

Solar Thermal Heating and Freeze Concentration for Non-Centrifugal Sugar Production: Design and Performance Analysis

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Abstract: Non-centrifugal cane sugar (NCS), known as Jaggery, is a form of unrefined sugar which contains molasses. The integration of renewable energy resources in the production of NCS, have been analysed. The work investigates the energy requirements of a system incorporating a freeze-concentrator and a solar thermal heater to reduce the reliance on the combustion of bagasse or other fuels in a Jaggery production process. Depending on the extent to which freeze concentration can be incorporated into the process, results show that the minimum theoretical energy required to produce Jaggery can be reduced by 91.30% overall. Although difficult in practice, this theoretical analysis demonstrates that the integration of freeze concentration close to the eutectic limit of concentration has significant advantages. For optimal configuration and ideal operation of the system the analysis reports a requirement of approximately 3.8 MJ to produce a kilogram of Jaggery from cane juice. When typical process efficiencies (furnace, boiling pan, solar thermal collector, and chiller) are included, the energy required ranged from 4.8–5.2 MJ/kg Jaggery. This represents a potential energy saving in excess of 38 MJ/kg Jaggery and a fuel saving of more than 2 kg of bagasse/kg of Jaggery produced.

Keywords: Jaggery; NCS; sugarcane; solar thermal; FC; freeze concentration; bagasse; furnace

Nomenclature

ΔT_d :	Temperature Depression [K]
K_f :	Cryoscopic Constant [-]
K_b :	Ebullioscopic Constant [-]
m :	Molality [mol/kg]
$Brix$:	Ratio of solutes by mass [%]
Q_{0-1} :	Heat from ambient conditions to the first freezing point [kJ]
Q_{1-2} :	Heat from the first freezing point to the second freezing point [kJ]



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Q_{2-3} :	Heat from the second freezing point to the boiling point [kJ]
Q_{3-4} :	Heat from the boiling point to the strike point [kJ]
$Q_{Lat,FC}$:	Heat from latent ice removal [kJ]
$Q_{Lat,V}$:	Heat from latent steam removal [kJ]
Q_{in} :	Heat from the burning of bagasse in the furnace [kJ]
Q_{Loss} :	Heat rejected from the furnace in the form of flue gases [kJ]
C_P :	Specific heat capacity [kJ/kgK]
$C_{P,w}$:	Specific heat capacity of water [kJ/kgK]
$C_{P,1}$:	Specific heat capacity at the first freezing point [kJ/kgK]
$C_{P,2}$:	Specific heat capacity at the second freezing point [kJ/kgK]
$C_{P,3}$:	Specific heat capacity at the boiling point [kJ/kgK]
$C_{p,f}$:	Specific heat capacity at the flash point [kJ/kgK]
T_{in} :	Temperature of cane juice entering the process [°C]
$T_{Fre,1}$:	Temperature of the first freezing point [°C]
$T_{Fre,2}$:	Temperature of the second freezing point [°C]
T_{Boil} :	Temperature of the boiling point [°C]
T_{Fre} :	Temperature of the freezing point [°C]
T_{Strike} :	Temperature of the strike [°C]
T_C :	Temperature of the cold space [K]
T_H :	Temperature of the hot space [K]
T_m :	Mean temperature of the solar collector [°C]
T_{amb} :	Temperature of ambient conditions [°C]
T_{Flue} :	Temperature of the flue gasses [°C]
M_{in} :	Mass fraction into the process [kg/kg]
M :	Mass fraction at the process final concentration [kg/kg]
M_{Flue} :	Mass fraction of the flue gas [kg/kg]
M_B :	Mass fraction of the bagasse [kg/kg]
H_F :	Latent Heat of fusion [kJ/kg]
H_V :	Latent Heat of vaporisation [kJ/kg]
COP:	Coefficient of performance [-]
η :	Thermal efficiency of solar collector [%]
η_0 :	Optical efficiency of solar collector [%]
a_1 :	First thermal loss coefficient [-]
a_2 :	Second thermal loss coefficient [-]
G^* :	Solar Irradiance [W/m ²]
η_F :	Thermal efficiency of furnace [%]
R_m :	Mass Ratio of moisture in bagasse [-]
R_A :	Mass Ratio of ash in bagasse [-]
R_{Bx} :	Mass Ratio of solutes in bagasse [-]
LCV:	Lower calorific value [kJ/kg]
AFR:	Air-Fuel ratio [-]

1 Introduction

Jaggery (also known Panela) is a non-centrifugal sugar (NCS) produced in India, South America, Africa and the Caribbean [1]. Jaggery is golden in colour and is typically produced by the partial reduction of sugarcane juice, although it can be made from other high sugar juices such as date juice or palm sap. It is

composed of glucose and sucrose, whereas white centrifugal sugar contains glucose and fructose [2]. The composition of Jaggery and white centrifugal sugar also differ as Jaggery is a mixture of sugars and molasses whereas white sugar is devoid of molasses. White centrifugal sugar is obtained by applying a centrifugal force to the NCS mixture, as the mixture spins the molasses and sugar crystals separate. The manufacture of white sugar is difficult in a rural context as it involves multifaceted, expensive machinery. Jaggery is more suited to this setting due to the simple process involved in its manufacture, and as such sees little innovation and investment. The demand for Jaggery is high in India and it contributes up to 40% [3] of the nation's demand for sweeteners. It is an important part of the traditional 'Ayurvedic medicine' [2] and has more nutritional value than white sugar as it retains more vitamins and minerals. Around half of the sugarcane harvested in India is converted to 8–10 million tonnes of Jaggery [3] and is a large source of employment in rural India.

Jaggery is a seasonal industry and is dependent on the harvest of sugarcane which occurs between November and April [1], however the demand for Jaggery is year-round which introduces the need for appropriate storage methods for continuous supply. In India, Jaggery is available in three primary forms: solid (Gur), liquid (Kakavi), and powdered (Khandsari). For solid Jaggery the moisture content must be in the range of 5–7% with the optimum being 6% according to the Bureau of Indian standards [3]. Liquid Jaggery, by nature has a higher water content of 30–36%. Total NCS production in India is comprised of 80% solid Jaggery and 20% liquid or powder Jaggery [3]. In the present study, Jaggery produced by the proposed process has moisture content of 5%.

The main market competition for the Jaggery industry is the white sugar industry, and from 1971 to 2010 the amount of sugarcane utilised for Jaggery production has dropped from 55.81% to 25.29% of the available sugarcane, while the demand and sugarcane utilisation for white sugar has increased [4]. This is a clear downturn as historically Jaggery has been the most popular form of sweetener in India. This drop-in market share can partially be blamed on changing trends; consideration must also be given to other factors such as the high energy demand for producing Jaggery. While white sugar is a global industry with high levels of research and established modern methods of production, Jaggery is typically a rural industry, and as such it is probable that white sugar is made in a manner more efficient than Jaggery. Despite this, there is certainly still a market for Jaggery, and a modern approach to the production process may be able to revitalise the industry.

Much of the research to improve the Jaggery production process has focused on increasing the efficiency of bagasse furnaces and boiling pans. Comparatively little research has investigated how renewable energy can contribute to Jaggery production, and how processes such as freeze separation may be able to radically reduce the specific energy required to produce Jaggery. The current research investigates the potential for energy savings by incorporating alternative processes and technologies, namely freeze concentration, and solar thermal heating to significantly decrease the need for bagasse fuel; the eventual aim is to reduce greenhouse gas emissions and to significantly increase the economic viability of the Jaggery industry.

Jaggery is traditionally produced by crushing sugarcane, separating the cane juice from the fibrous matter known as bagasse, which is largely made up of cellulose and lignin. When dried, bagasse can be used as a biomass fuel source [5]. The cane juice is then heated to its boiling temperature in open pans suspended above furnaces which burn the bagasse. During this process, impurities in the mixture rise to the top and are skimmed off; chemical clarificants are also added to ensure the Jaggery product has a golden yellow colour which is perceived as a mark of quality [6]. The moisture is then boiled out of the juice until the juice reaches a concentration of roughly 84°Bx. At this point, it is heated to its strike point temperature (~118°C), to ensure the maximum moisture removal. The strike point temperature is the point at which the sugar completes a single crystallisation process [7]. The solution is then transported to pans where it can cool for a time, while more moisture is removed by evaporation caused by the residual

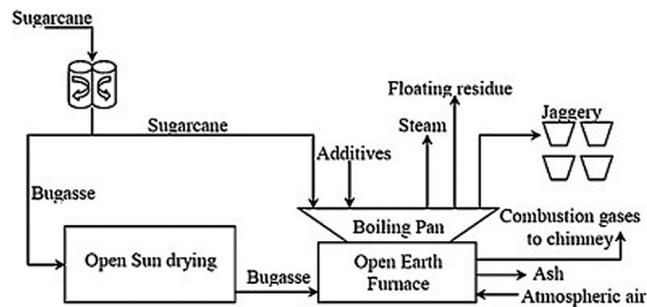


Figure 1: Schematic of conventional jaggery process [7]

heat within the syrup. Once the syrup has cooled to ambient temperature ($\sim 30^{\circ}\text{C}$), it can be transported into moulds where it solidifies into Jaggery blocks [6]. This process is shown diagrammatically in Fig. 1.

The bagasse burnt during the traditional Jaggery production process results in the emission of a significant amount of greenhouse gases, De Figueiredo et al. [8] found that the equivalent of 2.41 kg of CO_2 is released per kilo of sugar produced. This emission not only contributes to GHG emissions but also has an adverse effect on the health of the workers and labourers present during the process. Limiting the amount of bagasse burnt can significantly reduce both these effects, and thus is a worthwhile pursuit from a human health and environmental perspective.

The process of Jaggery production has changed little over the past 100 years and is generally energy inefficient with significant potential for energy savings. Jaggery pans are largely uninsulated and so incur large heat losses to the environment [6]. The traditional method of Jaggery production also does not recover any heat from the flue gases produced during the combustion of the bagasse; this is an issue addressed by the multi-pan production method [9]. The multi-pan method uses pans at different temperatures to increase the energy utilisation of the process. The highest temperature pan is located directly above the bagasse furnace, and thus the highest temperature available is used to heat the juice to its strike point. The lower temperature pans are heated by the flue gases leaving the bagasse furnace. Juice is transferred from pan to pan as it is heated (Fig. 2), and the concept is analogous to a counter-flow heat exchanger.

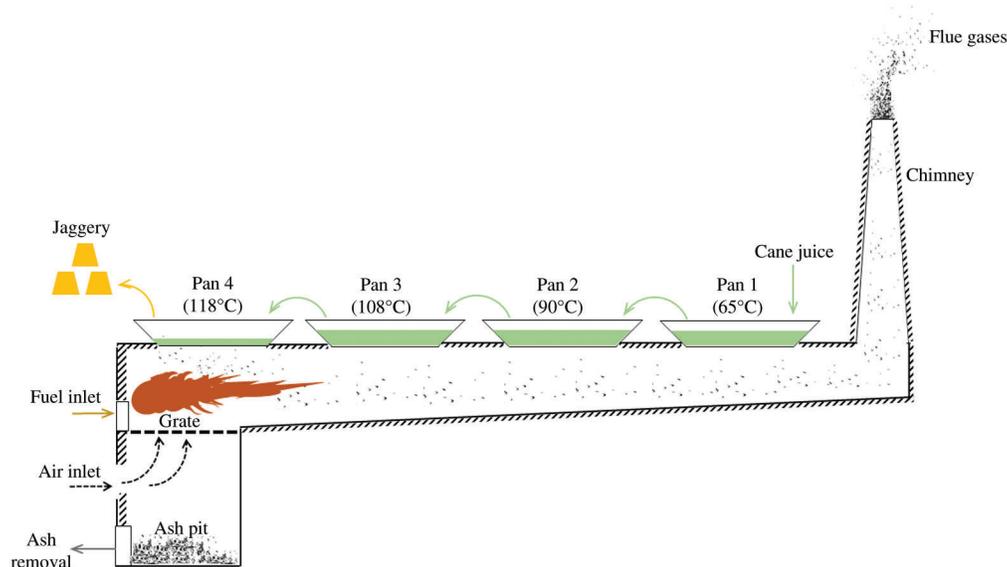


Figure 2: Thermal performance evaluation of a four pan jaggery processing furnace [10]

The method was pioneered by Anwar [9] who achieved a fuel saving of 31.34% with a two-pan system. Sardeshpande et al. [10] evaluated a four-pan system (Fig. 2), and showed a reduction of fuel consumption from 2.39 kg bagasse/kg Jaggery to 1.73 kg bagasse/kg Jaggery, when compared with a single pan furnace.

Venkata Sai et al. [11] also found that an overall heat efficiency improvement of 3.14% (and a 1.70% exergy efficiency improvement) could be achieved by modifying the geometry of the boiling pan. Having a closed pan with a small opening for steam extraction, and a narrower lid diameter than base diameter allowed for these improvements when compared with the traditional method.

Another important consideration when attempting to improve the efficiency of a Jaggery production process, is the method for bagasse drying. Dried bagasse has a higher calorific value [5,12] and also leads to more efficient combustion as less heat is lost to the excess bagasse moisture. In a traditional process, bagasse is sun-dried in large piles [6]. More modern techniques of bagasse drying use flue gases from a combustion process; this drying method reduces the moisture content of the wet bagasse (45–55%) to a moisture content of 30–40%. A solar powered bagasse dryer was designed and tested in 1983 at a biofuel production factory in Consuelo, Dominican Republic, but did not see any wide scale adoption [12]. A new method of bagasse drying, fluidised superheated steam drying (FSSD), has already been applied in the beet pulp industry and has potential for bagasse drying applications also [12]. This method involves the fluidising of superheated steam and bagasse powdered mixture acting as a single fluid within a cyclone. The fluid is then separated by particle size, allowing for the smaller moisture droplets to be removed. Dry biomaterial and moisture can then be separated out as they rotate at different radii due to their respective inertias. This method has the potential to dry bagasse to a moisture content of 10–20%, which would give a ‘High Calorific Value’ (HCV) of: 14,641 to 16,602 kJ/kg [5% Ash, 2% Solutes] [10,13]. This method has the potential to utilise the steam that is removed during the juice boiling process however, this would need to be superheated further as the lowest found inlet temperature is 150°C [12].

One identified technology with a high potential to improve the Jaggery production process is solar thermal heating used in conjunction with bagasse burning. Using both bagasse and solar power has been tested in large scale cogeneration plants, which found that the use of solar thermal power could provide a levelised cost of energy of 220 USD/MWh, which would make it a competitive option for renewable power [14]. However, a new area emerging where solar thermal energy can be utilised, is in the pre-heating of cane juice prior to the boiling process. This concept has been investigated previously by Jakkamputi et al. [15]; it was found that using a solar thermal preheater to heat the cane juice to near its boiling point prior to the boiling process, allowed for a potential bagasse saving of 0.236 kg bagasse/kg Jaggery [15]. A reduction in sensible heating of 8.74% has also been experimentally shown by using solar thermal heating to preheat the cane juice [16]. Thus, there is clear potential for solar thermal heating to reduce the energy demand from the combustion of bagasse or other fuel sources.

Another emerging technology which has been applied to the Jaggery industry is the process of freeze-concentration (sometimes called cryoconcentration) and is a form of fractional freezing. This is a process where moisture is removed from a solution by cooling it to just above freezing, at a point where the solvent (water in this case) begins to crystallise [17]. These ice crystals can then be extracted from the solution, concentrating the solute. It is usually used where ingredients are heat sensitive and cannot be concentrated through evaporation [18]. However, it has clear potential for energy saving due in large part to the much lower latent heat of fusion of water compared with its latent heat of vaporisation, as well as the typically higher coefficient of performance associated with cooling, compared to the efficiency associated with heating. Progressive freeze concentration is applicable to many areas, but importantly it is applicable to sucrose solutions and has been shown to produce extremely high concentrations [19]. Early attempts to apply this technique to Jaggery production have shown promise. Rane et al. [20] modelled the

process and predicted bagasse savings of 1.338 kg bagasse/kg Jaggery using a freeze concentrator which increased the concentration of the cane juice by 20°Bx (which is a measure of the solute concentration with in a solution) prior to the evaporation/boiling process [20]. Despite this promise, a key issue with the use of freeze concentration is the significant loss of product in the extracted ice. Rane et al. [21] suggested that applying a freeze concentration step to the Jaggery production process could result in a loss of 32.3% of the available Jaggery yield [21]. While this is high, Pazmiño et al. [22] showed that by using fractionated thawing within a standard freeze concentration process, 50% of the solutes present in the extracted ice could be recovered, and using this in combination with block freeze concentration, ice of 0.3°Bx could be produced [22]. Venkata Sai et al. [11] also proposed that implementing a modified heating pan, a freeze concentrator, and a solar preheater, that as much as 38,120 kg of bagasse could be saved yearly (0.42 kg bagasse/kg Jaggery), assuming 300 ‘clear days’ in a year. The state of the art, when considering a combined process of freeze concentration, solar heating, and efficiency furnace and pans is an area which has not been investigated experimentally. Srinivas et al. [23], has constructed a model of this process, but has not considered the respective efficiency changes brought about by these technologies. Also, the method of temperature elevation and depression calculation, and slightly different latent heat values, and specific heat capacity calculations used. The sensitivity of this process to changing efficiencies has also not been addressed.

The objective of this research is to establish the potential of freeze concentration and solar pre-heating to reduce the specific energy requirement of jaggery production. The changing material properties associated with the concentration and temperature of a sucrose-water solution are accounted for in the analysis; the estimated energy conversion efficiency of each of the processes of the system are taken into account. The sensitivity of the results to efficiency variation is considered; this allows for the optimisation and balancing of these technologies with respect to energy efficiency and fuel usage. These results can then be used to inform design decisions to optimise Jaggery production and to estimate the possible fuel savings of these improvements. The citations utilised in this section can be found in [Tab. 1](#).

1.1 Literature Survey

Table 1: Literature survey

Topic	Citation
Description of Cane Jaggery	[1–3,13]
State of non-centrifugal cane sugar industry in India	[3,4,11]
Traditional non-centrifugal cane sugar production	[6,7]
Non-centrifugal cane sugar production fuels and emissions	[5,8–10,12]
Non-centrifugal cane sugar production with improved pans	[11,24]
Non-centrifugal cane sugar production with solar power	[14,15]
Non-centrifugal cane sugar production with freeze concentration	[18–22]
System and process modelling	[16,23,25]

2 Methodology

MATLAB R2019a has been employed to assess the energy requirements of each stage of the Jaggery production process. The theoretical analysis is used to determine the optimum combination of processes and operating parameters for non-centrifugal sugar production. The energy required to concentrate the cane juice to produce Jaggery has been assessed. As shown in [Fig. 3](#), it does so in a stepwise manner for

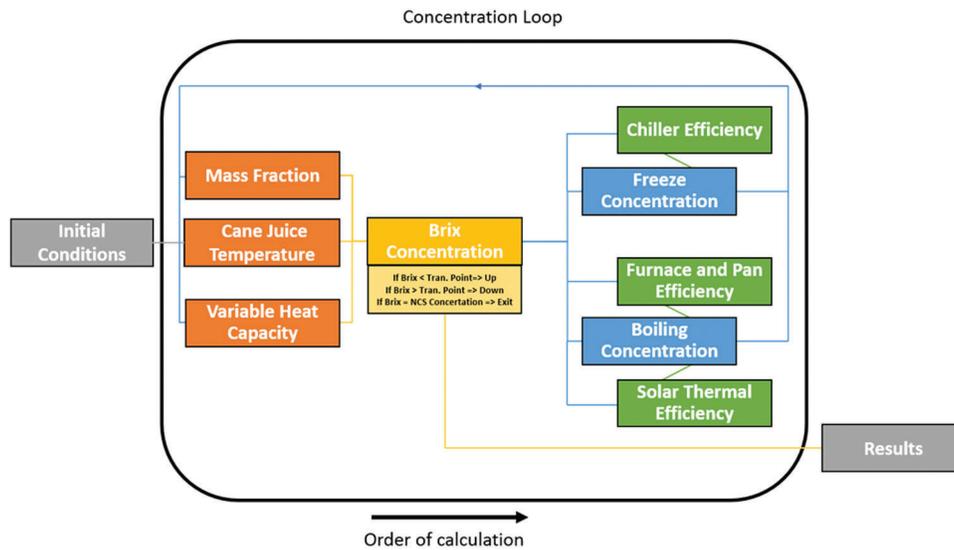


Figure 3: MATLAB flow chart

each concentration increment (°Bx) and for sequential processes of freezing, heating and evaporation. The heat removed by the freeze concentration system per degree brix is calculated from its initial state to a predefined transition concentration where the heating and evaporation process start. The energy required to increase the concentration of the cane juice and when combined with individual process efficiencies calculates the energy required by each process (freeze concentration chiller, solar thermal preheater, and bagasse furnace), has also been calculated.

2.1 Solution Properties

‘Brix’ (°Bx) is a measure of concentration by mass and indicates the ratio of sucrose to water in a solution [6,26]. It is typically determined by using the refractive index of the solution [27]. In an ideal water-sugar solution, both the freezing point, and boiling point of the solution depress and elevate respectively as the concentration of solute within the solution increases. The change in freezing point can be calculated using a simple linear relationship known as ‘Blagden’s Law’. The boiling point can also be calculated in a very similar fashion. It should be noted that in both cases, it is assumed that the actual concentration of the solution is equal to the concentration measured by the solutions mass, and thus the ‘van’t Hoff factor’ can be ignored.

$$\Delta T_d = K_f * m \tag{1}$$

$$\Delta T_e = K_b * m \tag{2}$$

where ΔT_d is the magnitude of the temperature depression of the freezing point; ΔT_e is the magnitude of the elevation of the boiling point temperature; k_f and k_b are linear constants known as the cryoscopic constant, and the ebullioscopic constant respectively and m is the molality of the solution. The cryoscopic and ebullioscopic constants are dependent on the nature of the solvent; for water they are 1.853 kgK/mol and 0.512 kgK/mol [28,29] respectively.

Eqs. (1) and (2) are used to determine the variation of the freezing and boiling points of the solution as the sugar concentration varies; the relationship are plotted in in Figs. 4a and 4b. These are important fluid properties needed to accurately determine the rates at which concentration can be increased in cooling and boiling processes.

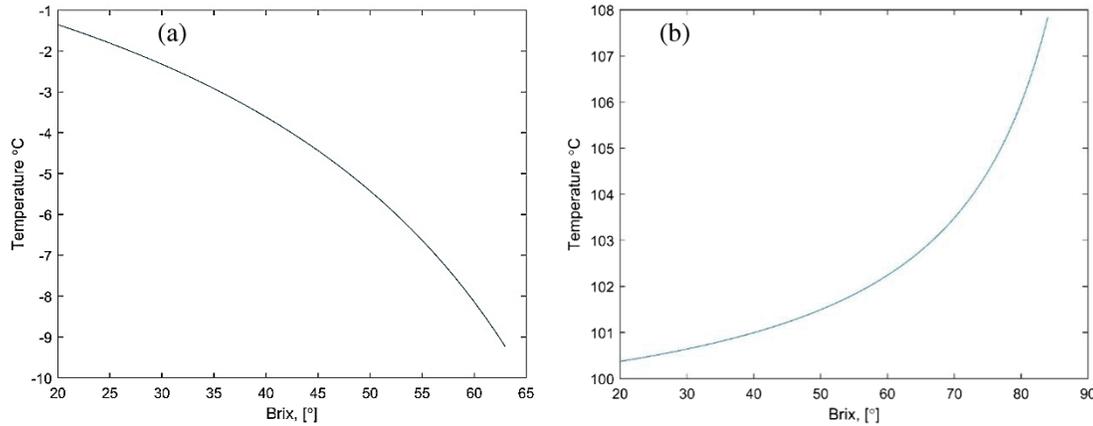


Figure 4: (a) Cryoscopic temperature depression and (b) Ebullioscopic temperature elevation

A sucrose-water solution is a eutectic solution i.e., a solution that has a freezing point which is lower than the freezing point of the solute (or the solvent) and as such can be separated by partial crystallisation [30] (freeze concentration). Eqs. (1) and (2) demonstrate an increasing rate of change of temperature point, with respect to concentration, in both cases (depressed freezing point, and elevated boiling point). This effect is, however, limited by the ‘eutectic point’, the temperature below which the entire solution will freeze, and water content alone will not partially crystallise. As the concentration of the solution relates to its freezing point, the eutectic point temperature corresponds to a specific concentration of the solution. In the case of an ideal sucrose-water solution, its eutectic temperature is -9.24°C , which corresponds to a concentration of 63°Bx [21]. This is the theoretical concentration limit of freeze concentration, and as the concentration of Jaggery is 88°Bx , freeze-concentration alone is insufficient to produce Jaggery.

The specific heat capacity of a solution has been shown by Hugot [25] to decrease linearly with increasing concentration as indicated by Eq. (3):

$$C_P = C_{P,w} * (1 - 0.0056 * Brix) \quad (3)$$

where, $C_{P,w}$ is the specific heat capacity of water (4.187 kJ/kgK).

2.2 Freeze Concentration

The energy required for a freeze concentration process includes sensible heat removal from the initial temperature to its freezing point, latent heat removal and further sensible heat removal associated with the depression of the freezing point which occur concurrently. These are calculated using the Eqs. (4)–(6). It should be noted that mass is not included in Eq. (4) as initially it is assumed that the mass is unity, and all subsequent masses are fractions of this.

$$Q_{0-1} = C_{P,1}(T_{in} - T_{Fre,1}) \quad (4)$$

$$Q_{Lat,FC} = H_F(M_{in} - M) \quad (5)$$

$$Q_{1-2} = \frac{C_{P,1} + C_{P,2}}{2} (T_{Fre,1} - T_{Fre,2}) \frac{1 + M}{2} \quad (6)$$

where, $C_{P,1}$ and $C_{P,2}$ are the heat capacities of the cane juice at the initial concentration final concentration levels respectively; $T_{Fre,1}$ and $T_{Fre,2}$ are the freezing points of the cane juice at the respective concentration

values. The mass of the cane juice at that final concentration is M , and the mass of the cane juice input into the process is M_{in} , H_F is the latent heat of fusion of water (333.55 kJ/kg).

It is assumed that the process of heat removal due to the depression of the freezing point is linear, and so the ‘average’ specific heat capacity and mass (this is the first process and so the initial mass fraction is unity) are used, accounting for the fact that both the specific heat capacity, and mass change throughout the process. This is reasonable as the equations are solved in a stepwise manner, solving to one concentration, recording the result, then beginning again, except solving to a slightly higher concentration.

Freeze concentration has the potential to be a very energy effective process, as the electrical energy required to cool the solution is factored by a Coefficient of Performance. The coefficient of performance of an ideal reverse heat pump is indicated in Eq. (7):

$$COP = \frac{T_C}{T_H - T_C} \quad (7)$$

where T_C is the freezing point of the solution i.e., the required chiller temperature, and T_H is the temperature of the environment. For the relevant range of temperatures, the ideal coefficient of performance ranges from approximately 8.5 to 6.5 based on the freezing temperature depression and an ambient temperature of 30°C.

Rane et al. [21] found that a freeze concentration chiller, typically performed at an efficiency ($\eta = Actual\ CoP / Ideal\ CoP$) between 50% and 66.67%, thus the actual coefficient of performance will operate within the range of 3.25 and 5.7 depending on solution and ambient temperatures. The two limit curves have been plotted against concentration in Fig. 5. This relationship is used in a sensitivity analysis calculation, in order to investigate the influence of chiller efficiency on the specific energy requirements of the sustainable Jaggery.

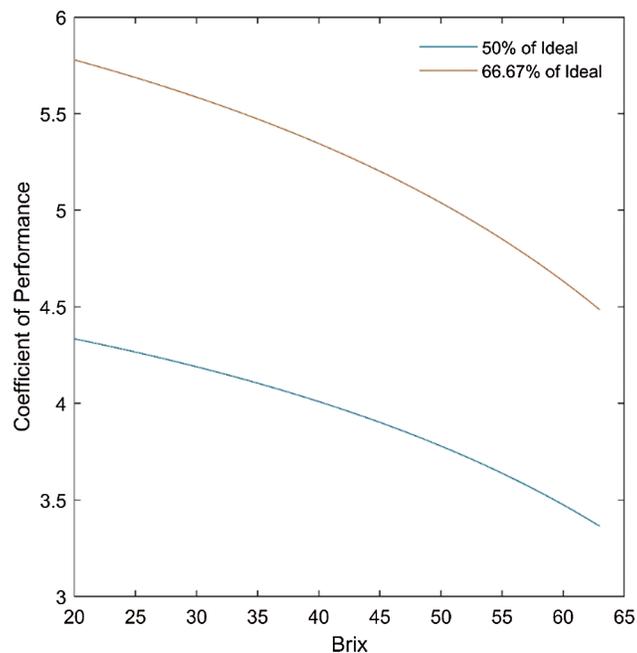


Figure 5: CoP of chiller-limit curves

2.3 Evaporative Concentration

Sensible heat addition from the freezing point to the boiling point, and the latent heat addition to remove the moisture through vaporisation are calculated. The sensible heat addition is from the boiling point to the strike point temperature, instead of to the elevated final concentration boiling point, as to produce Jaggery, the cane juice must be heated above its boiling point to a specific temperature (strike temperature). Eqs. (8)–(10) are used for this process:

$$Q_{2-3} = C_{P,2}(T_{Boil} - T_{Fre})M_{in} \quad (8)$$

$$Q_{Lat,V} = H_V(M_{in} - M) \quad (9)$$

$$Q_{3-4} = \frac{C_{P,2} + C_{P,3}}{2}(T_{Strike} - T_{Boil})\frac{M_{in} + M}{2} \quad (10)$$

where, T_{Boil} and T_{Fre} , are the boiling and freezing point temperatures at the transition from freeze concentration to evaporation concentration; $C_{P,2}$ is the specific heat capacity at this stage and $C_{P,3}$ is the specific heat capacity of the cane juice at the step concentration (as the solver reruns the equation at each step, in the final step $C_{P,3}$ will have a specific heat capacity corresponding to the specific heat capacity of pure Jaggery). T_{Strike} and H_V are both constants and are the strike point temperature ($\sim 118^\circ\text{C}$), and the latent heat of vaporisation of water (2256.4 kJ/kg).

Heat is required to increase the temperature of the solution sensibly and to evaporate moisture to increase the concentration. Solar thermal has the potential to add zero carbon heat and the characteristic performance of the system is assessed here. Eq. (11) relates the efficiency of the collector to temperature difference between the solution and the environment for a fixed solar irradiance.

$$\eta = \eta_0 - a_1 \frac{T_m - T_{amb}}{G^*} - a_2 \frac{(T_m - T_{amb})^2}{G^*} \quad (11)$$

where η_0 is the maximum or zero-thermal-loss efficiency (optical efficiency) of the collector; a_1 , and a_2 are collector thermal loss coefficients. The mean internal collector temperature is T_m (i.e., the temperature of the fluid output by the collector); T_{amb} is the ambient temperature and is G^* is the solar irradiance.

The efficiency curves of three typical solar thermal collectors are plotted in Fig. 6 and are sourced from Solar Keymark certification of each collector [31–33]. These data are used to calculate the energy required to sensibly heat the cane juice from ambient temperature to its boiling point. Of the three collectors considered, two are evacuated tube collectors, and one is flat plate solar collector. It should be noted that the DF100 evacuated tube collector performs at a base efficiency significantly above what is typical for evacuated tubes.

The data presented in Fig. 6, however, extends beyond the usual range of temperatures of a solar thermal collector to include mean operating temperatures that are below the ambient temperature. This is to allow consideration of the scenario where the cane juice enters the collector after a freeze concentration process. As evident in this, the maximum efficiency is now greater than the η_0 optimal efficiency and the a_1 and a_2 thermal loss coefficients represent coefficients of thermal gain from the surroundings. In the case where the collectors are used to heat the juice from ambient temperature, the DF100 evacuated tube collector had a higher overall efficiency. However, in the case where the collector is required to heat the cane juice from its freezing temperature, the HPC25 flat plate collector performed better overall. This is due to HPC25 collector operating at a higher efficiency until around 60°C mean temperature, at which point the evacuated tube collector becomes less efficient. For this reason, the HPC25 flat plate collector is the more efficient collector for wider range of temperatures.

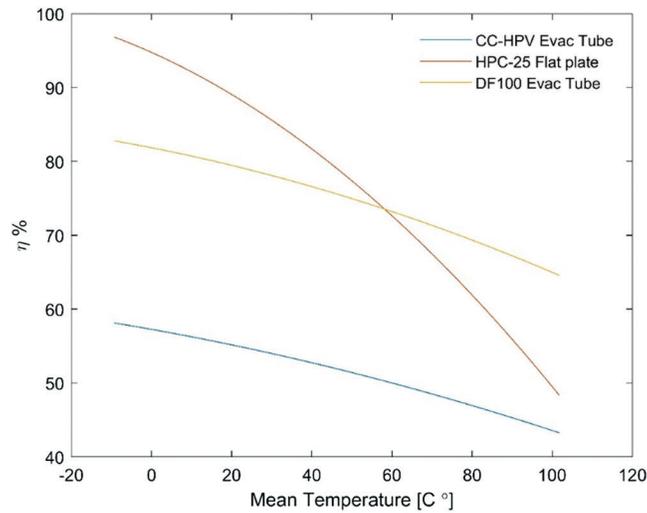


Figure 6: Efficiency curves of solar thermal collectors

As solar thermal efficiency decreases significantly at higher temperatures, it is necessary to use a furnace to further concentrate the solution in boiling pans. Many studies have investigated the pan efficiency [9,10] and their findings are used as inputs to inform the efficiency assumed here. Anwar established that the ‘heat utilisation efficiency’ [9] can be increased from 20.12% for an un-finned pan to an efficiency of 29.56% for a finned pan [9].

The calculation of the furnace efficiency is somewhat more complex and uses the heat lost in the flue gas as to calculate the efficiency. First the lower calorific value of the bagasse burnt is calculated using Eq. (12) from Sardeshpande et al. [10].

$$LCV = 18260 - 207.1R_m - 182.06R_A - 37.1R_{Bx} \tag{12}$$

where, R_m , R_A , and R_{Bx} , are the respective ratios of moisture, ash, and solutes (all by mass) to the total mass of the bagasse. A typical bagasse furnace air-fuel ratio, which has been calculated by Cortez et al. [25], of 3.208 [25] is then used along with the mass of dry bagasse available per kilo of Jaggery (also calculated by Sardeshpande et al. [10]), to calculate the mass of flue gases exiting the furnace, Eq. (13).

$$M_{Flue} = AFR * M_B \tag{13}$$

where AFR and M_B are the air-fuel ratio and the mass of the bagasse respectively.

The mass of the bagasse can then be multiplied with the lower calorific value of the bagasse to give a theoretical heat in Eq. (14)

$$Q_{in} = LCV * M_B \tag{14}$$

The heat lost to the flue gases can be calculated using Eq. (15).

$$Q_{Loss} = M_{Flue}C_{p,f}(T_{Flue} - T_{amb}) \tag{15}$$

where T_{Flue} , T_{amb} , and $C_{p,f}$, are the flue gas temperature, the ambient temperature, and the specific heat capacity of the flue, respectively. A flue gas temperature of 550°C has been used as this is what has been measured in the field and shown to be generally accurate using CFD simulations by La Madrid et al. [24]. Assuming the flue gas is 11% H₂O, 13% CO₂, and 76% N₂, and has a temperature of 550°C, the specific heat capacity of the gas is

1.185 kJ/kg.K [34], using the established specific heat capacities of the constituents. Furnace efficiency can then be calculated using Eq. (16).

$$\eta_F = \left(1 - \frac{Q_{Loss}}{Q_{in}}\right) * 100 \text{ [%]} \quad (16)$$

3 Results & Discussion

3.1 Energy Requirement

Initially the specific energy requirements to produce concentrated Jaggery from cane juice are found; the results here do not account for the efficiency of the technologies used.

The specific energy requirement of each concentration process as a function of concentration is presented in Fig. 7. As indicated in Fig. 7, two scenarios are considered, where the transition from freeze-concentration to evaporation concentration occurs at 40°Bx (typical achievable, [21] and 63°Bx (theoretical maximum)). Heating is then used to increase the temperature of the solution and to further concentrate by evaporation of the water from the solution. Before concentration by evaporation can be achieved however, the solution requires sensible heat to take the concentrated juice from the final FC chiller temperature to the solution's boiling point.

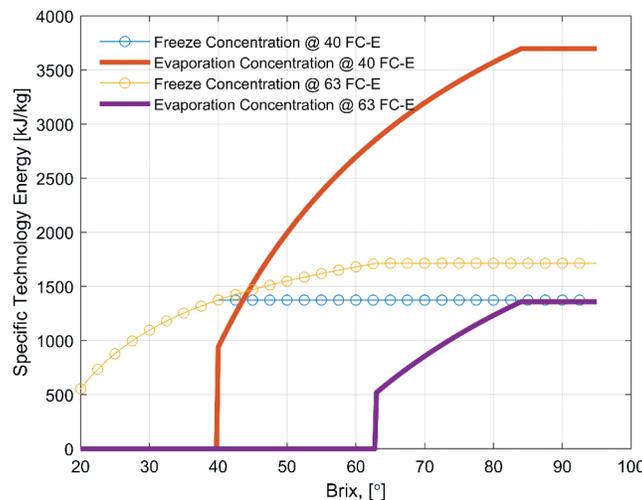


Figure 7: Required energy of concentration methods

The evaporation process requires energy to increase the solution concentration as a combination of latent heating of the water content and sensible heating of the remaining concentrate. At 84°Bx, and when the strike point is reached no further heating is required and further concentration occurs through evaporation as the solution cools, up to a jaggery concentration of 88–95°Bx [6].

A comparison of the total specific energy required to concentrate the juice is presented in Fig. 8 with different FC-E transition points. As indicated in Fig. 7, 19.86% less specific energy is required by the freeze concentrating process for the FC-E transition point of 40°Bx over 63°Bx. The heat required to further increase the concentration from these points is 172.23% higher for the evaporation concentration process, and 65.04% higher overall when transitioning at 40°Bx. This is due to a number of factors: 1) the heat of fusion required to transition liquid water into solid ice is much lower than the heat of vaporisation required to change liquid water into gaseous steam (~334 kJ/kg and ~2,230 kJ/kg, respectively), 2) there is a smaller temperature difference between ambient temperature (typically 30°C)

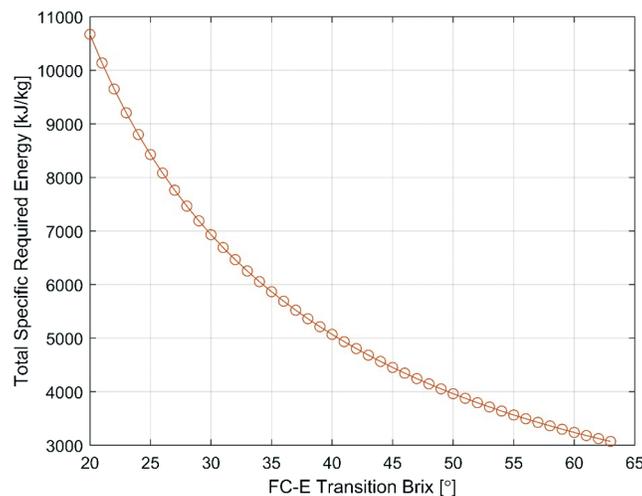


Figure 8: Total required energy at varying FC-E transition points

and freezing temperature (-1.36°C), than there is between ambient temperature and boiling temperature (100.37°C) and therefore the temperature change required to begin the moisture removal process is lower for the freeze concentration process 3) as more moisture is removed from the solution by freeze concentration, less moisture eventually needs to be heated from freezing to boiling temperatures.

The relative benefit of freeze concentration decreases as the temperature of the solution approaches the eutectic point, however. This is, to a small extent, as a result of the reduction of the freezing point temperature as the concentration increases and the subsequent extra heat required to increase the temperature from its freezing point to its boiling point (-1.36°C and -9.24°C , at the initial concentration and the eutectic point concentration, respectively). However, the decreasing energy saving is mostly as a result of the reduced mass to be removed in order to increase the concentration of the sugar solutes within the solution. For example, to increase the concentration from 20°Bx to 40°Bx , 50% of the total solution mass is removed, which corresponds to the removal of 62.5% of the initial water content of the juice. To increase the concentration from 40°Bx to 60°Bx , only 16.67% of the total solution mass must be removed in the form of water, which corresponds to the removal of only 20.83% of the initial water content. Significantly less specific energy is required in the form of latent heat of evaporation, to further increase the concentration.

The data shown in Fig. 8 clearly demonstrates that maximising the concentration by freezing, minimises the overall process energy requirement. Fig. 8 also shows a total specific energy required of 3072.26 kJ/kg Jaggery, at a transition degree of 63°Bx . This is in reasonable agreement with previous similar analysis of this process by Srinivas et al. [23] who estimated that NCS could be produced for 536.10 kJ/kg of Juice (2903.88 kJ/kg Jaggery). The difference can be attributed to a different method in temperature elevation and depression calculation, and to slightly different latent heat values, and specific heat capacity calculations used.

Fig. 9 illustrates the energy required for each concentration increment where the process transitions from freeze concentration to evaporation concentration at the theoretical maximum of 63°Bx .

It should be noted that the sensible heating energies, while still significant, are omitted from this plot. This is because it is assumed that the concentration does not increase during this portion of the process and thus would have an infinite gradient in the plot.

Clearly, the highest energy requirement per degree brix is the initial concentrating energy which requires $79.73 \text{ kJ/kg}\cdot^{\circ}\text{Bx}$; this reduces exponentially to $11.39 \text{ kJ/kg}\cdot^{\circ}\text{Bx}$ at the eutectic point, 63°Bx where the process

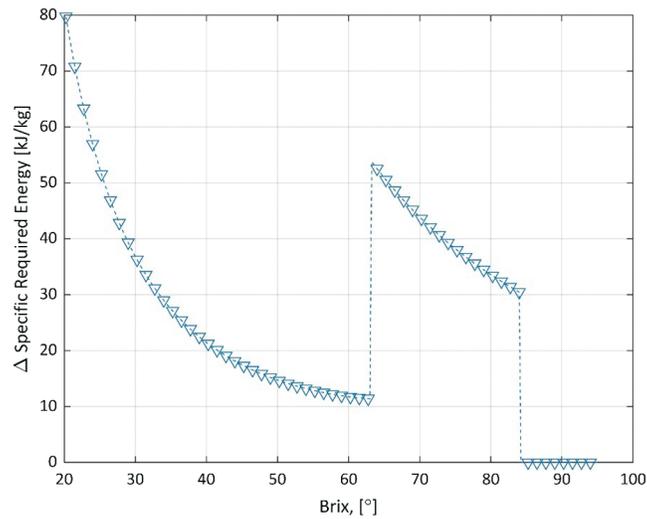


Figure 9: Required Energy per degree concentration

transitions from freeze concentration to evaporation. The energy required then increases 53.81 kJ/kg.°Bx and falls exponentially to 30.48 kJ/kg.°Bx, before dropping to zero as the final concentration can be done without further energy input. This highlights the ‘diminishing returns’ for both the freeze concentration process and the evaporation process, when it comes to how much energy can be ‘saved’ as the concentration increases. This agrees with the previous results (Fig. 7).

With both methods of concentration (freeze concentration, and evaporation), the higher the degree of concentration, the lower the energy requirement to further concentrate. This is much more pronounced in the FC portion, where the minimum energy requirement is only 14.29% of the maximum requirement, whereas the evaporation concentration has a minimum energy requirement 56.64% of the maximum.

3.2 Process Efficiency

Results presented thus far have considered the theoretical minimum specific energy requirement to concentrate cane juice (20°Bx) to form jaggery (84°Bx). As described in Section 2 the coefficient of performance associated with the freezing process and the thermal efficiency of the solar heating and the bagasse burning processes are now considered in this section.

The specific energy required to sensibly cool the cane juice initially to its freezing point is 553.77 kJ/kg Jaggery; this is based on a coefficient of performance (COP) that is 66.67% (the upper limit found by Rane et al. [21]) of the ideal COP. Thus, the specific energy supplied for this initial stage is 95.83 kJ/kg Jaggery, based on this COP. As the water is separated from the juice in the freeze concentration process, the specific energy required then increases for the latent cooling as well as a small proportion of sensible cooling (12.52% of total energy during the freeze concentrating) due to the freezing point depression for the changing solution molality.

The specific heat capacity of the solution decreases as the concentration increases, further reducing the specific energy requirement. This effect, along with the previously mentioned reduction in sensible cooling due to reduction in mass, results in a decrease in the gradient of the curve, from 14.10 kJ/kg.°Bx, until the gradient turns and begins to increase at 47°Bx (where the gradient is 4.98 kJ/kg.°Bx), up to 6.94 kJ/kg.°Bx, when the freeze concentration process ends. This is shown in Fig. 10, with the turning point marked by a circle. This differs from the Fig. 9, which shows the same data but for ‘energy required’. The reason for this increasing gradient is the decreasing Carnot coefficient of performance as the temperature difference

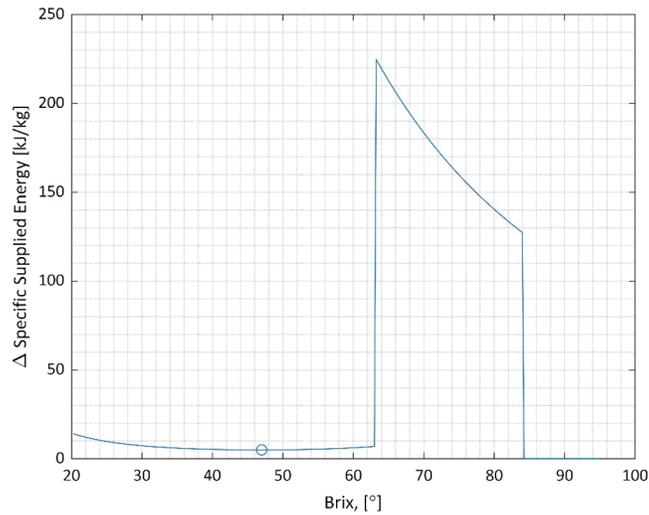


Figure 10: Supplied energy per degree concentration

between the hot and cold space increases, which in turn reduces the maximum coefficient of performance of a chiller. This effect occurs throughout the freeze concentration process, but overtakes the aforementioned energy decreasing effects following the 47°Bx turning point.

Solar thermal collectors, as described in Section 0 are used to provide the sensible heating from the freezing temperatures of the concentrated cane juice to its boiling temperature as part of the evaporation concentration process. In this case the Solar Keymark data for the DF100 Evacuated tube collector is used [31]. As indicated in the Fig. 6, the efficiency of the solar thermal collectors also decreases with increasing fluid temperature. A small portion of the heat (5.6%) is also required as the concentration begins, as a result of the a slight (5.30°C) lift in the boiling temperature as the molality of the solution increases. The overall energy requirement for the evaporation process in Fig. 11 is shown to be approximately 4,400 kJ/kg Jaggery (the sum of ‘Solar Irradiance Energy’ and ‘Bagasse Chemical Energy’ lines); and is approximately a factor of 11.5 times greater than the energy required in the freeze concentration portion of the overall process.

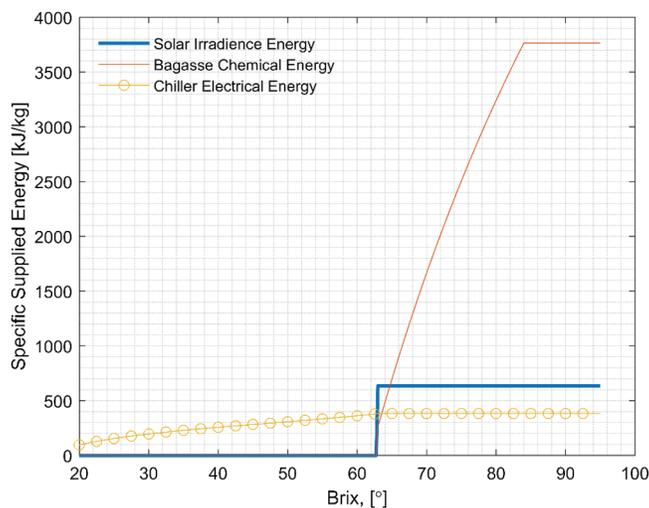


Figure 11: Supplied energy of each system component

While solar thermal can provide 636 kJ/kg Jaggery, 14.5% of the total heat needed to further concentrate the solution by evaporation, the dried bagasse from the sugar cane can be burnt as a fuel to supply a further 3,764 kJ/kg Jaggery. A typical or traditional bagasse furnace and boiling pan have a thermal efficiency of approximately 30%, according to Anwar [9] if the pan is finned, and approximately 20% if the pan is unfinned (a finned pan has been considered). Therefore, the specific heat required from the burning of the bagasse is up to 5 times that needed to evaporate the moisture to concentrate the solution. Importantly, the bagasse heating is also providing the sensible heat to the solution required to reach the 'strike point' (118°C), further increasing the energy requirement from bagasse.

It should also be noted that the change in energy per unit concentration supplied decreases as the concentration increases (Fig. 10). This is due to the decreasing specific heat capacity of the solution as the concentration increases, coupled with the reduced mass needing to be sensibly heated as moisture is removed.

When all these factors are considered, the relative influence of both the freeze concentration followed by the evaporation concentration are evident (Fig. 11) for an FC-E transition concentration level of 63°Bx. For an FC-E transition at 40°Bx, the specific energy required from the burning of bagasse is significantly larger than the other processes (a factor of 11 times larger than the solar contribution, and 47 times larger than the chiller). This is not the case when the FC-E transition is at, or close to the theoretical maximum concentration achievable by freeze concentration (eutectic temperature point). In this case, the energy required by the chiller increases by approximately 49% due mostly, to the increased mass of moisture removed by this process. The solar sensible heating which follows then requires 636 kJ/kg Jaggery. However, this heating process still requires 43% less energy than for the equivalent stage with the 40°Bx FC-E transition point; this is due to the lower mass to be heated to the boiling point. The effect of the larger temperature lift requirement, due to the increased concentration depressing the freezing point and lifting the boiling point is small ($\approx 7\%$). As evident from Fig. 11, the most significant change in specific energy requirement (when compared with specific energy supplied) is that of the bagasse, which now requires 3,764 kJ/kg Jaggery. The energy required by the bagasse furnace corresponds to a bagasse mass of 0.207 kg bagasse/kg Jaggery. This would represent of bagasse saving of 2.2 kg bagasse/kg Jaggery. This large saving in bagasse is due to the much lower latent heat of vaporisation required by this process, which now only needs to concentrate from 63°Bx to 84°Bx. This process is still necessary however, as the concentration of the solution from 84°Bx to 95°Bx, is as a result of the heat addition in this process. Stirring the solution after 84°Bx, and its strike point temperature being reached results in this further concentration, with no extra heat energy addition.

3.3 Sensitivity Analysis

The sensitivity of certain system design parameters is now found. As the focus of the research was to analyse the performance of solar thermal and freeze concentration for jaggery production, the sensitivity of the total specific energy required to solar collector type and chiller efficiency, was considered. As before, the FC-E transition was maintained at 63°Bx, the flue gas temperature is 550°C, and the bagasse burnt is made-up of 63% combustibles, 30% moisture, 5% ash, and 2% solutes.

Fig. 12 shows the total specific energy required for each solar collector type as a function of chiller efficiency. The efficiency range considered here is from 50% to 67% (the range of freeze concentration chilling efficiencies found by Rane et al. [21]) and is a ratio of the expected operating performance of a chiller to the ideal Carnot efficiency.

As expected, the specific energy required decreases as chiller efficiency increases, as more heat can be extracted from the juice with less input energy. However, as the efficiency of the chiller increases, the amount of energy saved overall decreases, and the slope of the curves decrease. i.e., improving the 'efficiency' of a

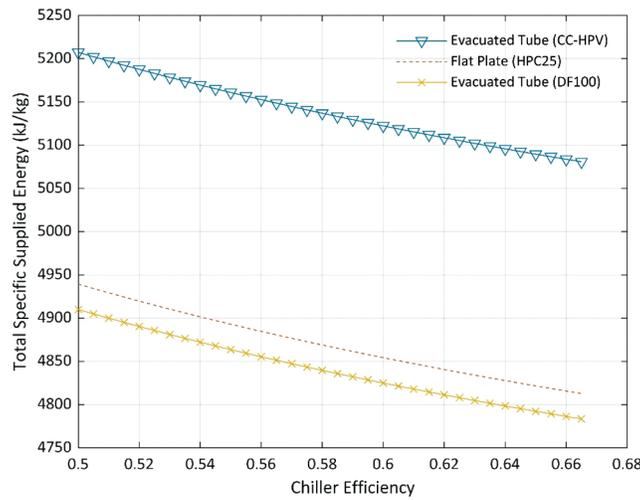


Figure 12: Sensitivity analysis of chiller ‘efficiency’ and collector type

chiller from 50% to 55% results in a 42% increase in energy saving (46 kJ/kg Jaggery) than improving the efficiency of a chiller from 60% to 65% (32.68 kJ/kg Jaggery).

The DF100 Kingspan evacuated tube collector performed best in this case, but only marginally better than the HPC25 flat plate collector. The benefit gained by this collector does, however, decrease at lower chiller efficiencies.

Overall, using freeze concentration and a solar thermal sensible heater results in a total specific energy provision of 5,207 kJ/kg Jaggery, using the lowest chiller efficiency, and the lowest performance collector. Selecting a standard flat plate collector, or a top specification evacuated tube collector can result in a saving of between 268 kJ/kg Jaggery and 297 kJ/kg Jaggery compared with using a standard specification evacuated tube. Using the upper value for chiller efficiency, a saving of 126. kJ/kg Jaggery is estimated when compared with the lower value.

Overall an energy provision of 5,207–4,783 kJ/kg Jaggery is predicted, which is much lower than the traditional system which requires a provision of 43,239 kJ/kg Jaggery. Currently about 2.39 kg of bagasse per kg of Jaggery is burnt in a traditional system [10]. The bagasse is assumed to have 30% moisture, 5% ash, and 2% solute contents which corresponds to a lower calorific value of 18,096 kJ/kg Bagasse. It should also be noted that in all calculations, the efficiency of the bagasse furnace and boiling pan is the lowest of the three concentration processes. Thus, the traditional method consumes 43,249 kJ/kg Jaggery, which means that using freeze concentration and solar could represent a potential saving of as much as 38,467 kJ/kg Jaggery, which corresponds to 2.13 kg of bagasse per kg Jaggery. However, this is slightly misleading, as the energy type required by this system is slightly different than the traditional system. As the freeze concentrator requires electrical energy, and the solar thermal collector requires solar energy. In an ideal system 3,764.36 kJ/kg of bagasse supply energy is required, which corresponds to 0.21 kg of bagasse, so in fact bagasse savings could be as much as 2.18 kg of bagasse/kg of Jaggery, if 636 kJ/kg Jaggery, and 382 kJ/kg Jaggery, are supplied by a solar thermal heater, and a chiller, respectively.

Table 2: Traditional and proposed system total energy

	Traditional System	Proposed System
Total Specific Supplied Energy	43.249 MJ/kg Jaggery	4.783 MJ/kg Jaggery

4 Conclusion

The results presented demonstrate that the evaporation process will require more energy than the freeze concentration process; this is true, except in the scenario where the FC-E transition point is close to the 63°Bx eutectic limit. The total energy required by a system which transitions at 63°Bx is 39% less than that of a system transitioning at 40°Bx. In order to minimise the specific energy requirement therefore, the point where a system transitions from a freeze concentration process to an evaporation process should be as close to the limit as possible, which results in a specific energy of 3072 kJ/kg Jaggery. This finding has then been used to set the transition point at the eutectic limit in the process analysis portion of this work, as this will minimise the overall energy requirements provided that the 'efficiency'/'coefficient of performance' of the freeze concentrator is higher than the overall efficiency of the evaporation concentrator system. Although, it should be noted that transitioning at 63°Bx may result in significant loss of product, and excessively high solution viscosity [21].

The process analysis demonstrates that the chiller will require a small initial energy input to pre-cool the juice to its freezing temperature (96 kJ/kg Jaggery); thereafter it requires less energy per degree brix as the concentration increases. Preheating with the solar thermal can contribute 14.5% of the heat input required, but the evaporation process will still be highly reliant on the burning of the bagasse, (86% of the heat requirement; 3764 kJ/kg Jaggery). A fuel saving of 2.18 kg of bagasse/kg of Jaggery is predicted (which corresponds to a 91.30% reduction in fuel use/energy required), when incorporating solar preheating and freeze concentration.

The sensitivity analysis demonstrated that an increased chiller efficiency would result in a lower total energy requirement by 126 kJ/kg Jaggery; the analysis also showed that the effect would reduce as the chiller efficiency increased. It is also clear that the DF100 evacuated tube solar thermal collector is the best suited collector to this application, however it is only a marginal improvement (0.6% smaller total energy supplied) over the lower specification HPC25 flat plate collector.

It has been established, that even at the lower end of the 'chiller efficiency' ($\approx 50\%$), freeze concentration can still offer very significant energy saving (38,467 kJ/kg Jaggery). From this it would be advisable for a system designed to again balance the importance of energy saving, versus the extra cost associated with higher specification chilling equipment.

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