CHEMICAL ENGINEERING TRANSACTIONS

VOL. 88, 2021

A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.cetjournal.it

Guest Editors: Petar S. Varbanov, Yee Van Fan, Jiří J. Klemeš

ISBN 978-88-95608-86-0; **ISSN** 2283-9216

DOI: 10.3303/CET2188166

Efficiency Improvement in Sugar Mills through Bagasse Gasification

Umang Kumar, Pratham Arora*

Hydro and Renewable Energy Department, Indian Institute of Technology Roorkee, Uttarakhand, India
pratham.arora@hre.iitr.ac.in

Biomass energy is useful in mitigating greenhouse gases as biomass growth captures CO_2 from the atmosphere. This captured CO_2 is eventually released upon the use of these biomass feedstocks, leading to a short duration carbon cycle. One prominent biomass feedstock is the sugarcane bagasse that is a by-product of sugar mills. Conventionally, the bagasse produced after crushing sugarcane is utilized in mills by directly burning it in the boilers. However, an efficient way of utilizing this biomass fuel would be through gasification. The biomass gasification process produces syngas which can be used as fuel for meeting the heat and power demands of the sugar mill, as well as surplus electricity, which can be supplied to the grid. The present study aims to highlight the efficiency improvement potential of bagasse gasification. The entire sugar mill as well as the bagasse gasification process, have been modeled in the ASPEN Plus® software. Heat integration has been performed to optimize the process flowsheets. The electrical energy generated by combusting bagasse is estimated to be 0.57 kWh/kg of bagasse combusted. In contrast, the gasification process can increase this energy generation up to 1.16 kWh/kg of bagasse at 10 % moisture content (by wt.). This study aims to provide awareness about the cleaner and efficient utilization of the energy that lies dormant in these industrial residues.

1. Introduction

Renewable energy is considered an important contributor in meeting the ever-rising energy demand. Renewable energy based on biomass, particularly bagasse, which is a residue from sugar manufacturing industries can be used for meeting the growing energy demands. Sugar production from sugarcane is an energy-intensive process, requiring both processed steam and electricity. The major inputs in the sugar mills are sugarcane, water, and energy (both steam and electricity), the main output is sugar, and by-products are bagasse, filter cake, and molasses. Bagasse is a lignocellulose fibrous leftover after the sugarcane is crushed and milled in the juice extraction process. Bagasse is produced at a rate of 0.25 - 0.30 t/t of sugarcane crushed. It usually has a high moisture content of about 47-52 % by weight as it leaves the last mill. Conventionally, the bagasse produced after crushing sugarcane is utilized in mills by directly burning it in the boilers. The boiler provides steam to meet the heat requirements. The excess steam is also utilized to produce electricity through steam turbines, making the complete process energy independent. Some sugar mills producing extra electricity are able to export electricity to the grid. Operational data for few selected sugar mills globally is presented in Table 1. There is also a demand to make these sugar mills free from any government subsidy, especially in countries like India (NITI Aaayog, 2020). India is one of the largest producers and consumers of sugar, but less than one-third of the sugar mills have cogeneration facilities (TERI, 2012). The average crushing capacity of an Indian sugar mill is 150 t/h with 136 days of operation. A major part of the cogeneration potential of these sugar mills remains underutilized. The bagasse in these sugar mills is used only for steam production. Recently there is an increased emphasis on the efficient utilization of the bagasse produced. Gasification, a thermochemical conversion method, is regarded as an efficient technology for the conversion of bagasse (Anukam et al., 2016). This study aims to highlight the potential benefits that can be derived by updating the conventional sugar mills with bagasse gasification.

Paper Received: 14 June 2021; Revised: 23 August 2021; Accepted: 10 October 2021
Please cite this article as: Kumar U., Arora P., 2021, Efficiency Improvement in Sugar Mills through Bagasse Gasification, Chemical Engineering Transactions, 88, 997-1002 DOI:10.3303/CET2188166

Table 1: Comparison of operating parameters of sugar mills (Birru, 2016)

S No.	Sugar Mill	Cane (t/h)	Bagasse (t/h)	Electricity consumed (MW)	Electricity exported (MW)	Total Electricity (kWh/t of cane)
1.	Agroval Sugar factory Brazil	500	125	6.5	0	13
2.	Pelwatte Sugar mill, Sri Lanka	150	41	2.2	0	15
3.	Fincha Sugar Factory, Ethiopia	178	54	5	0	27
4.	Aruna sugar mill, India	208	64	6.25	0	31
5.	Ugar Sugar mill, India	416	128	14	30	105
6.	Pioneer mill, Australia	565	176	17	44	108
7.	Mackay mill, Australia	500	132	9	43	105

Modeling and simulation are efficient means to evaluate the potential of any new technology. In the past, different software tools have been utilized for modeling the sugar manufacturing process and the biomass gasification process. Starzak and Davis (2017) have utilized the Matlab® software for modeling the sugar manufacturing process in South Africa. An ASPEN Plus® model replicating the sugar manufacturing process has been proposed by Guest et al. (2019). The ASPEN Plus® software has been utilized by different authors to model the biomass gasification process (Motta et al., 2018), as well as power production from the gasification syngas (Sun et al., 2014). Another study stated that the NO_x and SO_x emissions are very low in the bagasse gasification as compared to the traditional cogeneration plant (Keche et al., 2015). However, the energy integration of the bagasse gasification process with the sugar production process has not received much emphasis. The present study would utilize the ASPEN Plus® software to model the sugar manufacturing process and its integration with the bagasse gasification process. The results would be compared to the conventional sugar manufacturing process using boilers for steam and electricity generation.

2. Sugar Manufacturing

The sugar manufacturing process starts with the arrival of sugarcane at the mill (Figure 1). Then the cane is subsequently prepared for juice extraction. The received cane is washed with water to remove any dirt that has been carried with the cane. These washed-up canes are then cut and shredded. The juice is extracted by using high-pressure mill rollers, which squeeze the juice out of cane stalks. The addition of imbibition water is done for improving the efficiency of the mill; the juice leaving the mill is known as mixed juice. Bagasse is produced as the by-product of milling. This mixed juice is then subjected to clarification. This involves the removal of suspended solids from the juice by including coagulators which will result in the precipitation of mud, waxes, and fiber. These suspended impurities are then filtered out. The clarification process produces clarified juice which is then sent to the evaporation process. The filter cake is the by-product of clarification which consists of lime, fiber, and other impurities. In the evaporation unit, the clarified juice that is obtained from the clarification process is concentrated to form a thick syrup. As the juice travels along the evaporators, water is evaporated in the process resulting in a more concentrated juice or syrup. This syrup formed is then sent to the crystallization module. This procedure includes the formation of crystals. The syrup is boiled at low temperatures under vacuum, which results in the growth of crystals. Centrifuges are utilized for the separation of crystals from the mother liquor. Drying is the final step in the processing of raw sugar before it is packed. The drying process is crucial for the storage purpose of the sugar. Dry air and low-pressure steam are utilized for drying of sugar.

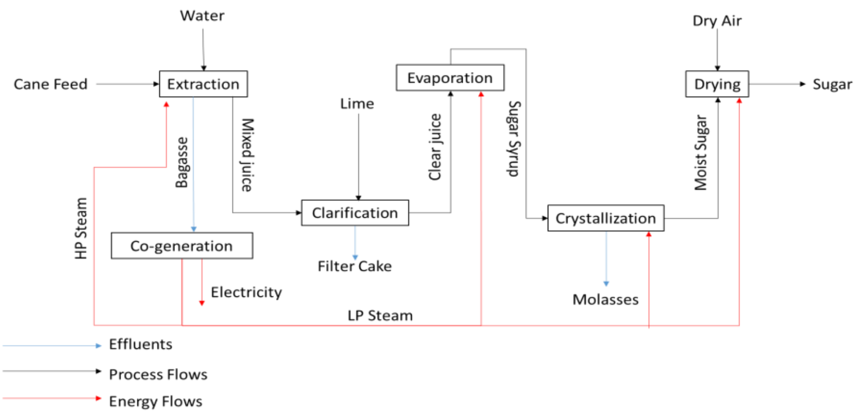

Figure 1. Schematic of a sugar manufacturing industry

Cogeneration is defined as the process of generating both thermal and electrical energy from a common fuel source (Figure 1). In sugar mills, bagasse is used as a fuel source to produce steam and electricity to be utilized in the mill, and surplus electricity is sold to the grid. The bagasse-based cogeneration system uses a topping cogeneration cycle in which electricity is produced first and then steam, which is used for different processes in the sugar mill. The cogeneration system works on a typical Rankine cycle. In this thermodynamic cycle, heat is used in the boilers to convert water into steam which then expands through a steam turbine to generate electrical energy. Cogeneration can also be implemented by using the gasification of bagasse rather than combusting it directly in boilers. For this study, an entrained flow biomass gasifier is considered. This is because of the low tar content in the syngas, ease to fabricate, and simple operation. They are also expected to be more efficient for power generation. The entrained flow gasifiers are expected to be economical beyond 700 t/d of dry biomass intake (E4Tech, 2009). A majority of new sugar mills would produce bagasse beyond this capacity.

3. Methodology

ASPEN Plus® version 9.0 was used to model the sugar mill integrated with a cogeneration plant. The models were developed for the different scenarios of boiler (cogeneration) module viz. gasification and combustion. This study will compare the results between the traditional sugar mill with cogeneration and the sugar mill using a gasification power plant.

3.1 Model Formulation

The chemical components used to assemble the simulation include fructose, lime, sucrose, water, bagasse, and air. Bagasse is defined as a non-conventional component with ultimate and proximate analysis. The UNIQUAC thermodynamic model was used based on the recommendations of Guest et al. (2019). The basic modules available in ASPEN Plus® were used to model different processes in the sugar mill, such as pumps, separators, heaters, heat exchangers, reactors, etc. Cane received in the mill was assumed to have 70 % water, 15 % fiber (bagasse), 13 % sucrose, and 2 % fructose (by wt.). For every 100 t of sugarcane crushed, about 12 t of sugar is produced.

3.2 Sugar Mill Modeling

The different processes in the sugar mill (as shown in Figure 1) was modeled in Aspen Plus® using different modules known as hierarchy. These hierarchies are interconnected to form a basic model of a sugar mill. The flowsheets, along with the stream connections, are shown in Figure 2.

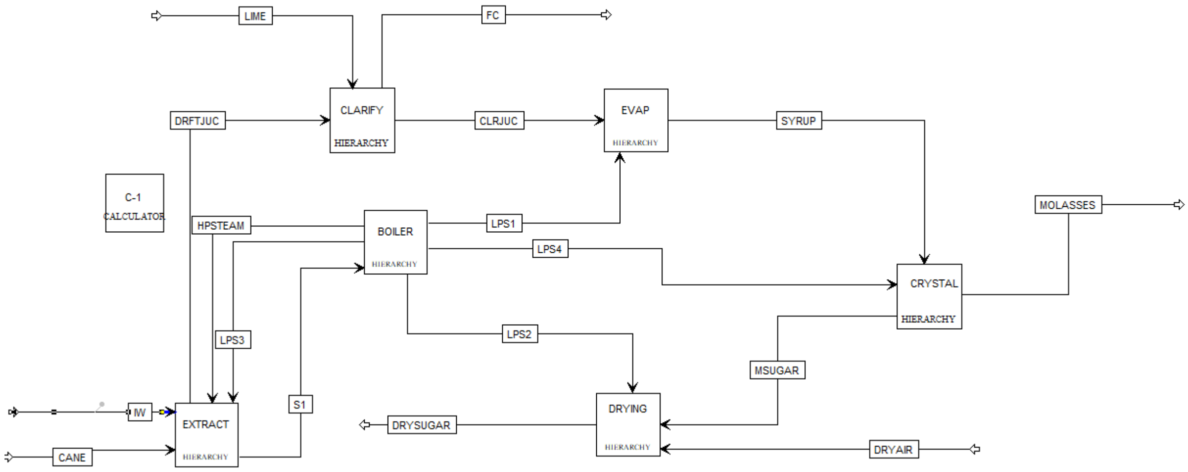

Figure 2. Flowsheet of the sugar manufacturing process

3.3 Sugar Mill Processes

This section elaborates on the methodology adopted to model the sugar manufacturing process.

3.3.1 Extraction Module

The study considers a cane input of 244 t/h and a water input of 110 t/h. The process of cane preparation comprises of turning whole stick cane into fine mulch. After this, sucrose, along with water, can be comfortably extracted from the mulch. This leads to the production of 279 t/h of mixed juice. This module also leads to the production of bagasse (having 50 % moisture) at 75 t/h. The process also utilizes 25 t/h of high-pressure steam for meeting the process requirement of the shredders and the dewatering mills. The boiler flue gas is used for drying the bagasse to 10 % moisture content.

3.3.2 Clarification Module

The juice must be cleaned to remove the suspended particles when extracted from the diffuser. In this clarification module, the impurities are settled, and the pH is optimized by the addition of 7.6 t/h of lime. The lime also helps in preventing sucrose inversion. The mixed juice is then heated and flashed. This heating of the juice is accomplished through the vapor bleed from the multiple-effect evaporators in the evaporation module (not modelled in this study). The phosphates found in sugarcane react with the added lime, which leads to the formation of a calcium phosphate precipitate. In order to settle this precipitate from the mixed juice, a clarifier is deployed. The filter cake is the resulting by-product that contains some bagasse, lime, and other suspended impurities.

3.3.3 Evaporation Module

Clear juice from the clarification module is directed to the evaporation unit to increase the concentration of the sucrose in the juice. Water from the juice is evaporated by exchanging heat from the low-pressure steam that is generated as the exhaust steam from the cogeneration turbine. The juice left after the evaporation is called syrup which is extracted as a primary product from this module. The syrup is sent to the crystallization module for further processing.

3.3.4 Crystallization Module

The objective of crystallization is to recover the maximum amount of sucrose at the highest possible purity. After reducing the water content of the syrup in the pans, massecuite is obtained. This results in a mix of mother liquor and sugar crystals. The massecuite is cooled in huge crystallizing units, where the crystal grows continuously. The massecuite is passed on to centrifugation to separate the mother liquor. The mother liquor is thereafter known as molasses (11 t/h).

3.3.5 Drying Module

To enhance the quality of raw sugar, it needs to be dried. In order to decrease the moisture content of raw sugar, the sugar crystals are placed in a dryer, where dry air is passed through them. Prior to entering the dryer, the temperature of the dry air is raised to 70 °C by the exhaust steam from the turbine. The air heater is modeled using a heat exchanger.

3.3.6 Boiler Module

The dried bagasse is combusted in huge boilers to produce superheated steam at 390 °C and 31 bar. The combustion module is modeled as a standard stoichiometric reactor incorporating combustion reaction and having a thermal efficiency of 98 %. The module works with 15 % excess air. The hot flue gas having a temperature of 500 °C is utilized for bagasse drying. A majority of this steam is then utilized in a steam turbine to produce electricity. The steam turbine is assumed to have an isentropic efficiency of 0.7 (1). The remaining high-pressure steam is sent to the extraction module. The exhaust steam from the turbines is modeled to have a temperature of 121 °C and a pressure of 2 bar. The exhaust steam is utilized to meet the energy requirement of the evaporation, crystallization, and drying modules.

3.3.7 Gasification module

Bagasse combustion uses a steam turbine for electricity generation, whereas bagasse gasification can potentially use both the gas and steam turbine for electricity generation. Another flowsheet was created to replace the conventional boiler with a biomass gasification process. The gasifier was modeled to produce syngas at 815 °C, having 14 % H_2, 19 % CO, 9 % CO_2, and 50 % N_2 (by volume). The cold gas efficiency for the gasifier is assumed to be 75 %. A yield reactor was utilized to break down bagasse into individual components, and gasification reactions occur in a standard Gibbs reactor. Both the reactors are heat integrated. This syngas was combusted in a gas turbine with 15 % excess air. The hot flue gas is utilized for bagasse drying. The exhaust of the gas turbine was utilized to produce superheated steam at 390 °C and 31 bar. The steam produced by the gasifier module was approximately 40 % of the steam produced in the combustion section. The two flowsheets differed only in the way bagasse was utilized. All other modules remained similar.

4. Results and Discussions

Two flowsheets for a sugar manufacturing plant consuming 244 t/h of sugarcane and producing 28 t/h of sugar were modeled. All the processes (modules) have similar parameters except for the boiler module. The boiler module is modeled for both combustion and gasification of bagasse to present the energy generation comparison. In the first scenario, bagasse is received from the extraction module and combusted in the boilers to generate steam (Figure 3). The surplus electricity is generated by a steam turbine is 22.3 MW after meeting the plant electricity requirements. High-pressure steam (25 t/h) is sent to the extraction unit for meeting the process requirement of the shredders and the dewatering mills. The low-pressure steam is utilized in the evaporation, crystallization, and drying modules. The electricity production potential is similar to the reported value of advanced sugar mills presented in Table 1.

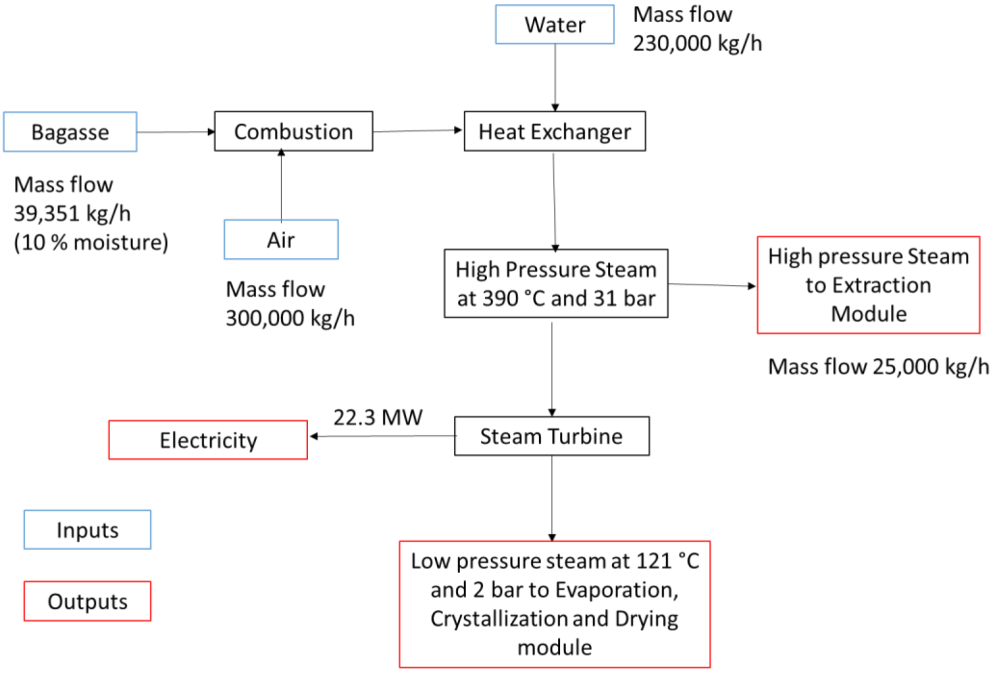

Figure 3. Flowsheet of a Boiler Module (Bagasse Combustion)

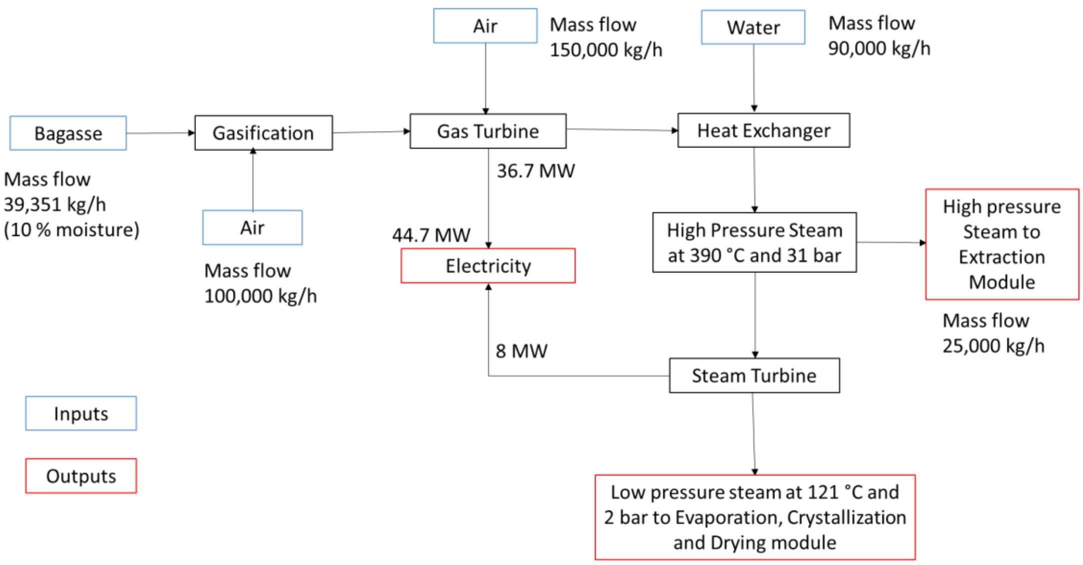

Figure 4. Flowsheet of a Boiler Module (Bagasse Gasification)

In the second scenario, bagasse is gasified to produce electricity and steam (Figure 4). The syngas produced from the gasification process is combusted in a gas turbine. The exhaust gas from the gas turbine is utilized for raising steam. This high-pressure steam is utilized to produce an additional 8 MW of electricity. The surplus electricity is generated by the gas and steam turbine is 44.7 MW after meeting the plant electricity requirement, and 25 t/h high-pressure steam is sent to the extraction module. The utilization of bagasse gasification can increase the surplus electricity by 22.4 MW when compared to the conventional cogeneration process. The urplus electricity generated by the combustion integrated plant was 91 kWh/t of cane crushed. The surplus electricity generated by the gasification integrated plant was 183 kWh/t of cane crushed. The increased electricity production potential can provide additional revenue to the economically struggling sugar mills. This technology up-gradation could be beneficial for countries like India, where less than one-third of sugar mills have cogeneration facilities. If average emissions for grid electricity are considered to be 750 g CO_2eq./kWh electricity, this modification in energy generation can lead to a potential carbon footprint reduction of 54,835 t of CO_2eq (for 136 days of operation). The gasification-based cogeneration is also expected to reduce the water footprint by employing a smaller steam cycle. A robust life cycle assessment would be required to get a better estimation of the carbon reduction. However, the economic trade-offs of this modification also need to be studied in the future. The proposed gasification technology is expected to have a capital expenditure of 4.44×10^7 USD (2020) (Basu, 2013). If electricity is considered to be sold at 75 USD/MWh for 136 days of plant operation, the proposed gasification technology is expected to have a simple payback period of 8 y, omitting the time value of money.

5. Conclusions

Sugarcane bagasse is a prominent feedstock for bioenergy applications worldwide. The present study highlights the potential benefits that can be derived by updating the conventional combustion-based cogeneration systems with gasification. Two flowsheets for a sugar manufacturing plant consuming 244 t/h of sugarcane and producing 28 t/h of sugar were modeled. Energy integration was carried out for the determination of surplus electrical energy generation. The surplus electricity generated by the combustion integrated plant was 91 kWh/t of cane crushed, and the surplus electricity generated by the gasification integrated plant was 183 kWh/t of cane crushed. Gasification technologies can prove to be much more efficient than traditional cogeneration technologies, almost doubling the amount of surplus electricity that can be generated. This modification in energy generation can lead to a potential carbon footprint reduction of 54,835 t of CO_{2eq}. Furthermore, the efficiency of the cogeneration system could be enhanced by using high-pressure and temperature boilers.

References

Anukam A., Mamphweli S., Reddy P., Meyer E., Okoh O., 2016. Pre-processing of sugarcane bagasse for gasification in a downdraft biomass gasifier system: A comprehensive review. Renewable and Sustainable Energy Reviews, 66, 775–801.

Basu P. (Ed.), 2013, Biomass Gasification, Pyrolysis and Torrefaction. Academic Press, London, UK. ISBN: 9780123965431.

Birru E., 2016. Sugar Cane Industry Overview and Energy Efficiency Considerations. PhD Thesis, KTH School of Industrial Engineering and Management, Stockholm, Sweden.

E4Tech, 2009. Review of Technologies for Gasification of Biomass and Wastes Final report. NNFCC, The Bioeconomy Consultants, June, 1–130. <https://www.e4tech.com/resources/95-review-of-technologies-for-gasification-of-biomass-and-wastes.php?filter=year%3A2009>, accessed 24.02.2021.

Guest K., Stark A., Starzak M., 2019. Development and verification of an ASPEN Plus ® model of a sugarcane biorefinery. Proceedings of South African Sugar Technology Assessment, 92, 254–273.

Keche A.J., Gaddale A.P.R., Tated R.G., 2015. Simulation of biomass gasification in downdraft gasifier for different biomass fuels using ASPEN PLUS. Clean Technologies and Environmental Policy, 17(2), 465–473.

Motta I.L., Miranda N.T., Filho R.M., Maciel M.R.W., 2018. Sugarcane bagasse gasification: Thermodynamic modelling and analysis of operating effects in a steam-Oxygen-Blown fluidized bed using Aspen Plus™. Chemical Engineering Transactions, 65, 169–174.

NITI Aaayog, 2020. In Final Report of the Task Force on Sugarcane & Sugar Industry (Vol. 2, Issue 1). <niti.gov.in/sites/default/files/2020-02/Annual_Report_2019-20.pdf>, accessed 24.02.2021.

Starzak M., Davis S.B., 2017, MATLAB® modelling of a sugar mill: Model development and validation. International Sugar Journal, 119(1422), 442-452.

Sun L., Xu B., Smith R., 2014, Power and chemical production analysis based on biomass gasification processes. Chemical Engineering Transactions, 38, 61–66.

TERI, 2012. Widening the coverage of PAT Scheme Sectoral Manual-Sugar Sector Prepared for Shakti Sustainable Energy Foundation, <www.teriin.org/sites/default/files/2018-02/Sugar Report.pdf>, accessed 24.02.2021.