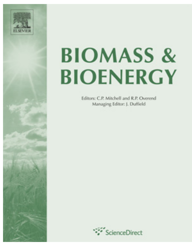
BIOMASS AND BIOENERGY 55 (2013) 163–174

Available online at www.sciencedirect.com

SciVerse ScienceDirect

http://www.elsevier.com/locate/biombioe



Thermal gasification or direct combustion? Comparison of advanced cogeneration systems in the sugarcane industry

Ranjit Deshmukh[a], Arne Jacobson[a,*], Charles Chamberlin[a], Dan Kammen[b]

[a] Schatz Energy Research Center, Humboldt State University, 1 Harpst St., Arcata, CA 95521, USA
[b] Energy and Resources Group, University of California, Berkeley, USA

ARTICLE INFO

Article history:
Received 18 February 2010
Received in revised form
6 October 2012
Accepted 31 January 2013
Available online 11 March 2013

Keywords:
Gasification
Cogeneration
Sugarcane
Bagasse
Renewable energy

ABSTRACT

We compare different cogeneration system scenarios for efficient energy production from bagasse fuel in an Indonesian sugar and ethanol factory. These scenarios include the use of condensing-extraction steam turbines, variable speed electric drives for process equipment, measures to reduce low pressure steam demand for process needs, and two advanced cogeneration systems. One advanced system includes an 80 bar high pressure direct combustion steam Rankine cycle (advanced SRC), while the other uses a biomass integrated gasifier combined cycle (BIGCC); both utilize fuel dryers. Using steady-state thermodynamic models, we estimate that the net electricity generation potentials of the BIGCC and advanced SRC systems are approximately seven and five times the potential of the existing factory, respectively. The maximum net electricity generation potentials for the respective systems are 170 kWh/tc (BIGCC) and 140 kWh/tc (advanced SRC). However, the BIGCC system needs a bagasse feed rate that is 50 percent higher than the advanced SRC system to satisfy the factory low pressure steam demand for sugar and ethanol processing, which may affect its ability to provide steam and electricity during the off-season. For the Indonesian sugar factory, the annual revenue potential of the BIGCC system is US$14 million per year, approximately 50 percent higher than that of the advanced SRC system (electricity sale rate: US$45/MsWh; carbon credit price: US$13.60). BIGCC technology is still in an early stage of development and there are no commercial systems in sugar factories, so an advanced SRC system may be a more suitable option in the near future.

1. Introduction

In the sugarcane based sugar and ethanol industry, high pressure steam Rankine cycle (SRC) systems are an increasingly common and commercially viable option for in-house cogeneration and production of surplus electricity for export to the electric grid. Biomass integrated gasifier combined cycle (BIGCC) systems have been touted as a more efficient alternative that might play a significant role in the coming years [1,2]. Our analysis confirms that BIGCC systems have the potential to increase electricity exports relative to SRC systems. However, BIGCC faces significant challenges in producing enough process steam to meet the needs of most sugar factories if they use just the bagasse[1] produced in-house in

---

* *Corresponding author*. Tel.: +1 707 826 3184; fax: +1 707 826 3616.
E-mail addresses: arne@humboldt.edu, Arne.Jacobson@humboldt.edu (A. Jacobson).

[1] Bagasse is the fibrous byproduct created when cane juice is separatsed from sugarcane stalks in the factory milling machines, and serves as the primary fuel for the cogeneration of electricity and steam in sugar factories.

http://dx.doi.org/10.1016/j.biombioe.2013.01.033

the factories. The challenge for BIGCC only increases in factories that also include a distillery to produce ethanol from molasses. The use of sugarcane residue i.e. leaves and tops, referred to as “cane trash,” which is often left in the field after unburned sugarcane harvesting, provides one potential additional fuel source to the existing bagasse fuel and increase the ability of systems based on BIGCC technology to meet factory steam demand. In the immediate future, drying bagasse using the exhaust flue gas from the boiler (provided the exhaust gas has adequate energy) before using it in a high pressure SRC system could be an effective alternative for sugar factories to increase their electricity generation potential.

In 2007, the world sugar and ethanol industry processed 1.6 billion metric tons of sugarcane [3]. This generated approximately 240 million metric dry tons of bagasse,[2], which corresponds to an electricity generation potential of 240 TWh at a net conversion efficiency of 20 percent.

The world sugar industry was only able to generate a fraction of this electricity, however, as most electricity generation equipment in this industry has not been designed to operate at high efficiencies. Typically, bagasse is generated at a rate that is higher than what is needed by the industry for its in-house sugar and/or ethanol processing needs. Historically, sugar factories have been stand-alone units, not connected to the electric grid. Due to the surplus amount of bagasse, the factories burn bagasse inefficiently in low pressure boilers, more as a means of disposal than for efficient energy generation [4]. Hence, their low pressure SRC co-generation systems have typically been designed to be relatively inefficient in order to ensure that little or no bagasse disposal costs are incurred [1].

This historic inefficiency provides an opportunity to do “more with less.” In recent years a number of factories have explored possibilities to reduce their in-house steam consumption and/or use advanced co-generation systems that are highly efficient. These measures would enable them to export electricity to the grid in addition to satisfying their in-house energy demands. Today, the advanced cogeneration systems that are being implemented are in the form of high pressure direct combustion SRC systems that have a significantly higher electricity generation and export potential than the low pressure SRC systems. Integration of gasification technology into sugar factories by using BIGCC cogeneration systems has the potential for even higher electricity generation than high pressure SRC systems.

Developing countries are host to three-quarters of the sugar industry in the world [5]. As these countries continue to grow their economies, this electricity generation potential has become quite attractive to their energy starved utilities. Additionally, since bagasse is an agricultural waste product, the electricity generated by the sugar industry is considered renewable. Bagasse-based electricity exported to the grid is assumed to displace electricity with carbon intensity equivalent to the local grid mix. In light of global warming, this is an important contribution to mitigating the greenhouse gas emissions associated with fossil fuel burning.

By installing and operating advanced efficient cogeneration systems and feeding the surplus electricity to the grid, the sugarcane industry stands to earn revenues through electricity sales in addition to sugar and ethanol sales. In developing countries, an additional potential for revenue generation is the sale of Certified Emissions Reductions (CERs) under the Clean Development Mechanism (CDM) of the Kyoto Protocol [6].[3]

In this paper, we compare the electricity generation and export potential of the two advanced cogeneration systems – high pressure direct combustion SRC system and BIGCC system. We use steady state thermodynamic models to simulate a stand-alone (not connected to an electricity grid) Indonesian sugar factory and various improved scenarios for electricity generation and export. We also discuss the challenges and limitations associated with the two advanced cogeneration systems.

2. The sugar industry

2.1. *Sugar/ethanol processing and cogeneration*

At tropical and subtropical sites around the world, harvested sugarcane is transported to a sugar factory where it is often washed to remove excessive amounts of soil and debris [2]. After being washed, the cane enters the extraction system where it is prepared using rotating cutters and shredders that reduce the cane into small pieces. Subsequently, a number of mills in series separate the bagasse and the juice by compression of the sugarcane. Bagasse constitutes approximately 30 percent of the harvested sugarcane on a mass basis and typically has a moisture content of about 50 percent. The wet bagasse that comes out of the juice extraction system is directly sent to the factory’s cogeneration system, where current practice is to burn it in boilers to generate high pressure steam. This steam is used to produce electricity and provide mechanical power for the cutters, shredders and mills as well as fans and pumpss for the cogeneration system [1]. The low pressure exhaust steam is used for sugar and ethanol processing. Fig. 1 shows the flow diagram of the sugar factory processes that we describe here.

The typical properties of bagasse are given in Table 1 and Table 2.[4] As the values in Table 2 indicate, bagasse has a small

---

[2] The calculation used to estimate world bagasse production is based on an assumption that the dry bagasse yield rate is equal to 15% of harvested sugarcane on a mass basis.

[3] The Kyoto Protocol is a protocol to the United Nations Framework Convention on Climate Change (UNFCCC), an international environmental treaty produced at the United Nations Conference on Environment and Development. The treaty is intended to achieve stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. Official UNFCCC site: www.unfccc.int. A CER is a carbon credit, equal to one metric ton of carbon dioxide equivalent. Under the Clean Development Mechanism of the Kyoto Protocol, an entity in a developing or non-Annex I country has the potential to earn CERs for reducing carbon emissions. These CERs can be sold on the market to entities in a developed or Annex I country, for them to achieve their carbon emissions reduction targets.

[4] Ultimate analysis is the determination of the percentages of carbon, hydrogen, nitrogen, sulfur, chlorine and (by difference) oxygen in the biomass sample. The heating value of a fuel is the amount of heat released by combusting a specified quantity of that fuel. The lower heating value (LHV) assumes that the latent heat of vaporization of water in the fuel and the reaction products is not recovered while the higher heating value (HHV) includes the heat of condensation of water in the combustion products.

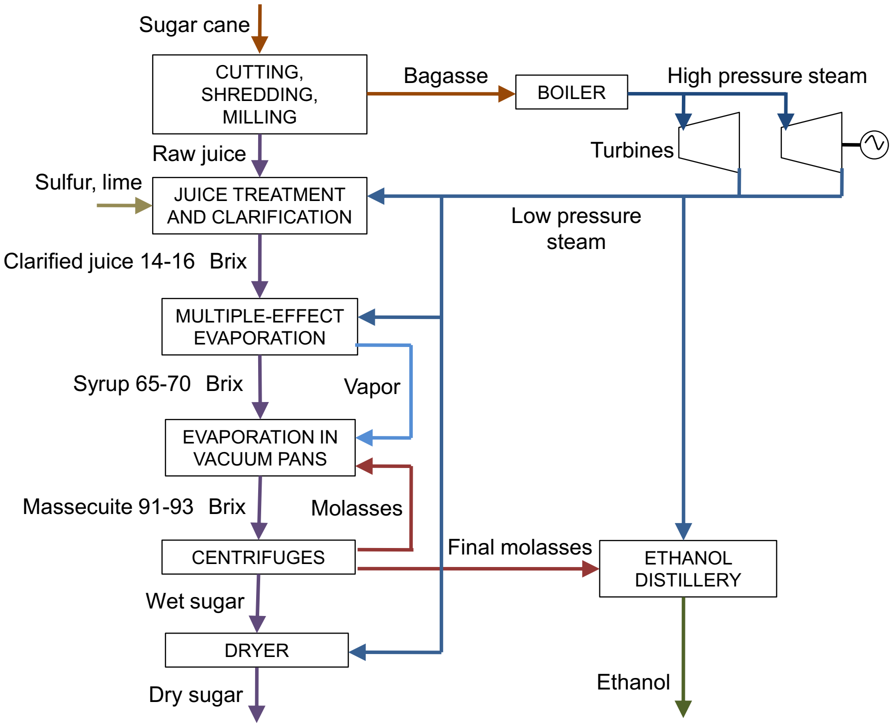


Fig. 1 – Flow diagram of sugar facstory processes.

particle size, low bulk density and is very wet. Any excess bagasse is stored for off-season energy generation or is sold for energy generation in other industries or for other uses like the production of paper, fiber board or animal feed.

The high pressure steam generated in the boiler is expanded through multiple turbines. Some of the turbines run generators to produce electricity for the factory and are usually multi-stage turbines. Other turbines provide mechanical power to the cutters, shredders and mills for processing the sugarcane, as well as auxiliary equipment for the cogeneration system like pumps, blowers and fans. Most of the turbines that provide mechanical power are small in capacity and are usually single-stage turbines. Only some equipment like the shredder need a large amount of power and, hence, require multi-stage turbines. Typically, stand-alone sugar factories with no incentive to produce surplus electricity have “inefficient” cogeneration systems that utilize relatively low pressure (~20–30 bar) boilers and back-pressure turbines (BPT). In a BPT, the steam exits at near atmospheric pressure. This low pressure steam is used for sugar and/or ethanol processing. A cogeneration system serving a sugar or sugar/ethanol factory must always satisfy the demand for process steam to run the factory during the cane crushing season [1]. A typical level of process steam consumption for a sugar factory is 400–550 kg steam/ton of sugarcane crushed (kg/tc) [1,2].

A stand-alone factory has a relatively fixed demand for electricity and mechanical power for internal consumption that is based on its cane throughput. In many sugar factories, the high pressure steam demand for electricity and mechanical power is lower than the low pressure process steam demand. For a stand-alone factory, the additional low pressure steam demand is made up by passing some high pressure steam through an expansion valve, effectively bypassing the turbines without doing any useful work. Conversely, whenever the high pressure steam demand is higher than the low pressure steam, the excess steam after expanding through the turbine is vented to the environment.

Some advanced sugar factories use condensing-extraction steam turbines (CEST). Unlike BPTs where all the steam exhausts at near atmospheric pressure and is used for process

Table 1 – Ultimate analysis of bagasse [7].

Ultimate analysis of bagasse	Weight (%) dry basis
C	47%
O	43%
H	6%
N	0%
S	0%
Cl	0%
Ash	4%
Lower Heating Value of Dry Bagasse	17.5 MJ/kg

Table 2 – Typical physical characteristics of wet bagasse as it comes out of the juice extraction system [7].

Physical characteristics of bagasse	
Particle Size	<50 mm
Bulk Density	50–75 kg/m^3
Moisture Content – wet basis	48–52%

needs, CESTs provide the ability to extract only the required amount of process steam at the required pressure from the turbine. The rest of the steam is expanded to below atmospheric pressure for additional work. CESTs are usually installed in sugar factories that are connected to an electric grid. Any surplus electricity beyond that required for the factory and associated operations is exported to the grid.

2.2. *Energy efficiency and increased electricity generation*

In order to realize the full potential of an advanced cogeneration system such as a high pressure direct combustion SRC system using CESTs or a BIGCC system, it is essential for a sugar factory to reduce both its in-house low pressure and high pressure steam requirement.

Various measures can be taken to reduce the low pressure process steam demand in sugar manufacturing and ethanol distillation. These include maximum evaporation in multiple effect evaporators, use of quintuple evaporator effects, maximum utilization of vapor bleeding, use of continuous sugar boiling pans and many others. In a sugar factory, these measures have theoretically the potential to reduce the typical low pressure steam consumption of 400–550 kg-steam/tc by approximately 30–50 percent to 280–300 kg-steam/tc [2,8]. A dual-pressure distillation system for hydrated ethanol production and molecular sieves for the dehydration step can reduce the typical steam consumption for ethanol production by approximately 50 percent, from 5 kg-steam/l-ethanol to 2.5 kg-steam/l-ethanol [2]. However, implementing these measures involves significant additional capital costs. In practice, sugar factories that are considered “efficient” typically consume 350 kg/tc to process raw sugar and 400 kg/tc to produce refined sugar. This low pressure steam consumption further increases by 15–25% when a distillery is attached to the sugar factory to process ethanol from molasses. Reducing the low pressure steam demand offers the opportunity to produce additional work by expanding more steam to below atmospheric pressure in CESTs.

Factories that use steam driven turbines for cane crushing and milling often have significant opportunities to reduce demand for high pressure steam. Upadhiaya [8] notes that variable speed electric drives can replace the single-stage steam turbines used for providing mechanical power for the sugar processing equipment as well as the auxiliary equipment for the cogeneration system. Single-stage turbines that provide the mechanical power need to operate at varying speeds and loads depending on the cane throughput. They are much less efficient than the multi-stage turbines used for electricity generation that operate at their rated speed and load when the factory is connected to the grid. It is true that variable speed electric drives require multiple energy conversions to provide the final mechanical power. However, they eliminate the heat losses through the steam lines required for steam turbines. They also respond better to the varying load conditions of the sugar factory equipment. Hence, the overall combination of multi-stage turbines for electricity generation with highly efficient variable speed electric drives proves to be more efficient than single-stage turbines for providing mechanical power. Electric drives, however, may have higher capital costs than steam turbines [8].

2.3. *Advanced cogeneration systems*

Advanced cogeneration systems in the form of high pressure direct combustion SRC systems and BIGCC systems have the potential to significantly increase the electricity generation capacity of sugar factories. For efficient cogeneration, sugar factories are installing higher pressure boilers and CESTs operating at pressures of 45–80 bar. In a few cases, factories have used boilers that operate at 100 bar. This combination of high pressure boiler and CESTs (Fig. 2) is capable of generating much more surplus electricity for export to the electric grid, as higher pressure steam (which is also higher temperature) can produce more work than lower pressure steam. However, high pressure systems, especially over 60 bar, require special construction techniques and materials that withstand the high pressure and associated high temperatures (over 450 °C) [8]. CESTs also require a condenser system with a cooling tower and pump. These additional capital and operating costs need to be considered to determine the actual net revenues from surplus electricity generation. INSERT.

Biomass integrated gasifier combined cycle (BIGCC) technology may have the potential to generate electricity more efficiently than a conventional SRC system while being cost competitive at the same time. Biomass thermal gasification is the incomplete combustion or partial oxidation of biomass that results in the production of combustible gases consisting mainly of carbon monoxide and hydrogen. The goal of the gasification process is to maximize the solid fuel carbon conversion as well as the heating value of the product gas [4]. The partial oxidation can be carried out using air, oxygen, steam or a combination of these. Most large scale gasification systems for electric generation use air and/or steam gasification. Air gasification produces a low heating value gas (4–5 MJ/Nm^3) due to a high concentration of nitrogen [4].

Table 3 shows the typical percentages by volume of the main constituents of the dry product gas from a gasifier using air as an oxidizing agent.

In a BIGCC system (Fig. 3), the product gas from the gasifier, after being cleaned and filtered, is fed into a gas turbine to run an electric generator. The surplus heat in the exhaust gases from the gas turbine is used to generate steam in a heat

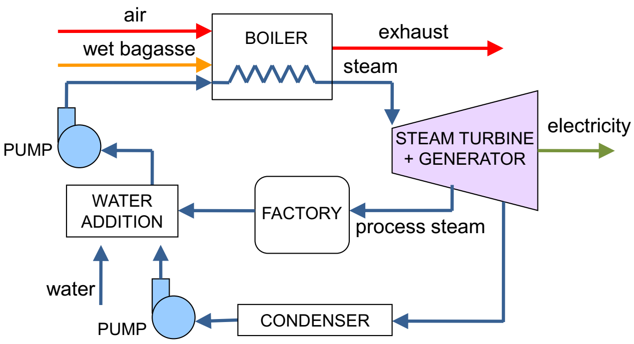


Fig. 2 – Process diagram of a steam Rankine cycle cogeneration system for a sugar factory.

Table 3 – Typical product gas composition from an air gasification process [2,7].

Gas Component	Volume
Carbon Monoxide, CO	15–20%
Hydrogen, H_2	15–20%
Carbon Dioxide, CO_2	8–12%
Methane, CH_4	1–3%
Nitrogen, N_2	45–50%

recovery steam generator (HRSG) and run a bottoming steam Rankine cycle for additional electricity generation. In the case of sugar factories, some steam can be extracted from the CEST for the processing needs of sugar and/or ethanol. The exhaust flue gases from the HRSG can be used in a bagasse dryer to extract waste heat. It is generally essential to reduce the moisture content of bagasse to $< 20\%$ depending on the type of gasifier used.

Several types of gasifier designs exist depending on the scale, fuel, fuel size and other parameters. Circulating fluidized bed (CFB) is one of the more suitable technologies for use with bagasse in a BIGCC system, especially for gasifiers with fuel capacities greater than 10 MW thermal. In general, the biomass particle size of bagasse (<50 mm) allows for higher efficiency conversion in fluidized bed gasifiers due to better mixing with the bed material and greater carbon conversion rates [7]. CFBs allow for more complete carbon conversion and permit higher specific throughputs than bubbling beds [9].

Gasifiers can be pressurized or operate at atmospheric pressure. In the pressurized gasifier system, the fluidizing agent is compressed to the operating pressure of the gasification system before introducing it in the gasifier. The product gas that exits is already at the elevated pressure and does not need compression prior to the gas turbine.

On the other hand, the product gas from an atmospheric pressure gasifier needs to be compressed before injecting into the gas turbine as shown in Fig. 3. Since the mass and volume of the product gas is greater than the mass and volume of the fluidizing agent (air or steam), the atmospheric pressure gasification system has higher parasitic loads than the pressurized gasifier system [4,10]. Additionally, the reactor size is smaller and the reaction rates between solids and gases are higher for a pressurized gasifier system. However, the gasifier and the gas cleanup/conditioning system need to be built to withstand high pressure and temperature, thus increasing costs. Also, feeding systems for a pressurized gasifier can be difficult to design and operate, and may need a supply of pressurized inert gas, further increasing capital and operation costs [4]. The atmospheric pressure gasifier system has a simpler feeding system. However, since the gas needs to be cooled before it is compressed, this system needs more rigorous gas cleanup/conditioning to remove the tars that would otherwise condense at the low operating temperature.

A BIGCC cogeneration system converts a high fraction of the biomass fuel input into electricity. This system correspondingly converts a smaller fraction of the fuel input into process steam and cannot satisfy process steam demand via cogeneration using only the bagasse generated at the factory, unless measures are taken to improve the low pressure process steam efficiency in sugar and ethanol production [1].

BIGCC is a relatively new technology and is in its development stage. Large scale BIGCC systems have been installed only as demonstration projects and none of them are continuously operating today.[5] Although preliminary studies and pilot scale projects have been initiated to study the possibility of integrating a BIGCC system into a sugar factory, no large scale bagasse based BIGCC system has been installed and operated at any sugar factory.

Refinement of the direct combustion cogeneration system can yield electricity generation rates of 120 kWh per ton cane, compared to typical factory performance of about 10 kWh per ton cane worldwide [4]. According to some estimates, BIGCC technologies under development are projected to attain even higher overall efficiencies, yielding electricity generation rates greater than 200 kWh per ton cane [4]. It is important to compare the electricity generation potential of the BIGCC technology with that of a high pressure SRC system using CESTs while operating in conjunction with a sugar factory.

3. Thermodynamic models and comparison methodology

The criteria for the comparison between the two advanced cogeneration systems for the sugar industry - a high pressure direct combustion steam Rankine cycle (SRC) system and a biomass integrated gasifier combined cycle (BIGCC) system - are their net electricity generation potential (electricity generation after accounting for the electricity required to operate the power plant) and the subsequent export of surplus electricity to the electric grid. In addition, it is important to understand the capability and limitations of each system in satisfying the factory in-house demand for low pressure steam for sugar and/or ethanol processing. For this purpose, we developed two steady-state thermodynamic models that balance the mass and energy flows for a sugar and ethanol factory. We used Microsoft Excel® along with three add-in

---

[5] Skydkraft-Foster Wheeler's 6 MW_e/9 MW_{th} pressurized BIGCC demonstration plant at Värnamo, Sweden operated from 1993 to 2000 [11]. TPS Termiska's 8MW_e Arable Biomass Renewable Energy (ARBRE) BIGCC plant located in Selby, UK never reached commercial operation and was shut down in 2002 [12]. TPS Termiska's two BIGCC projects in Brazil, a 32 MW_e plant that would have operated on wood and another plant to be integrated with a sugar factory operating on bagasse did not proceed beyond the design stage [13]. The BIGCC plant at the HC&S sugar factory on Paia, Hawaii, which was based on the Renugas technology developed by the Institute of Gas Technology, was the closest to being the first BIGCC system to be integrated with a sugar factory. Before being fully operational, the plant was discontinued in 1998 due to various technical and financial reasons. A circulating fluidized bed gasifier based on Batelle technology was built next to the McNeil biomass power station in Burlington, Vermont with the intention to operate an 8 MW_e gas turbine [4]. The project is currently at a standstill due to financial reasons.

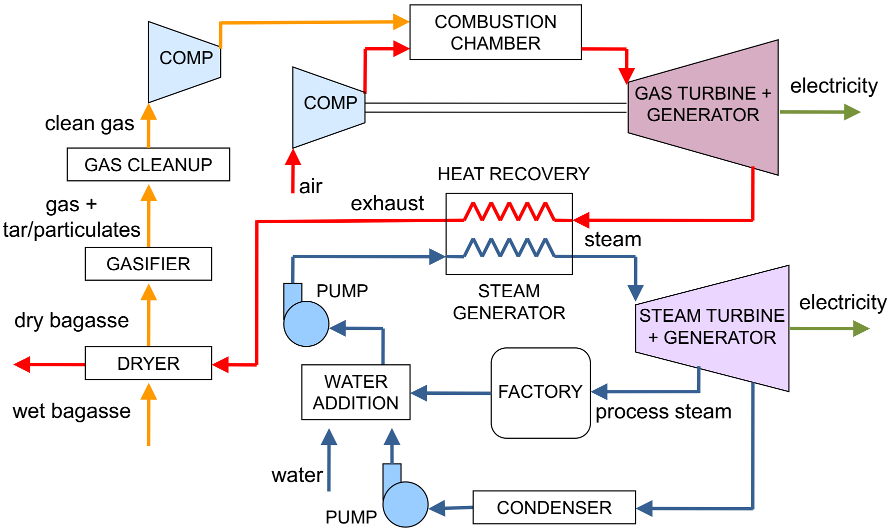


Fig. 3 – Process diagram of a biomass integrated gasification combined cycle cogeneration system for a sugar factory.

programs: PowerSim,[6] Water97[7] and Solver[8] to develop these models. The first model simulates an SRC cogeneration system, while the second simulates a BIGCC cogeneration system. We used these models to simulate an existing Indonesian sugar factory and five progressively improved scenarios if they were to be implemented at the Indonesian sugar factory. The factory includes a distillery for ethanol production from molasses along with sugar production process equipment. In developing the scenarios for the models, we chose the input parameters based on literature sources [1,2,4,7,10,14–16] and the Indonesian sugar factory's specifications and annual reports [17]. The data from the Indonesian sugar factory are presented in Table 4. All five improved scenarios assume that the sugar factory is connected to the grid. The scenarios further assume that only the bagasse generated at the factory is used for fuel. The first improved scenario uses CESTs in place of BPTs. In addition to the CESTs, the second scenario uses variable speed electric drives instead of steam driven mechanical drives. The third improved scenario assumes the implementation of measures to reduce the low pressure process steam consumption to 400 kg/tc in the sugar factory.

The last two improved scenarios assume the implementation of the two advanced cogeneration systems: a high pressure direct combustion SRC system and a BIGCC system. Both advanced cogeneration systems use CESTs for steam turbines. We also assume a low pressure process steam requirement of 400 kg/tc for the factory and the use of variable speed electric drives for sugar processing and auxiliary cogeneration equipment. For the high pressure direct combustion SRC system, we assume a boiler pressure of 80 bar, which is becoming the norm as a high pressure advanced cogeneration system for sugar factories and has been considered in many articles in the literature [1,2,18,19]. For the BIGCC scenario, we assume an air-based atmospheric pressure gasification system. The gas turbine pressure ratio of 15 that we use in the BIGCC base case scenario represents a relatively high pressure ratio for an industrial turbine. Lower steam production being a constraint for BIGCC systems, we did not assume aero-derivative gas turbines that have higher turbine pressure ratios (>20) than industrial turbines. Higher turbine pressure ratios result in lower exhaust gas temperatures and subsequently lower steam production in the HRSGs. We assume a low pressure HRSG system operating at 30 bar, 340 °C, which results in a relatively higher steam production than a high pressure HRSG system and increases the ability of a BIGCC system to satisfy factory process steam requirements (assuming that only the bagasse generated at the factory is used for fuel).

The key output parameters that we use to evaluate and compare the above scenarios are electricity generation potential and the minimum bagasse required for each cogeneration option to satisfy the process steam demand. In addition to a technical comparison, we provide an economic comparison based on gross revenues for a sugar factory from its sales of surplus electricity. Since BIGCC is not yet a commercial technology, especially for cogeneration in the sugar industry, the costs involved are not well known. Hence, a complete economic comparison of the advanced cogeneration systems that includes investment and lifecycle costs was not possible.

4. Results

The thermodynamic modeling exercise provides a comparison between the improved scenarios and the two advanced

---

[6] PowerSim is an add-in program for Microsoft Excel® developed by FinnFuture Oy. It provides a set of functions for calculating thermodynamic and transport properties for water, steam and gases.

[7] Water97_v13 is an add-in program for Microsoft Excel®, which provides a set of functions for calculating thermodynamic and transport properties of water and steam using the industrial standard IAPWS–IF97.

[8] Solver is an add-in program developed by Microsoft Corporation for Microsoft Excel® and is part of a suite of commands called the what-if analysis tools. It is used to find an optimal value for a formula in one cell.

Table 4 – The 2007 Indonesian sugar factory data for base case scenario.

Parameter	Value
Total cane crushed per year	1,800,000 tc/y
Bagasse yield from cane	0.32 ton/tc
Capacity factor of sugar factory	0.45[a]
Steam consumption of sugar factory	440 kg/tc
Total ethanol production per year	60,000 kL/y
Capacity factor for distillery	0.8
Steam consumption of ethanol distillery	4700 kg/kL-etoh ~90 kg/tc[b]
Total steam consumption	530 kg/tc

tc: ton cane, kL-etoh: kilo-liters of ethanol.
a Based on the number of milling days in 2007.
b Calculated from total ethanol production and capacity factor.
Source: Indonesian sugar factory annual report for 2007.

cogeneration systems integrated into the Indonesian sugar factory: the BIGCC cogeneration system and the high pressure direct combustion SRC cogeneration system.

4.1. *Comparison of improved scenarios with existing factory*

Table 5 shows the results for the existing Indonesian sugar factory and the five improved scenarios in terms of net electricity generation and export potentials per ton of cane and net electricity exported during the cane crushing season for the factory. Although the bagasse yield rate from cane crushing is 41 kg/s, all scenarios presented in this section assume a bagasse input rate of 36 kg/s, which is the approximate steady state input rate for the Indonesian sugar factory during the 2007 cane crushing/sugar processing season. This bagasse input rate enables the comparison of the improved scenarios with the existing factory. The five improved scenarios show a progressive increase in the net electricity generation and subsequent increases in electricity export.

The first improved scenario replaces the BPTs in the existing factory with CESTs. The surplus high pressure steam, instead of expanding through an expansion valve, is sent through the power generation turbine and expanded to below atmospheric pressure to generate additional electricity. Also, since the factory is connected to the grid, the power generation turbines can run at approximately constant speeds, operating close to their rated outputs. Unlike the turbines in a stand-alone factory that operate at partial load, turbines in grid-connected factories do not need to adjust their speed based on the fluctuating electric loads within the factory. The electric grid may be able to absorb the variations in the surplus electricity, allowing the turbines to operate at constant loads. Hence, we assume a higher efficiency of 75 percent for the CESTs in the grid-connected improved scenarios than that for BPTs in the existing factory (~67 percent).

The second improved scenario illustrates the advantage of using variable speed electric drives for sugar processing and auxiliary cogeneration equipment. Instead of passing high pressure steam through the mostly single-stage turbines providing mechanical drives, the steam is expanded through the multiple-stage power generation turbines generating more electricity that in turn, run the variable speed electric drives. The use of high pressure steam to produce electricity and the use of this electricity to drive the variable speed electric drives is more efficient than the direct use of high pressure steam in single-stage turbines providing mechanical power. This overall combination of the multi-stage power generation turbine and the variable electric drives increases the net electricity generation potential in spite of an increase in electricity consumption.

The third improved scenario includes the reduction of low pressure steam demand for sugar and ethanol processing to 400 kg/tc. The low pressure steam consumption can be reduced by implementing measures such as addition of evaporator effects, maximum utilization of vapor bleeding, and use of continuous sugar boiling pans in sugar production, as well as dual-pressure distillation systems and dehydration

Table 5 – Comparison between existing Indonesian sugar factory (back-pressure steam turbines (BPT) and no grid connection) and grid connected factory scenarios with condensing-extraction steam turbines (CEST), variable speed electric drives and reduced process steam consumption, as well as high pressure direct combustion steam Rankine cycle and biomass integerated gasification combined cycle (BIGCC) systems. All scenarios include a distillery for ethanol production from molasses. The bagasse input rate is 36 kg/s, the approximate steady state input rate for the Indonesian sugar factory during the 2007 cane crushing season.

Scenarios			Net electricity generation (kWh/tc)	Electricity export (kWh/tc)	Net electricity exported during season (MWh)
0	BPT/Stand-alone	30 Bar, 340 °C, 530 kg-steam/tc, mechanical drives	20	0	0
1	CEST/Grid Connect	30 bar, 340 °C, 530 kg-steam/tc, Mechanical Drives	46	26	48,000
2		30 bar, 340 °C, 530 kg-steam/tc, Variable Electric Drives	73	37	66,000
3		30 bar, 340 °C, 400 kg-steam/tc, Variable Electric Drives	82	45	81,000
4	Advanced CEST/Grid Connect	80 bar, 480 °C, 400 kg-steam/tc, Variable Electric Drives	103	66	118,000
5	BIGCC/Grid Connect	HRSG - 30 bar, 340 °C, 400 kg-steam/tc, Variable Electric Drives	142	106	191,000

using molecular sieves for ethanol production. In this scenario, these measures are implemented in addition to the use of CESTs and variable speed electric drives. The reduction in process steam requirement leads to less steam being extracted at the process steam pressure of 2 bar and more steam expanded to below atmospheric pressure (0.1 bar in this scenario), thus increasing the net electricity generation and export potential.

Each of the two advanced cogeneration systems assumes the implementation of CESTs, variable speed electric drives and measures for process steam reduction in the sugar factory. The fourth improved scenario is an 80 bar high pressure direct combustion cogeneration system. Due to the inherent advantages of a higher pressure - higher temperature thermodynamic cycle, the net electricity generation potential during the cane crushing season is 103 kWh/tc, which is approximately five times the potential of the existing factory. The net electricity export potential for this scenario is approximately 118 GWh during the cane crushing season, which is approximately 50 percent greater than the export potential of the 30 bar system.

The fifth improved scenario is the BIGCC cogeneration system integrated into the sugar factory. This scenario has the highest net electricity generation potential (142 kWh/tc) and export potential (106 kWh/tc) during the cane crushing season. The net electricity generation potential is 40 percent greater than the potential of the high pressure direct combustion system of scenario four, and about seven times the potential of the existing factory. In addition, the electricity export potential of the BIGCC system is 191,000 MWh in the cane crushing season, which is approximately 60 percent greater than the high pressure direct combustion system. Fig. 4 shows the cumulative effect of implementing the above scenarios on electricity export potential.

4.2. *Comparison of advanced cogeneration systems*

To assess and compare the maximum potential of the two advanced cogeneration systems - high pressure direct combustion SRC systems using CESTs and BIGCC - in terms of their electricity generation, we assume the maximum possible bagasse input rate of 41 kg/s for both systems, which is the same as the 2007 steady state bagasse yield rate from cane crushing. This bagasse input rate allows the estimation of the maximum electricity generation potential of the cogeneration systems where all the bagasse is used during the cane crushing season and no bagasse is left over for the off-season.

Both advanced cogeneration system scenarios assume the implementation of CESTs, variable speed electric drives and measures for process steam reduction in the sugar factory, similar to scenarios 4 and 5. Conventional high pressure direct combustion SRC systems that are being implemented in the industry today do not utilize a bagasse dryer. To illustrate its advantages we consider a scenario with a dryer used with the advanced SRC cogeneration system. The dryer utilizes the exhaust flue gas from the boiler to reduce the moisture content of the bagasse to the same level as that assumed in the BIGCC system. Table 6 shows the results for the three scenarios.

The BIGCC cogeneration system has a higher maximum net electricity generation potential (170 kWh/tc) and a higher export potential (133 kWh/tc) than the high pressure direct combustion SRC system. This system generates 40 percent more electricity and has a 60 percent higher electricity export potential than the high pressure direct combustion SRC system without a dryer. The energy utilization factor (EUF) is a measure of efficiency used for cogeneration systems and is the sum of net electricity generation and process heat divided by the energy supplied by the fuel. The EUF for BIGCC is higher than the direct combustion SRC system, indicating higher energy conversion efficiency. Further, a higher Power to Heat Ratio of 0.69 indicates that the BIGCC system has a greater portion of energy generation in the form of electricity than the direct combustion SRC system. Utilizing a dryer with the high pressure direct combustion SRC system to reduce the moisture content of bagasse to 12.5 percent increases its net electricity generation potential by 17 percent and electricity export potential by 25 percent.

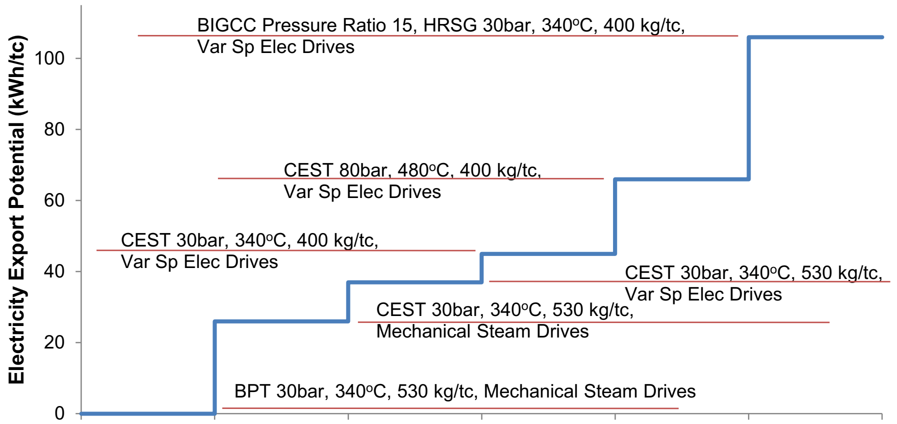


Fig. 4 – Electricity export potential for the Indonesian sugar factory in implementing condensing-extraction steam turbines, variable speed electric drives, reduced process steam consumption, a high pressure direct combustion steam Rankine cycle and a biomass integrated gasifier combined cycle. All five improved scenarios assume that factory is grid-connected. The bagasse input rate is 36 kg/s, the 2007 steady state consumption rate for the Indonesian sugar factory.

Table 6 – Comparison between high pressure direct combustion steam Rankine cycle and biomass integrated gasifier combined cycle cogeneration system scenarios. The bagasse input rate is 41 kg/s, which is the same as the bagasse yield rate from cane crushing. The process steam demand is 400 kg/tc. The BIGCC gas turbine pressure ratio is 15.

Scenarios	Net electricity generation (kWh/tc)	Electricity export (kWh/tc)	Electrical efficiency	Energy utilization factor	Power to heat ratio	Net electricity exported (MWh)
Advanced SRC 80 bar, 480C	120	82	15%	47%	0.48	148,000
Advanced SRC 80 bar, 480C with dryer	140	103	18%	50%	0.57	185,000
BIGCC HRSG 30 bar, 340C	170	133	22%	54%	0.69	239,000

4.3. *Sensitivity analysis*

We present a sensitivity analysis on the key output of the two models, i.e. the net electricity generation, by varying each of the input parameters over a range of values found in the literature [1,2,4,7,10,14–16]. We varied each input parameter between its upper and lower limits while keeping all other input parameters at their base case values. For each input parameter, the sensitivity of the net electricity output is indicated by its percentage change (between the upper and lower limits of that input parameter) relative to its base case value (Base case value of the net electricity output is calculated using the respective base case values of all input parameters). A larger percentage change indicates greater sensitivity of the net electricity output to that particular input parameter. Table 7 and Table 8 show results for input parameters where the net electricity output potential changed by more than five percent when the input parameters were varied.

Both models are very sensitive to the initial moisture content of bagasse, since a substantial amount of energy is required to dry it. Boiler efficiency affects the net electricity generation potential of a direct combustion SRC the most. Hence, the implementation of economizers and air preheaters that can increase the overall efficiency of the boiler are important to increase the overall efficiency of the system. For both models, an increase in the efficiencies of the power generation equipment, the steam turbine in the case of SRC and the gas turbine and compressor in the case of BIGCC, increase the net electricity generation potential substantially. The low pressure process steam consumption affects the net electricity generation potential as an increase in the amount of steam extracted for process needs reduces the amount of steam available for expansion to below atmospheric pressure in the CESTs.

In case of the BIGCC system, as the carbon conversion factor of the gasifier increases, more carbon in the fuel is converted into useful product gas. As the equivalence ratio[9] for the gasifier decreases, less oxygen is available for combustion reactions and, subsequently, less carbon dioxide and more combustible carbon monoxide can be produced. However, decreasing the equivalence ratio also causes the temperature in the gasifier reactor to drop due to lack of combustion or exothermic reactions and the gasifier may not be able to sustain steady state operation. Moreover, additional air could be provided to raise the gasifier reactor temperature in order to thermally crack the tars in the product gas. This would result in a lower energy content but cleaner product gas. Hence, the equivalence ratio is dependent on the particular gasifier design, and the strategies that are implemented to operate it successfully. The gas turbine pressure ratio in the BIGCC system is also critical for the net electricity generation potential. Increasing the pressure ratio increases the amount of work performed by the cycle. However, a higher pressure ratio results in lower exhaust temperatures, which affects the amount of steam that is available for process needs. Finally, the flue gas exhaust temperature from the dryer and the dryer efficiency is critical in a BIGCC system. Increasing the energy that can be extracted from the flue gas to dry the fuel reduces the amount of additional bagasse that must be burned in the dryer to achieve the target fuel moisture content.

Although the BIGCC system has a greater electricity generation potential, it is important to evaluate its ability to satisfy the low pressure steam demand for sugar and ethanol processing. Fig. 5 show the minimum amount of bagasse required by the advanced cogeneration systems to satisfy the different levels of process steam demands. The present process steam demand for the Indonesian sugar factory is 530 kg/tc for sugar and ethanol processing, and 440 kg/tc for sugar processing alone. As seen from Fig. 5, the direct combustion SRC system needs much smaller quantities of bagasse to generate the required process steam than the BIGCC system. For the base case scenario of 400 kg/tc process steam demand, the BIGCC system needs a minimum bagasse feed rate that is about 45 percent higher than the rate for the high pressure direct combustion SRC system. The BIGCC system generates 440 kg/tc steam by consuming approximately 41 kg/s of bagasse, which is the same as the yield rate of bagasse from cane crushing. To generate the present process steam demand of 530 kg/tc of the Indonesian sugar factory, the BIGCC system would need an even higher bagasse feed rate. Consequently, this limitation affects the BIGCC system's ability to save bagasse during the cane crushing season in order to generate electricity during the off-season if the only fuel it uses is the bagasse generated at the factory. Hence, it is

---

[9] Equivalence ratio is the ratio of the actual air-fuel ratio to the air-fuel ratio required for complete stoichiometric combustion.

Table 7 – Sensitivity analysis results for the direct combustion steam Rankine cycle (SRC) model. Negative values indicate a decrease in the net electricity generated.

Direct combustion Rankine				Net electricity generated
Parameter	Base value	Upper limit	Lower limit	% change
Boiler thermal efficiency	80%	85%	75%	14%
Power turbine isentropic efficiency	75%	80%	70%	13%
Fuel Moisture Content	50%	52%	48%	−9%
Exhaust steam pressure from CEST turbine (bar)	0.1	0.4	0.08	−7%
Process steam for sugar processing (kg/tc)	400	440	280	−7%

Table 8 – Sensitivity analysis results for the biomass integrated gasifier combined cycle (BIGCC) model. Negative values indicate a decrease in the net electricity generated.

Biomass integrated gasifier combined cycle				Net electricity generated
Parameter	Base value	Upper limit	Lower limit	% change
Gas turbine polytropic efficiency	85%	90%	80%	16%
Compressor polytropic efficiency	85%	90%	80%	14%
Fuel moisture content - initial	50%	52%	48%	−13%
Carbon conversion in gasifier	0.97	0.99	0.95	7%
Air ratio or equivalence ratio	0.33	0.35	0.32	−6%
Dryer efficiency	80%	90%	70%	6%
Pressure ratio	15	19	11	5%
Process steam for sugar processing (kg/tc)	400	440	280	−5%
Gas turbine mechanical efficiency	98%	99%	97%	5%

important to reduce the process steam demand in a sugar factory in conjunction with the implementation of a BIGCC system.

4.4. *Economic analysis*

To truly evaluate the economic benefits of advanced cogeneration systems, it is important to perform a lifecycle cost analysis that includes all their initial and capital costs as well as their recurring and operations costs. A few papers provide estimates of BIGCC system capital costs and cost of generation [20–23]. Some others also provide a comparison of these costs between BIGCC and SRC systems [24,25], estimating BIGCC specific capital costs to be approximately 20–50% greater than SRC systems. These estimates depend on factors that include but are not limited to installed capacity, the specific technology used, application to cogeneration, operations and maintenance costs, and financial parameters such as discount and interest rates. Further, because BIGCC is not yet a fully commercial technology, it is difficult to provide an accurate estimate of its costs. We therefore limit our economic analysis to the estimation of potential gross revenues for the sugar factory from the sale of electricity and carbon credits. We present our results in Table 9.

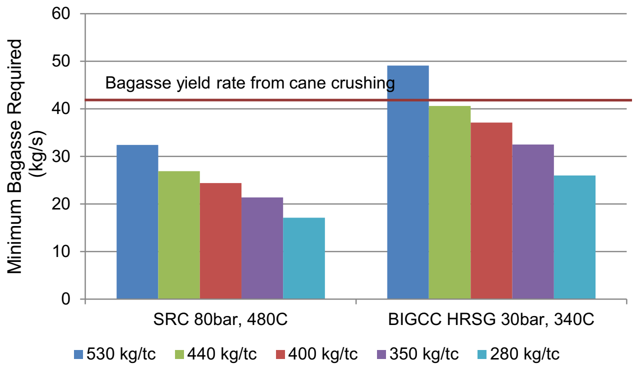


Fig. 5 – Sensitivity of minimum bagasse required to satisfy low pressure steam demand for sugar and ethanol processing for advanced cogeneration scenarios.

In estimating the potential annual revenues from electricity sales, we assume the price of US$45/MWh. This price is within the tariff range of US$42-49.3/MWh that was negotiated by the local Indonesian utility (PLN) with 14 independent power producers by 2003 [26]. This may be a conservative price for many locations for a biomass electricity generation facility operating only during the crushing season. For example, feed-in tariffs for bagasse cogeneration based electricity in India are in the range of US$70-100/MWh [27].

The second revenue stream is through the sale of certified emission reductions (CERs). The sugar factory, being located in Indonesia, has the potential to receive CERs under the Clean Development Mechanism of the Kyoto Protocol. The number of CERs depends on the local grid emissions factor (GEF) to which the electricity is exported. Indonesia has an overall GEF of between 0.85 and 0.87 tCO_2/MWh [28]. However, the local South Sumatran grid where the sugar factory is located has a GEF of 1.05 tCO_2/MWh [28] indicating that there is more fossil fuel based electricity generation in the local grid mix than the overall Indonesian grid mix. In 2009, the prices for contracted

Table 9 – Potential revenues for the Indonesian sugar factory from the sale of electricity and certified emissions reductions (carbon credits).

	Electricity exports (MWh/y)	Certified emissions reductions (tCO_{2e}/y)	Revenues from electricity sales ($1000/y)	Revenues from CERs ($1000/y)	Total revenues ($1000/y)
Advanced SRC 80 bar, 480C	148,000	155,400	$6660	$2113	$8773
Advanced SRC 80 bar, 480C with dryer	185,000	194,250	$8325	$2642	$10,967
BIGCC HRSG 30 bar, 340C	239,000	250,950	$10,755	$3413	$14,168

Price of Electricity = $45/MWh.
Grid Emissions Factor = 1.05 tCO_{2e}/MWh.
CER Price = $13.60/$tCO_{2e}$.

CERs were reported in the range of US$12-20, with an average price of US$13.60 [6]. We assume this average price in estimating the potential revenues from the sale of CERs. Note that by the second half of 2012, however, CER prices had dropped to US$4 due to oversupply and uncertainties in the CDM market [29].

The annual revenue potential for the BIGCC cogeneration system is US$14 million per year, approximately 60 percent higher than the US$9 million per year for the high pressure direct combustion SRC system without a bagasse dryer. Utilizing a dryer could increase the revenue potential of the SRC system by 25 percent. The revenues from the sale of CERs are approximately a fourth of the total revenues for both cogeneration systems using 2009 CER prices, but these values will drop significantly with lower CER prices.

Although the revenue potential from electricity exports for the BIGCC system is greater than the SRC system, it is important to compare the lifecycle costs of generation that includes capital and other costs. Based on assumptions that include BIGCC capital costs that are 30 per cent higher than those for a SRC system with a dryer, recurring costs that are 5 percent of the capital costs for each system, and a 25 year lifetime, the two systems have similar internal rates of return. These assumptions are consistent with literature values cited above [25]. However, the cost of generation and the internal rates of return vary significantly with capital and recurring costs assumptions and the prices of electricity and CERs.

5. Discussion and conclusions

From our analysis, BIGCC systems integrated with sugar factories have a much greater electricity generation and export potential than the high pressure direct combustion SRC systems that are beginning to be used in the sugar industry today. We estimated the electricity generation potential assuming that all bagasse generated during the cane crushing season is used by the cogeneration system during that season. However, sugar factories that can export electricity year around at some minimum power level are likely to be able to get a higher price for their electricity than those that only generate in season. Continuous production also ensures that the factories utilize its energy generation system and, in effect, its investment to its full potential. BIGCC, however, with its limitations in producing process steam for factory consumption, will need to consume most of the bagasse during the crushing season. Factories with a sugar refinery and an ethanol distillery (to produce ethanol from molasses) make it even more difficult for a BIGCC system to satisfy their high process steam needs, even during the crushing season. SRC systems on the other hand, could operate at a lower capacity during the cane crushing season and save bagasse for electricity generation during the offseason.

Sugarcane residue or cane trash, which is often left in the field after harvesting, provides one potential additional fuel source that could augment the existing bagasse fuel and increase the ability of systems based on BIGCC technology to meet factory steam demand. According to Macedo, up to 125 kg/tc of dry cane trash could be recovered from the fields [30]. This could increase the fuel availability by 80% on a dry mass basis, thus increasing the electricity generation potential by the same extent (depending on the moisture content of the recovered cane trash). This will increase the BIGCC system's ability to satisfy process steam needs during the crushing season as well as generate electricity for export during the off-season.

BIGCC technology, however, is not commercial, especially in the sugar industry. In contrast, 80–100 bar high pressure direct combustion SRC systems are being implemented in the industry today. A bagasse dryer utilizing the waste heat from the boiler can significantly increase electricity generation and export potential of the SRC cogeneration system. Supercritical direct combustion SRC systems with steam parameters in the range of 290 bar and 600 °C could have electricity generation potentials comparable to atmospheric gasifier based BIGCC systems [31]. This technology is already being used in the coal power generation industry. However, supercritical SRC systems are not suitable for small installed capacities, due to problems related to the operation of the first stages of the turbine with small mass flows (reduced volumetric flow) requiring very small blades. This limits their size to above 280 MW, corresponding to sugar factories having very high crushing capacities (>6.5 million tons per year) [31].

BIGCC and supercritical SRC systems integrated with sugar factories can significantly increase their potentials for electricity generation. However, given the present status and limitations of these technologies, in the immediate future, high pressure direct combustion SRC systems operating at 80–100 bar in conjunction with a bagasse dryer and cane trash as additional fuel would be the most attractive option for sugar factories looking to export electricity for additional revenues.

Acknowledgments

We are grateful to the Sugar Group Companies of Indonesia for their generous funding support. We thank Enio Troiani for his technical inputs and valuable insights. One of the authors, Ranjit Deshmukh, thanks the Schatz Energy Fellowship for funding his research.

REFERENCES

[1] Larson ED, Williams RH, Leal MRLV. A review of biomass integrated-gasifier/gas turbine combined cycle technology and its application in sugarcane industries, with an analysis for Cuba. Energy Sustain Dev March 2001;V(1):54–76.

[2] Ensinas AV, Silvia AN, Lozano MA, Serra LM. Analysis of process steam demand reduction and electricity generation in sugar and ethanol production from sugarcane. Energy Convers Manag 2007;48:2978–87.

[3] Food and Agriculture Organization (FAO). FAOSTAT. The Statistics Division, Economic and Social Department, Food and Agriculture Organization of the United Nations, http://faostat.fao.org/site/567/DesktopDefault.aspx?PageID=567#ancor; 2007a. Site accessed on 4 October, 2009.

[4] Turn SQ. Biomass integrated gasifier combined cycle technology: application in the cane sugar industry, Part I. Int Sugar J 1999;101(1205).

[5] Food and Agriculture Organization (FAO). Food Outlook; 2007b. Global Market Analysis. November 2007.

[6] McNish T, Jacobson A, Kammen D, Gopal A, Deshmukh R. Sweet carbon: an analysis of sugar industry carbon market opportunities under the clean development mechanism. Energy Policy 2009;37:5459–68.

[7] Rodrigues M, Walter A, Faaij A. Performance evaluation of atmospheric biomass integrated gasfier combined cycle systems under different strategies for the use of low calorific gases. Energy Convers Manag 2007;48:1289–301.

[8] Upadhiaya UC. Cogeneration of steam and electric power. Int Sugar J 1992;Vol 93(1117):2–10.

[9] Williams RH, Larson ED. Biomass gasifier gas turbine power generating technology. Biomass Bioenerg 1996;10(2–3):149–66.

[10] Consonni S, Larson ED. Biomass gasifier/aeroderivative gas turbine combined cycles: part A – technologies and performance modelling. J Eng Gas Turbines Power 1996a; 118(3):507–15.

[11] Ducente AB. Large scale gasification of biomass for biofuels and power; 2006. A report prepared by Ducente AB for the European Commission Directorate-General Energy and Transport.

[12] Piterou, A., Shackley, S. and Upham, P., 2008. "Project ARBRE: Lessons for bio-energy developed and project-makers, " Energy Policy, 36 (2008) 2044-2050.

[13] Williams R. Technology assessment for biomass power generation-UC Davis; 2004. Final report, SMUD Regen program.

[14] Consonni S, Larson ED. Biomass gasifier/aeroderivative gas turbine combined cycles: Part B –Performance calculations and economic assessment. J Eng Gas Turbines Power 1996b; 118(3):516–25.

[15] Barroso J, Barreras F, Amaveda H, Lozano A. On the optimization of boiler efficiency using bagasse as fuel. Fuel 2003;82:1451–63.

[16] Hassuani SJ, Leal MRLV, Macedo IC. Biomass power generation: sugar cane bagasse and trash. Piracicaba, Brazil: Programa das Nacoes Unidas para o Desenvolvimento (PNUD) and Centro de Tecnologia Canavieira (CTC); 2005.

[17] Indonesian Sugar Factory. Fac Department, final Monthly report; November 2007.

[18] Beeharry RP. Extended sugarcane biomass utilization for exportable electricity production in Mauritius. Biomass Bioenerg 1996;11(6):441–9.

[19] Coelho S, Prado A, Junior SO, Zylbersztajn D, Cintra RB. Thermoeconomic analysis of electricity cogeneration from sugarcane origin. Third biomass conference of the Americas, Motreal, August 24-29 1997, Elsevier Science Ltd; Vol II: 1631-1640.

[20] Craig KR, Mann MK. Cost and performance analysis of biomass-based integrated gasification combined-cycle (BIGCC) power systems; 1996. National Renewable Energy Laboratory report.

[21] Klimantos P, Koukouzas P, Katsiadakis A, Kakaras E. Air-blown biomass gasification combined cycles (BGCC): system analysis and economic assessment. Energy 2009;34:708–14.

[22] Brown D, Gassner M, Fuchino T, Marechal F. Thermo-economic analysis for the optimal conceptual design of biomass gasification energy conversion systems. Appl Therm Eng 2009;29:2137–52.

[23] Tsakomakas NG, Pilavachi PA, Polyzakis AL. An economic comparison assessment of lignite and biomass IGCC power plants. Appl Therm Eng 2012;38:26–30.

[24] Bridgwater AV. The technical and economic feasibility of biomass gasification for power generation. Fuel 1995;74(5): 631–53.

[25] Dornburg V, Faaij A. Efficiency and economy of wood-fired biomass energy systems in relation to scale regarding heat and power generation using combustion and gasification technologies. Biomass Bioenerg 2001;21(2):91–108.

[26] Wu X, Sulistiyanto P. Independent Power Producer (IPP) debacle in Indonesia and Phillippines: Path dependence and spillover effects. In: Howitt M, Ramesh M, editors. De-regulation and its discontents: rewriting the rules in Asia; 2006. p. 109–23.

[27] Central Electricity Regulatory Commission. CERC (Terms and conditions of tariff determination from renewable energy sources) regulations; 2010.

[28] Restuti D, Michaelowa A. The economic potential of bagasse cogeneration as CDM projects in Indonesia. Energy Policy 2007;35:3952–66.

[29] European Energy Exchange, www.eex.com, accessed on 29th September 2012.

[30] Macedo IC, Leal MRLV, Hassuani SJ. Sugarcane residues for power generation in the sugar/ethanol mills in Brazil. Energy Sustain Dev March 2001;5(1):77–82.

[31] Pellegrini LF, Junior SO, Burbano JC. Supercritical steam cycles and biomass integrated gasification combined cycles for sugarcane mills. Energy 2010;35(2):1172–80.