The Canadian Society for Bioengineering

The Canadian society for engineering in agricultural,
food, environmental, and biological systems.

La Société Canadienne de Génie Agroalimentaire et de Bioingénierie
La société canadienne de génie agroalimentaire, de la bioingénierie et de l'environnement

Paper No. CSBE17-162

CONCEPTUAL DESIGN OF A MULTI-FEED INTEGRATED BIOMASS CONVERSION SYSTEM

Author#1

Saeed Ghanbari (saeed.ghanbari@usask.ca)

Author#2

Venkatesh Meda (venkatesh.meda@usask.ca)

Written for presentation at the
CSBE/SCGAB 2017 Annual Conference
Canad Inns Polo Park, Winnipeg, MB
6-10 August 2017

ABSTRACT As a potential source for sustainable production of fuels, biomass, mainly forestry residuals, had been used for small-scale production of biodiesel as motor fuel since early 1800s; however, large-scale production of fuels from biomass has decreased because of the pronounced drop in the price of petroleum in recent decades and competitive economics. In addition, process design engineers and researchers have been working on challenges such as environmental issues, low reactor yield, and uncertainties in biomass feedstock. Hence, extensive research has been performed in order to overcome these challenges. Biomass can be commercially converted to a wide range of fuels, chemical, solvents, and other valuable products using pyrolysis and gasification processes. A great deal of research and development has been done to optimize various independent operating variables, develop novel product upgrading methods such as bio-oil upgrading, and find innovative approaches to increase the reaction yield; nonetheless, the implementation of these methods for a multi-feed integrated biomass production plant has been rarely studied. In recent decades, the foundational blocks for the design of high-tech integrated biomass conversion systems have been significantly investigated and reported in the literature. This paper reports a conceptual design and feasibility study of such a system incorporating the new strategies and technologies at hand. As such, abundant sources of biomass in the Prairies (Saskatchewan) such as municipal solid wastes, agricultural solid wastes, forestry residuals, and industrial wastes were identified and characterized. A star model for a multi-feed integrated biomass conversion system in Saskatchewan was devised and simulated based on the available data on existing commercial biomass gasification/pyrolysis systems in the world. Important aspects of the design such as economics, net energy production, post-upgrading of products, and fallibility of the plant were discussed.

Keywords: Biofuel, Pyrolysis, Gasification, feasibility study, simulation

INTRODUCTION Biomass supplied a huge majority of the world's energy and fuel demands in mid 1800s. With the beginning of the fossil fuel era and the onset of the "first oil shock" in the mid 1970s, however, biomass industry started to phase out in developed countries, and was realized by many governments and officials as a potential domestic energy source capable of reducing oil consumption and the concomitant environmental issues (NRC, ISBN: 0-309-06779-0). For instance in Canada, biomass energy consumption was about 134,000 BOE/day (3%) in late 1970s, which was increased to 250,000 BOE/day (4.4%) by 1992 (Michael Hiete, 2009).

Unfortunately, fixed carbon-containing materials renew themselves over millions of years to replenish petroleum or natural gas deposits (Klass, 2010). Considering the today's energy demand, humankind cannot wait that long; hence, another approach is to convert CO_2 in the atmosphere into synthetic fuels and useful chemicals via development of fixed carbon supplies from renewable carbon sources. To this end, a convenient way is to reduce CO_2 with hydrogen in order to produce methane and water as end products, as follows:

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O \qquad [1]$$

Therefore, the core concept of renewable energy form biomass is growing through capturing of carbon from ambient CO2 and solar energy, conversion of biomass to fuels and chemical, and then combustion and return of fixed carbon to the cycle during photosynthesis to the atmosphere as CO2. This statement can be equally interpreted that all manufactured products from oil and gas industry can be produced from biomass feedstock (Klass, 2010).

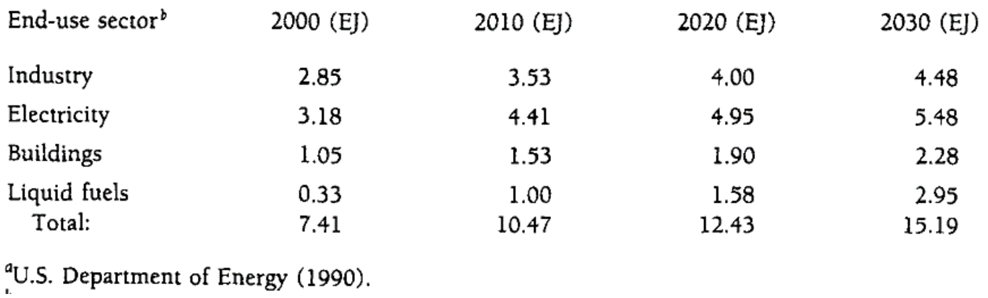
In recent years, that biomass energy is a substantial contributor to energy market has been acknowledged as an inevitable fact. Klass (1994) reported a grand total biomass energy consumption of 1,371,000 BOE[1]/day in 1990 in the United States, which accounts for 3.3 % of primary energy consumption. In another report form the U.S. Department of Energy, 2,026,200 BOE/day (4.8 % primary energy consumption) biomass energy consumption was reported as well. Municipal waste, wood/wood wastes accounted for 10 % and 84% of biomass energy use in 1990, respectively. Records in the literature strongly suggest that sustainable biomass energy consumption can be enhanced (Michael Hiete, 2009).

Many factors affect the market penetration of renewable energy from various biomass sources including energy demand, petroleum price, international and government policies, competitive feedstock, and the state-of-art in biomass net energy production-conversion industry. Table 1 shows the projected biomass energy contribution in the U.S. reported by the department of energy, in which the potential of biomass energy can be observed.

Table 1: projected biomass energy contirbution in the U.S. under a national premiums scenario from 2000 to 2030 (NRC, ISBN: 0-309-06779-0)

---

[1] Barrel of oil equivalent



End-use sector[b]	2000 (EJ)	2010 (EJ)	2020 (EJ)	2030 (EJ)
Industry	2.85	3.53	4.00	4.48
Electricity	3.18	4.41	4.95	5.48
Buildings	1.05	1.53	1.90	2.28
Liquid fuels	0.33	1.00	1.58	2.95
Total:	7.41	10.47	12.43	15.19

[a]U.S. Department of Energy (1990).

As for the global markets, 6.7 % of the world's energy demand in 1990 was supplied by biomass (NRC, ISBN: 0-309-06779-0). This energy source and its related technologies have been significantly grown in most developing countries in Africa, South America, and Asia. Sixty two billion liters of biofuels were globally produced in 2007 (Klass, 2010). Ethanol produced from fermentation of corn represents for more than 50% of ethanol production in the U.S., 38% in Brazil, 4.3 % in European Union, and 3.7 % in China (NRC, ISBN: 0-309-06779-0). In addition, as the results of UN study suggest (UNEP, 2008), jobs and employment potential in biomass renewable energy industries will be more than those in fossil fuels in 2030, where the projected investment of US$ 630 billion would result in at least 20 million jobs in this sector.

Although biomass energy and its market seem attractive, major barriers still must be overcome for large-scale production of fuels and chemicals worldwide (Klass, 2010). The most critical barrier now is the low price of petroleum that made this market very competitive. As discussed in detail later in his report, many large-scale integrated biomass conversion systems in the world were shut down due to sharp drop in the price of oil, as one of the main reasons (Michael Hiete, 2009). Concisely, with the advent of new technologies, strategies, and systems, the future of biomass energy industry seems promising, and it is very likely to overcome the current challenges.

PROSPECTIVE OF AN INTEGRATED BIOMASS PRODUCTION PLANT IN SASKATCHEWAN

OVERVIEW AND RATIONALE OF THE PLANT

Saskatchewan is ranked fifth out of ten provinces in total land area (651,036 km^2), where 117,000 km^2 of which is commercial forest zone (around one third), and 146,739 km^2 of which is crop area and parries (SK forestry report, 2016). According to the 2016 annual report from Saskatchewan Forestry Development Branch, the forest sector produces approximately 1.0 million ODT[2] of biomass per year, either from the harvest of timber or as wood waste during the manufacturing process. Saskatchewan Scarp Tire Co. reported that 806,013 scrap tires were collected in Saskatchewan in 2016 for recovery purposes, which are source of bioenergy (Scarp Tire Co, 2016). In another report from Canada animal waste management committee, 17,866,750 tons of cattle manure were produced in Saskatchewan in 2016. Close production numbers were also reported for the last two years. Comprising 3.2% of Canada's population, the population of Saskatchewan is expected to increase as well as the industry development, energy requirement, food production, and air pollution. That said, sustainable green energy programs are highly

---

[2] Oven Dried Tons

appreciated and welcome by the government of Saskatchewan for food security, sustainable energy production, and the improvement of environmental problems.

In this project, the authors attempted to investigate the available bioenergy sources in Saskatchewan, and do a feasibility study of an integrated multi-feed biomass conversion-production plant in the province. Figure 1 shows the overall scheme of this plant. Five different sources of biomass in the province were identified, selected, and analyzed: Agricultural residues, Forestry residues, Municipal Solid Wastes (MSW), Industrial wastes, and Virgin biomass. Approximate production numbers of each biomass feedstock were collected, their energy content were approximated, and technical factors such as feedstock delivery/receiving cycles throughout the year, availability, transport, storage, and handling were analyzed. Dimethyl ether (DME) and electricity are the final products of this plant.

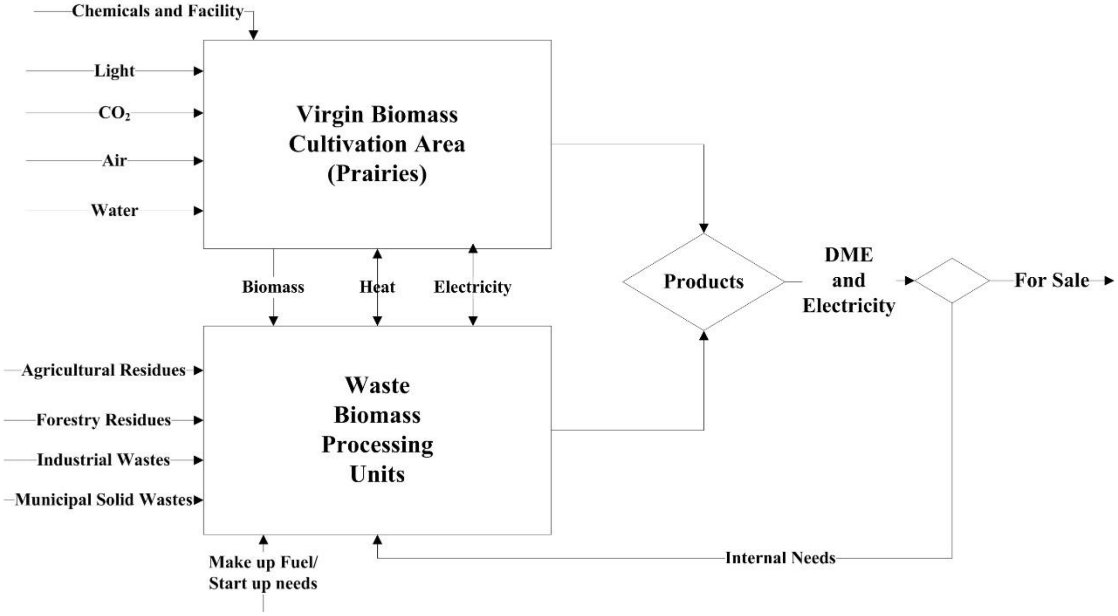


Figure 1: The overall scheme of the proposed design

The long-term plan of this feasibility study and design is sustainable production of fuels from available biomass in the province considering the current challenges as well as novel solutions suggested by researchers around the world. DME is a versatile biofuel that can be used for power generation or combined with LPG or diesel. It is also feed for production of dimethyl sulfate, and is used as an aerosol repellant as well. Modified DME can be used as jet fuel as well (Rupesh, et al., 2016). All units in this plant are designed based on a previously built commercial plant or successful pilot-plant. In the following sections, details of the design and results of this feasibility study are discussed.

BIOMASS FEEDSTOCKS IN SASKATCHEWAN

As previously mentioned, five different feedstocks were selected and investigated in the province. More specifically, agricultural residues from all crop districts in the province were approximated based on data from Statistics Canada. Forestry data were collected from Saskatchewan Ministry of Forest. Cattle manure production numbers were provided from Livestock Branch of Saskatchewan's Ministry of Agriculture. Industrial wastes produced in the province include shredded tires (Shercom Industries Inc.), black liquor (Paper Excellence Co.), and Activated Sludge (Saskatoon Waste Water Treatment Plant). The production numbers are summarized in Table 2.

Using average energy content reported in the literature (Klass, 2010), one can calculate the potential annual energy production from biomass available for this plant in the province (Table 2). According to Satatistics Canada, 624,467 terajoules energy was consumed in 2003 in Saskatchewan. Potential energy production from biomass is considerably higher than this total energy consumption. It is worthy of note that the energy content is a function of moisture content, which is different for each type of woody biomass and agricultural residues. Hence, these numbers are only approximates. Accurate results are calculated from computer simulations (ASPEN PLUS).

Table 2: Summary of biomass feedstocks available in Saskatchewan and their energy content [2, 3, 4, 8, 10]

Biomass type	Average production number	Average energy content (MJ/kg)	Potential energy production (PJ/year)
Agricultural residues	67,746,851 tons per year	15	1016.2
Forestry residues	20.11 million cubic feet per year	10.7	1.5
Cattle manure	17,866,750 tons per year	15.73	281.0
Activated Sludge	11.2 M lb/year	12.7	0.1
Shredded Tires	50 M lb/year	16	0.4
		Grand Total :	**1299.2 PJ/year**

PLANT DESIGN

This plant is designed to accept biomass feedstock from a variety of sources, which can be continuously supplied throughout the year. All the five units are designed based on existing commercial plants in the world. The design can be further optimized given time for a detailed study, simulation, and analysis. The plant is simulated in ASPEN PLUS in order to obtain mass and energy balance (capacity and energy requirement of the system).

Plant Layout

Plant's layout is illustrated in Figure 2. All biomass feedstocks are delivered to a "Feedstock Center" for preliminary analysis of moisture content, size distribution, and composition. Enough storage silos are considered with a capacity of one month of feedstock for each unit (based on the capacity of each unit). The circumference of the plant is considered as virgin biomass cultivation area, in which short rotating woody crops (SRWC) will be cultivated. These plants, which are also known as “Energy Crop”, grow quickly, and are usually felled when they are 15 cm wide at chest height. In contrast to standard forestry crops that grow in 60 years or more, it takes 6 to 20 years to grow. Hence, SRWC are suitable candidates for bioenergy production.

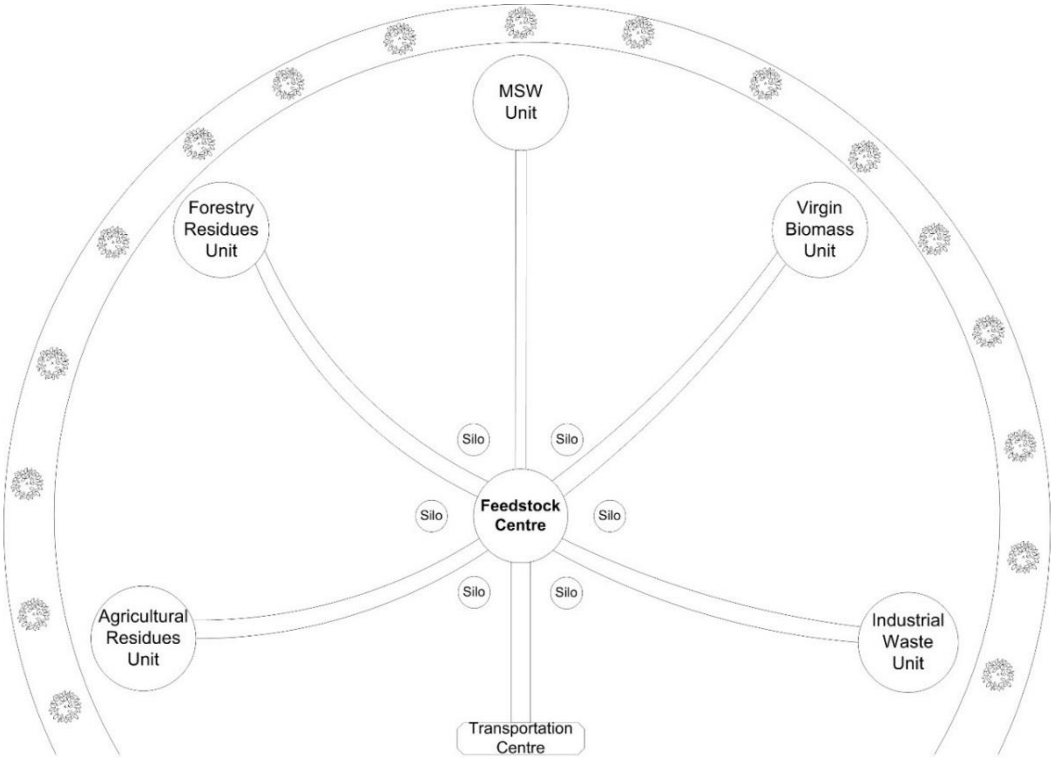


Figure 2: Plant's layout

Rotation length of 8-years is estimated for the SRWC. Therefore, the cultivation area will be divided into 8 equal sectors, and SRWC will be planted in each area every year. As such, each sector can be harvested after its rotation length (8 years), which supplies feedstock for the plant every year. The total required cultivation area is estimated based on the capacity of the Virgin Biomass Unit in the plant (Figure 2) using Alberta Agriculture and Forestry Decision Making tool. By following this 8-year cycle, continuous biomass feedstock can be supplied for the related unit in the plant.

Units Description

Several commercial, near-commercial, and pilot-plant systems including their applied technologies were studied, and suitable systems for the available biomass feedstocks in the province were chosen. In what follows, these selected systems are briefly explained.

In the agricultural residues unit, a twin-fluidized bed is used, in which sand is used as the heating medium for the gasification bed, while heat is supplied by combustion of biomass. Sand is recycled continuously between the two beds. The size distribution of biomass feed is critical in fluidized beds; hence, a hammer mill is used to reduce the particle size to below 6 mm. Cyclones are used to separate biochar from the produced gas. Biochar is recycled to the combustion bed, while a part of the produced gas is employed as medium gas to fluidize the gasification bed. In addition, combustion gas, which contains Nitrogen from air, is sent to other units for heat integration and electricity production. The temperature of gasification bed and combustion bed were controlled at 800 C and 950 C, respectively. It was reported that a medium-energy gas having a HHV of about 19.4 MJ/m^3 were produced. This plant yielded 670 m^3 of produced gas per ton of feed. This gas is further processed into high-energy methane gas (Klass, 2010).

Bioenergy with carbon capture and storage (BECCS) system is considered for the gasification of woody biomass. Lime is used in the gasifier bed, which reacts with carbon dioxide. Calcium carbonate, which is the product of this reaction, is sent into the CO_2 capture bed where it decomposes to lime and CO_2 again. This carbon capture process improves the gasification process in terms of yield and thermal energy (Crocker, 2010). The gas cleaning system and produced gas processing are similar to those of agricultural residues system.

ARBRE Energy Ltd Biomass Integrated Gasification/Gas Turbine (BIG-GT) system is considered for the Virgin Biomass unit. After size reduction and drying, the biomass feedstock is sent into the fluid bed gasifer using air (both medium and conveying gas). In the cracker, dolomite is used as the catalyst to convert tars to gases and lower molecular weight gases, which reduces the amounts of organics from the product gas, and minimizes water-treatment costs. The next stage is gas cooling using electrostatic precipitator and water quench systems. Afterwards, the produced gas is compressed and sent into gas turbines for electricity production. This hot gas is later used in the steam generation unit and the biomass dryer. Since the gas and steam turbines are not effected by scale up (Crocker, 2010), gases from other units are also sent into this unit for electricity production in the gas turbine system. The system used for gasification of cattle manure is similar to that of agricultural wastes; however, the operating conditions are different.

SIMULATION RESULTS

This simulation is done using ASPEN PLUS software. The overview of main flowsheet and sub-flowsheets is available in the appendix. RK-BM fluid package is used in biomass processing unit operations, while NRTL-RK fluid package is selected for distillation-stripper columns, and STEAM-TABLE is used in the combined heat and power generation (CHP) unit (Akhlas, 2015). Biomass is simulated as nonconventional inert solids (NCIS) in ASPEN PLUS, and ultimate, proximate, sulfanal analyses are used in order to simulate the gasification and pyrolysis reactions. Bio-oil is simulated as a petroleum assay based on distillation curves, viscosity curves, and flash data reported in the literature. Fortran statements are used for simulation of these units based on correlations and reaction yields reported in the literature (Abdelouahed, et al., 2012).

In the main flowsheet (figure 3), five biomass conversion units, CHP, CO shift unit, CO_2 removal unit, DME production unit, and storage unit are shown. The green line represents the final DME products (liquid 96.8% purity, gas 99.1% purity), and the gray line represents the bio-oil product. Blue lines are power produced or consumed by the units. Tetraethylamine (TEA) absorption unit is designed for CO_2 removal unit (figure 6). In DME production unit, two fischer tropsch reactors with Nickel catalyst, and one methane reforming reactor are designed. Unreacted reactants are recycled in the methane-reforming reactor (figure 7).

According to the simulation results, 3.1 tons of DME per hour, 1397 kg of bio-oil per hour, and 9,735.1 MWh of electricity are produced in this plant. In general, biomass is converted to syngas. The ratio of H_2/CO is adjusted to 2 in the CO shift unit, which is suitable for DME production. Afterwards, excess carbon dioxide is removed, and the syngas is sent into two fischer tropsch reactors. Hot exhaust gases are sent into the CHP plant for electricity and steam production. Three classes of steam (HPS, MPS, LPS) and abundant amounts of hot utility water are produced, which are used for internal energy use.

ECONOMIC ANALYSIS

ASPEN Economic analyzer module is used to perform a comprehensive economic analysis for this extensive simulation. The results are summarized in table 3. As can be noticed, the plant is not economical due to remarkably high operating costs. A capital investment of 230.91 million USD and annual operating cost of 1.01 billion USD are estimated, while the total sales income is 162.13

million USD. Due to the enormous production capacity of the plant, the capital investment can be returned shortly; however, this large capacity resulted extraordinary high operating costs, which would be expected in plants with solid processing and CHP units.

Table 3: Economic Analysis Summary

INVESTMENT			PROJECT CAPITAL SUMMARY		
	Total Cost	Currency		Total Cost	Currency
Total Project Capital Cost	230.91	MM USD	Purchased Equipment	121.96	MM USD
Total Operating Cost	1,014.19	MM USD/Year	Equipment Setting	5.12	MM USD
Total Utilities Cost	930.93	MM USD/Year	Piping	22.92	MM USD
Total Product Sales	162.13	MM USD/Year	Civil	4.01	MM USD
Total Operating Labor and Maintenance Cost	5.23	MM USD/period	Steel	0.43	MM USD
Operating Charges	0.30	MM USD/period	Instrumentation	5.28	MM USD
Plant Overhead	2.61	MM USD/period	Electrical	3.45	MM USD
Subtotal Operating Cost	939.07	MM USD/period	Insulation	2.86	MM USD
G and A Cost	75.13	MM USD/period	Paint	0.27	MM USD
			Other	42.32	MM USD
			Subcontracts	0.00	MM USD
			G and A Overheads	6.04	MM USD
			Contract Fee	5.87	MM USD
			Escalation	2.00	MM USD
			Contingencies	39.69	MM USD

High operating cost is the main factor that currently holds the biofuel industry from further development. Even though this plant design is highly optimized and combined with heat and power production and integrated biomass units, it is not economically feasible yet. This study brings us to the conclusion that further research in this area is required. Modern methods with lower operating costs, automated systems with fewer operating problems, and superior control systems must be further explored and studied.

CONCLUSIONS AND RECOMMENDATIONS

In this study, various sources of biomass in the Saskatchewan province including their production numbers were identified and obtained. Based on these findings, proper conversion system and technology were selected for the five different biomass feedstocks used in the designed plant. The results suggest that 1299.2 PJ energy can be approximately produced every year. Considerable amount of biomass is produced in the province, which has the potential of energy production. The required technologies are available as well; hence, an integrated biomass conversion plant can supply a significant amount of province energy demand. Afterwards, the plant was simulated in ASPEN PLUS in order to obtain mass and energy balance and to perform an economic analysis, and optimize the system. The results showed that this plant is not economical due to high operating costs. Solid processing is known for its associated technical difficulties. Additional cost factor of 1.5-3 suggested in the chemical plant design textbooks is an indicator of this fact. Ash management and odor management (cattle manure) spell technical problems for this plant, which must be taken care of in accordance to guidelines provided by the Ministry of Environment. Fouling of heat exchangers and solid-gas separation units due to tars, biochars, and fly ash is another issue in this system. Temperature control, electrostatic prevention methods, surface coating, and spare units are common methods usually applied in such systems.

The unreliability of biomass conversion systems is known as the number one challenge in these systems. The close scrutiny of most plants that were previously built and placed in operation in the world reveals that most of them encountered technical and operating problems, which were unexpected. More specifically, various composition of produced gas from gasifier, low yields, unstable bio-oil, fouling and difficulties with tars and biochars are some of the highlights. In addition, the competitive price of gasoline made this market very challenging. Constant feed is critical in running a steady-state chemical plant. In the case of biomass conversion plants, it can hardly be assumed that every batch of feed is identical. From an engineering perspective, this is very challenging because the operating costs, product yields and conditions are strong function of biomass feedstock. That said, advanced design and robust control/management are essential.

In conclusion, this research study shows that bioenergy can be produced from biomass; however, the process is not economical. In addition, this study indicated that further research in this area is essential. Biomass is a major source of clean energy and can supply a major part of province energy demand. Novel processes with lower operating costs and superior automated control systems must be studied. Advanced turbines with higher efficiency would make this plant more economical. Recently, pressure swing adsorption process has been conceived to be an effective process for CO_2 removal. This process is easier to control, and both the capital and operating cost are much lower that those of TME absorption process. In addition, very limited studies on advanced catalysts for gasification and pyrolysis reactions were published in the literature. Higher yield in those units would eliminate a considerable part of operating costs, and capital costs in downstream units, especially CO shift and CO_2 removal. That said, research on this area is highly appreciated and needed.

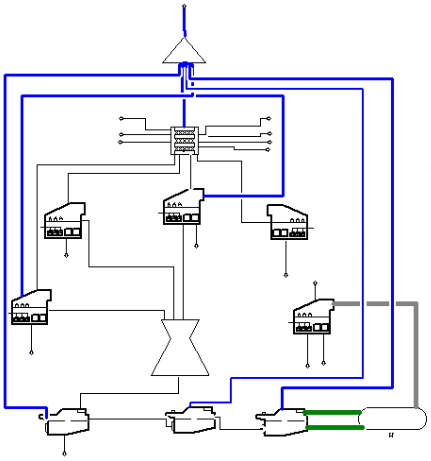
REFERENCES

1. *Committee to Review the R&D Strategy for Biomass-Derived Ethanol and Biodiesel Transportation Fuels, National Research Council, Review of the Research Strategy for Biomass-Derived Transportation Fuels, ISBN: 0-309-06779-0*
2. *Michael Hiete, Jens Ludwig, Christian Bidart, Frank Schultmann (Eds.), "Challenges for Sustainable Biomass Utilization", Proceedings of the Chilean-German Biociclo Workshop (Karlsruhe, 26.03.2009).*
3. *Klass, Donald L. Biomass for renewable energy, fuels, and chemicals. Academic press, 1998.*
4. *Crocker, Mark, ed. Thermochemical conversion of biomass to liquid fuels and chemicals. No. 1. Royal Society of Chemistry, 2010.*
5. *Saskatchewan's forestry sector, final report, May 2016.*
6. *Crop report, Ministry of Agriculture, Government of Saskatchewan, ISSN 0701 7085, Period November 15 to 21, 2016 Report number 28, November 24, 2016.*
7. *Canada Animal Waste Management Guide Committee, Canada Committee on Agricultural Engineering, 1972.*
8. *Saskatchewan Scrap Tire Co., Annual Report, For the year ended December 31, 2016.*
9. *Hinchee, Maud, et al. "Short-rotation woody crops for bioenergy and biofuels applications." Biofuels. Springer New York, 2011. 139-156.*
10. *www.bioenergyadvice.com*

11. *Rupesh, S., C. Muraleedharan, and P. Arun. "ASPEN plus modelling of air–steam gasification of biomass with sorbent enabled CO 2 capture." Resource-Efficient Technologies 2.2 (2016): 94-103.*
12. *Akhlas, Junaid, Fabio Ruggerib, and Alberto Bertuccoa. "Simulation of Steam Gasification of Coal with PreCombustion enabling Cleaner Coal Conversion." CHEMICAL ENGINEERING 43 (2015).*
13. *Abdelouahed, Lokmane, et al. "Detailed modeling of biomass gasification in dual fluidized bed reactors under Aspen Plus." Energy & Fuels 26.6 (2012): 3840-3855.*

APPENDIX

Simulation flowsheets:



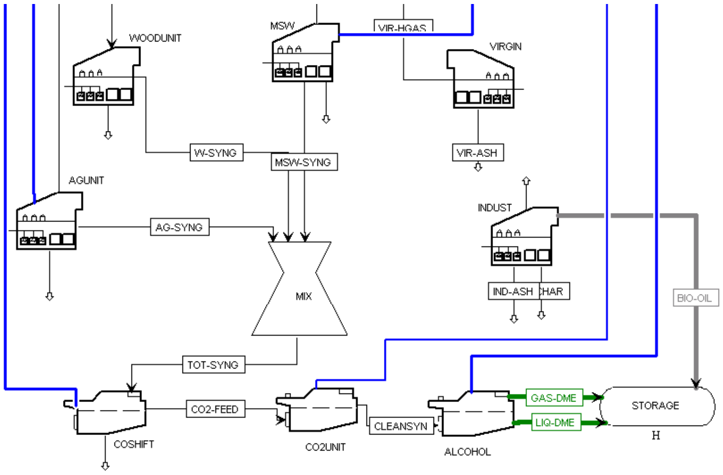


Figure 3: Main flowsheet

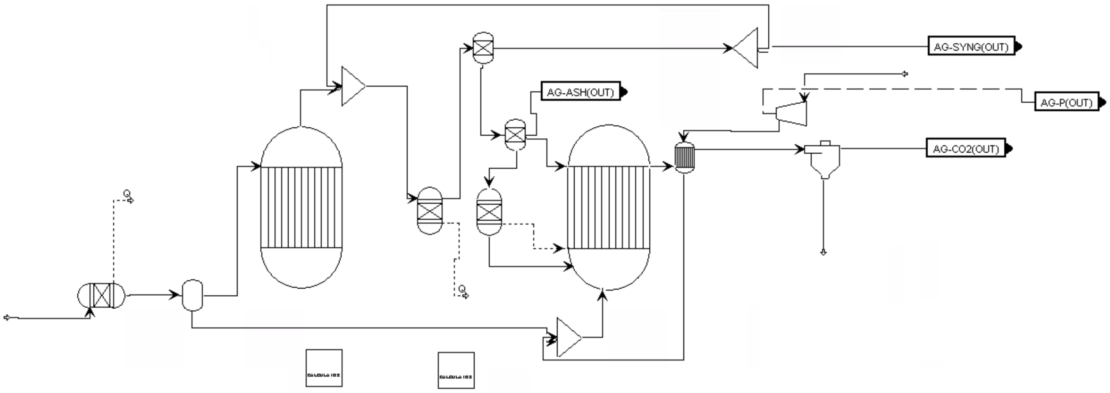


Figure 4: an example of a two-bed gasification flowsheet

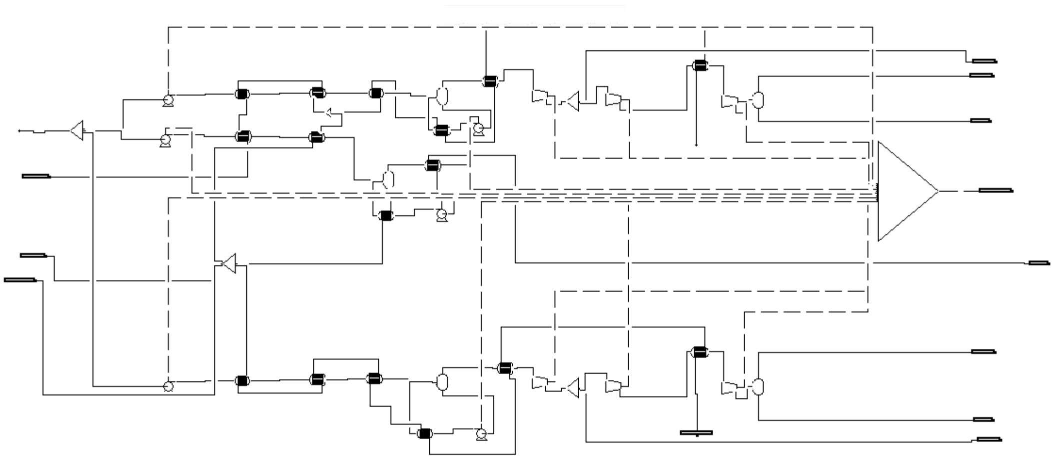


Figure 5: CHP unit

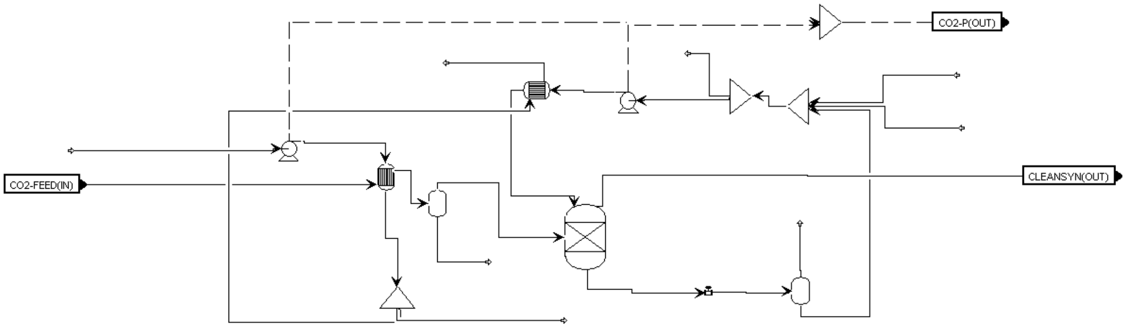


Figure 6: CO_2 removal flowsheet

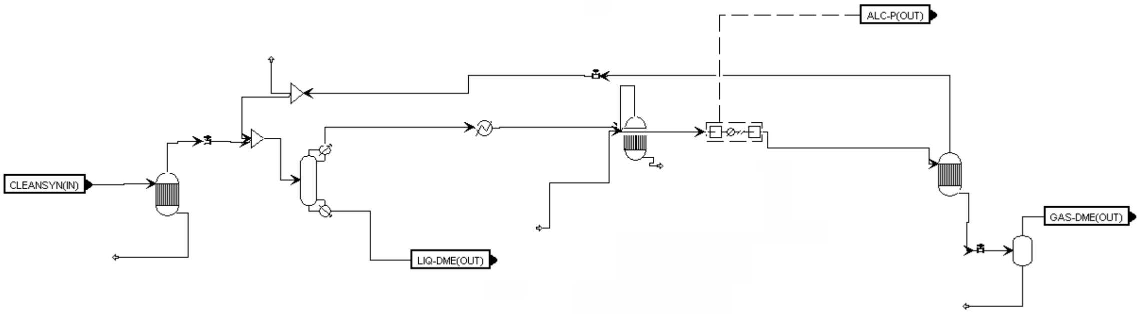


Figure 7: DME production and purification flowsheet