is a residue of the process, the energy is regarded as extremely cheap. However, the value of the energy is inflated by the opportunity cost associated with the alternative bagasse by-products, the additional consumption of coal and the prospect of exporting electricity for additional income.

Most of the processes within a raw sugar factory are relatively energy efficient, given that the bulk of the thermal energy demand is satisfied by waste heat recovery from the evaporators. Vapour is bled from the first three evaporation effects to supply heat to most of the heat sinks in the factory. In order to maximise the contribution of solar thermal process heat, it should be used to substitute the highest possible grade of steam or heating medium. Since the exhaust steam and vapour has already performed work, a reduction thereof will not necessarily result in a reduction of fuel consumption. Thus, most of the integration points can be disregarded due to the low grade of the conventional heat source. However, a reduction of exhaust steam could increase the cogeneration of electricity or save bagasse and coal by reducing live steam let-down.

Although the solar resource in the sugar producing areas of South Africa is relatively low compared to some of the other areas in the country, the expected yield of the solar thermal systems under investigation is reasonably high in relation to the existing systems in the rest of the world. The estimated total yield of the solar thermal systems installed worldwide is approximately 850 kWh/kW$_{th}$ (Mauthner & Weiss, 2014). The average expected yield for the considered integration concepts exceeds 1 000 kWh/kW$_{th}$.

8.2.2 Integration Assessment

A number of 23 potential solar process heat integration points have been identified within a generic sugar mill. However, only 6 of the 23 prospective integration points are regarded as feasible, namely (i) the production of live steam, (ii) the preheating of boiler feed water, (iii) the drying of bagasse, (iv) the production of exhaust steam, (v) the drying of raw sugar and (vi) the heating of mixed juice.

On the one hand, the production of live steam, the preheating of boiler feed water and the drying of bagasse is expected to reduce the fuel consumption of the boiler. On the other hand, the production of exhaust steam and the preheating of air for the sugar drying process is expected to reduce the exhaust steam consumption, which might lead to a reduction of the boiler's fuel consumption from the reduction of live steam let-down. Additionally, exhaust steam demand reduction is expected to result in an increase of electricity production if a pass-out condensing turbine is employed for the generation of electricity to export into the national grid. The heating of mixed juice prior to the tertiary heat exchanger in the clarification unit is not regarded as a priority integration point, but such an intervention would offset the highest degree of bleed vapour.

Although the production of live steam is expected to have the most significant direct impact on the fuel consumption of the boiler, only advanced concentrating solar thermal technology will be suitable to produce steam at more than 360 °C from feed water at 128 °C. A collector field of more than 105 000 m^2 would be required to supply the load of 74 MW_{th}. Such a system is expected to yield approximately 81 400 kWh_{th} during the crushing season given the annual system efficiency of 61 % related to GHI, thereby substituting about 24 % of the factory's heat demand at an estimated cost of R 0.85 /kWh_{th}.

The preheating of boiler feed water is expected to improve the efficiency of the boiler and therefore reduce its fuel consumption. However, most of the South African sugar mills employ waste heat recovery to preheat the feed water. Nevertheless, parabolic troughs can be used to elevate the feed water to 250 °C. A collector field of 20 000 m^2 would be required to provide only 10 % of the heat demand. This can be ascribed to the annual system efficiency of 26 %. The levelised cost of the thermal energy is about R 1.72 /kWh_{th}, which is regarded as relatively expensive.

The drying of bagasse should improve the boiler efficiency significantly. However, solar heat competes with waste heat recovery, since flue gas can also be used to the same extent, unless it is used to preheat combustion air or boiler feed water. Furthermore, a solar field of almost 2 400 m^2 will only be able to provide 24 % of the energy required for the drying of all the bagasse. The LCOH is R 0.91 /kWh_{th}, due to the annual system efficiency of 60 %. Furthermore, this intervention would require noteworthy additional investment, given that the drying of bagasse is not a common practice in South African sugar mills.

The advantage of live and exhaust steam production is the opportunity to supply heat to a multitude of processes with a single intervention. Exhaust steam is the direct heat source of the clear juice preheater, the first evaporator and the sugar drying process and essentially the primary heat source in a sugar factory. This improves the flexibility of solar heat integration. The integration of solar heat into the exhaust steam manifold is expected to reduce the exhaustion of live steam and, therefore, conserve bagasse and coal. However, the true potential of solar exhaust steam production is embodied in the escalation of electricity generation in a combined heat and power scenario. Evacuated tube collectors can be used to provide the energy required for the evaporation of feed water from 128 to 130 °C. A collector field of 90 000 m^2 is required to produce approximately 46 000 kWh_{th} during the season, thereby contributing to a solar fraction of 16 % of the entire factory's thermal energy demand. Approximately 74 % of the annual yield is available during the crushing season at a levelised cost of R 0.57 /kWh_{th}. The annual system efficiency is expected to be approximately 40 %.

The sugar drying process consumes exhaust steam to heat air from ambient to 80 °C. However, the process only requires approximately 1 % of the exhaust steam and consumes about 2 800 MWh per annum. Considering the low process temperature, flat plate water or air collectors can be applied to offset a portion of the process' energy consumption. A solar thermal system of 600 kW_{th}, consisting of 900 m^2 of collectors, is expected to provide approximately 27 % of the process's annual demand. Even though a portion of the waste heat can be recovered, solar heat can still contribute to the heat requirements. The annual system efficiency of 69 % contributes to an estimated levelised cost of heat of R 0.43 /kWh_{th}.

The consumption of V1 can be reduced by preheating the mixed juice prior to the tertiary heater from 95 to 105 °C. The 4 MW_{th} heat demand can be supplied by means of a solar field 3 400 m^2 of evacuated tube collectors. As a result of the annual system efficiency of 46 %, a solar fraction of 18 % can be achieved. The relatively low cost of evacuated tube collectors is expected to result in a cost of R 0.50 /kWh_{th}. However, the relatively low value of V1 eradicates the potential of the integration point.

8.2.3 Economic Assessment

The levelised cost of heat (LCOH) expected for the potential integration points vary from R0.43 to R1.72 /kWh. The LCOH can be improved by utilising a greater proportion of the potential annual energy yield for alternative processes such as sugar refining, electricity generation or bio-ethanol production. A reduction of the installation costs is also expected to reduce the LCOH significantly, since it is equally proportional to the capital expenditure. This can be achieved by obtaining of grant funding.

The IRR associated with a typical solar thermal project is expected to range between 5 and 25 %. Although the IRR is highly sensitive to the variation of the capital cost and the utilisation rate, the energy value is of utmost concern to the sugar industry, due to the low cost of thermal energy. The value of the energy in most sugar mills is expected to vary between R 0.30 and R 1.20 /kWh_{th}, depending on the steam grade and the fuel source. If the energy value is only R 0.65 /kWh_{th}, the typical hurdle rate of 15 % can be attained. Even if the value of conventional energy source is as low as R 0.45 /kWh_{th}, the IRR is expected to exceed the typical WACC of 10 %. Therefore, solar process heat can be regarded as a financially feasible opportunity.

8.2.4 Concluding Remarks

On the basis of this study alone, it is challenging to quantify the exact potential of solar thermal process heat in the South African sugar milling industry. However, it has been shown that it is technically and financially feasible to employ this technology to reduce the bagasse and coal consumption, as well as to increase the electricity cogeneration potential of a typical raw sugar factory.

The most noteworthy advantages of the integration of solar thermal process heat in the sugar industry include the potential reduction of coal consumption, the increase of surplus bagasse for the production of by-products, and the increased generation of cogenerated electricity. The potential levelised heating costs are relatively low and favourable returns can be attained by the adoption of solar thermal technology.

Based on the results of this preliminary study, however, the opportunity of solar thermal process heat integration into the sugar production industry is regarded as technically and financially feasible, although there are some entry barriers that have to be overcome. According to the integration and economic assessments, the production of live and exhaust steam and the drying of bagasse and raw sugar are the most promising solar heat integration points.

8.3 Recommendations for Further Work

The study highlights the opportunities for solar process heat in a typical sugar factory. Although the results are favourable towards the adoption of solar thermal technology, there are aspects that should be explored in further detail.

The potential solar gains provided in this study are based on preliminary integration concepts and yield simulations. It is, therefore, recommended that detailed hydraulic designs are developed in order to estimate the integration costs and solar gains in more detail. Nomograms should be developed to optimise the design of the collector field and storage volume of each of the prioritised integration concepts, as proposed by Hess et al. (2011).

The optimisation of solar heat integration into the sugar production process, according to the current design and operating strategies of the industry, is expected to require comprehensive engineering and design in collaboration with sugar technology experts.

Furthermore, the annual heat demand of the integration points in this study is based on a singular operation time for all the processes. Although this method provides a good idea of the extent of the processes' heat demand, the actual operation times of the various integration points should be determined to refine the general outcomes of this study.

Approximately 25% of the locally produced sugar is refined (Smith et al., 2013). Five of the South African sugar factories are equipped with back-end refineries (Smithers, 2014). According to Rein (2007), steam production is one of the most important contributors to the cost of sugar refining. The sugar refining process includes the melting and clarification of raw sugar, as well as evaporation, crystallization and drying of the refined sugar. Most of the processes occur at a temperature below 85 °C, which can be supplied in principle by solar thermal technology. Therefore, the opportunities of solar process heat integration in sugar refineries could also be explored.

Researchers are considering the potential contribution of organic residues from the sugar milling industry for the production of bio-ethanol. The ethanol fermentation and distillation process also requires low-temperature process heat, which can be supplied by solar thermal technology.

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Addendum A Thermal Energy Balance

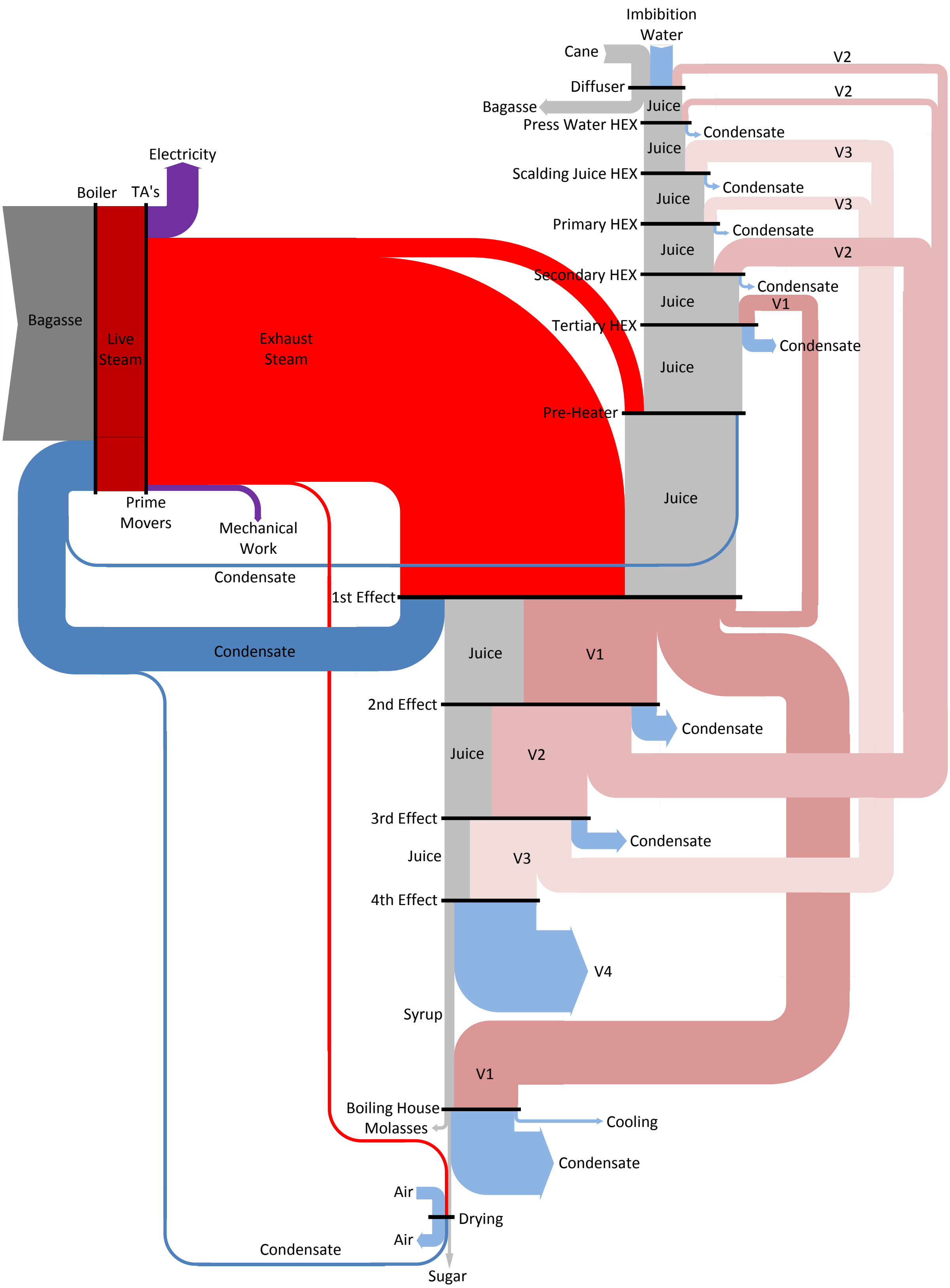

Figure A-1: Thermal Energy Balance (Based on values from Starzak & Zizhou, 2015)

Addendum B Integration Point Assessment

Table B-1: Assessment of the Integration Points within a Typical Sugar Mill

IP	Heat Sink	Process Medium	Mass Flow [t/h]	Fuel Offset	Inlet Temp [°C]	Final Temp [°C]	Temp Lift [°C]	Mean Load [MW]	Annual Heat Demand [MWh/a]	Potential Integration Concept
1	Live Steam	Live Steam	103	Bagasse /Coal	128	360	232	74	341 510	SL_S_PI
2	Feed Water Preheater	Feed Water	103	Bagasse /Coal	129	240	111	14	64 610	SL_S_FW
3	Make-Up Water Pre-Heater	Make-Up Water	0,2	Exhaust Steam	25	130	105	N/A	N/A	SL_S_MW
4	Combustion Air Heating	Air	N/A	Bagasse /Coal	25	200	175	N/A	N/A	N/A
5	Bagasse Drying	Bagasse	21	Bagasse /Coal	75	N/A	N/A	1,67	7 707	PL_E_IS
6	Diffuser	Juice	N/A	Vapour 2	80	N/A	N/A	3	13 845	PL_S_LP
7	Scalding Juice HEX	Scalding Juice	333	Vapour 3	25	100	75	6	27 690	PL_E_PM
8	Imbibition Water HEX	Imbibition Water	112	Vapour 2 & 3	57	80	23	N/A	N/A	PL_E_IS
9	Press Water HEX	Press Water	230	Vapour 2	70	80	10	2	9 230	PL_E_IS
10	Primary HEX	Mixed Juice	333	Vapour 3	65	75	10	4	18 460	PL_E_PM
11	Secondary HEX	Mixed Juice	337	Vapour 2	75	95	20	8	36 920	PL_E_PM
12	Tertiary HEX	Mixed Juice	337	Vapour 1	95	105	10	4	18 460	PL_E_PM
13	Lime Milk HEX	Lime Milk	3	Vapour 2	20	105	85	N/A	N/A	PL_E_IS
14	Mud HEX	Mud	48	Vapour 3	99	100	1	N/A	N/A	PL_E_IS
15	Clear Juice HEX	Clear Juice	287	Exhaust Steam	100	114	14	4	18 460	PL_E_PM
16	1st Effect	Clear Juice	287	Exhaust Steam	114	121	7	58	267 670	PL_I
17	2nd Effect	Syrup	197	Vapour 1	120	110	-10	34	156 910	PL_I
18	3rd Effect	Syrup	139	Vapour 2	110	95	-15	25	115 375	PL_I
19	4th Effect	Syrup	96	Vapour 3	95	60	-35	20	92 300	PL_I
20	Boiling Pans	Syrup	60	Vapour 1	59	60	1	16	73 840	PL_I
21	Remelter	Syrup	4	Vapour 3	50	70	20	0,025	115	PL_E_PM
22	Dryer	Sugar / Air	32	Exhaust Steam	25	80	55	0,6	2 769	PL_E_IS
23	CJ HEX, 1st Effect, Dryer	Exhaust Steam	103	Bagasse /Coal	128	130	2	63	288 899	SL_S_PI

Addendum C Solar Gains

The expected solar gains of the respective integration concepts are provided in Table C-1. The mean load and temperature characteristics are based on the processes' steady-state heat demand data provided by the BRTEM model (Starzak & Zizhou, 2015).

Table C-1: Solar Gains Estimations with Annual (A) and Seasonal (S) System Efficiencies

Heat Sink	Mean Load [MW_{th}]	Process Return Temp [°C]	Max Process Temp [°C]	Collector Type	System Efficiency [%]		Specific Gains [kWh/m^2a]	Max Field Size [m^2]	Solar Fraction [%]
					A	S			
Live Steam	74	128	360	PTC-HT	61	61	1 110	105 714	24
Feed Water	14	128	240	PTC-LT	25	26	455	20 425	10
Exhaust Steam	62	128	130	PTC-LT	29	31	535	89 238	12
				ETC	38	42	689	89 238	16
Juice Heating	4	95	105	ETC	44	48	797	5 638	18
				FPC	35	48	637	5 638	15
Bagasse Drying	2	26	200	FPC	58	64	1058	2 381	24
Sugar Drying	1	26	80	FPC	66	72	1203	899	27

The expected solar gains are based on rudimentary simulations provided by Hess (2015). However, the anticipated gains for the production of live steam are based on an assumed annual system efficiency of 55 % with regard to DNI. The results of the monthly yield simulations of the integration concepts have been used to calculate the annual system efficiency of the respective concepts in relation to the GHI as a basis of comparison. The seasonal system efficiency provides an estimation of the efficiency of the proposed systems during the crushing season[14].

The collector fields have been pre-dimensioned according to the mean thermal loads of the processes. As a rule of thumb, the installed capacity of the collectors have been assumed to be 0.7 kW_{th}/m^2. The solar fraction is based on the estimated energy consumption of the process and the estimated solar gains during the crushing season.

[14] The crushing season typically stretches from March to November.

Addendum D Integration Concept Assessment

Table D-1: Integration Assessment of the Most Suitable Integration Concepts

IP	Heat Sink	Integration Concept	Maximum Plant Size [m²]	Annual System Efficiency [%]	Solar Yield [MWh/m²a]	Seasonal Utilisation Rate [%]	Solar Fraction [%]	Replacement of Waste Heat or Heat Recovery
1	Live Steam	SL_S_PI	105 714	61	81 400	69	24	N/A
2	Feed Water Preheater	SL_S_FW	20 000	26	6 424	71	10	Economiser
5	Bagasse Drying	PL_E_IS	2 386	60	1 859	74	24	Flue Gas
12	Mixed Juice Heating	PL_E_PM	5 714	46	3 361	74	18	N/A
22	Sugar Drying	PL_E_IS	900	69	795	73	27	Wet Air
23	Exhaust Steam	SL_S_PI	90 000	40	45 900	74	16	N/A