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# Economic Analysis and Assessment of Syngas Production using a Modeling Approach

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**Abstract.** *Economic analysis and modeling are essential and important issues for the development of current feedstock and process technology for bio-gasification. The objective of this study was to develop an economic model and apply to predict the unit cost of syngas production from a micro-scale bio-gasification facility. An economic model was programmed in C++ computer programming language and developed using a parametric cost approach, which included processes to calculate the total capital costs and the total operating costs. The model used measured economic data from the bio-gasification facility at Mississippi State University. The modeling results showed that the unit cost of syngas production was \$1.217 for a 60 Nm$^{-3}$ h$^{-1}$ capacity bio-gasifier. The operating cost was the major part of the total production cost. The equipment purchase cost and the labor cost were the largest part of the total capital cost and the total operating cost, respectively. Sensitivity analysis indicated that labor costs rank the top as followed by equipment cost, loan life, feedstock cost, interest rate, utility cost, and waste* *treatment cost. The unit cost of syngas production increased with the increase of all parameters with exception of loan life. The annual cost regarding equipment, labor, feedstock, waste treatment, and utility cost showed a linear relationship with percent changes, while loan life and annual interest rate showed a non-linear relationship. This study provides the useful information for economic analysis and assessment of the syngas production using a modeling approach.*

**Keywords.** Bio-gasification, economic model, sensitivity, syngas, micro-scale.

## Introduction

Biomass can be converted into useful forms of energy using a number of different processes. Factors that influence the choice of conversion process are the type and quantity of biomass feedstock, end-use requirements, environmental standards, economic conditions, and project specific factors (McKendry, 2002). Recently, bio-gasification is one of the most commonly used biomass conversion technologies, as the gases from bio-gasification are intermediates in the high-efficient power production or the synthesis from chemicals and fuels (Boerrigter and Rauch, 2006, Li et al., 2010). In the process of gasification, biomass feedstock is converted into a synthetic gas (syngas) consisting primarily of hydrogen ($H_2$) and carbon monoxide (CO), with lesser amounts of carbon dioxide ($CO_2$), water ($H_2O$), methane ($CH_4$), and nitrogen ($N_2$). The produced syngas can be used for methanol and hydrogen production, each of which may have a future as fuels for transportation as well as power generation (McKendry, 2002).

In order to  understand the economic feasibility of a bio-gasification facility is a determination of its production cost, which is a function of biomass feedstock, transportation, conversion, conditioning of the produced syngas, other procurement, transaction, and opportunity costs (Walsh, 1998; Wei et al., 2009a). There are significant differences in construction, installation, and operating procedures for different types and scales of gasifiers, which will lead to significantly different costs. No universal costing model to assess all bio-gasification projects was actually available in the literature (Mitchell et al., 1995; Larson, 1998). A parametric-cost model such as factored estimate is an extremely useful tool for preparing early conceptual estimated when there are little technical data or engineering deliverables to provide a logical and predictable correlation between the physical or functional characteristics of plant and its resultant cost (Dysert, 2003). There are several studies performed to evaluate economics of bio-gasification system (Mitchell et al., 1995; Craig and Mann, 1996; Dowaki et al., 2005; Jin et al., 2009; Larson et al., 2003; Stassen and Knoef, 1995; Wei et al., 2010). Most of the previous studies have concentrated on the economic analysis of electricity power production from biomass since bio-gasification project have typically been developed to generate electrical power. Research studies on  economic analysis for syngas production from bio-gasification are relatively few (Wei et al., 2009a; Li et al., 2010).

Some studies have assessed advantages of micro-scale or small-scale bio-gasification system (Margo et al., 2009; Wei et al., 2009a). An economic model can be  used  to evaluate economic feasibility and examination of the probable cost of syngas production. Modeling also offers the possibility for quantitatively evaluating and comparing the economic feasibility under different conditions and scenarios (Borjesson and Ahlgren, 2010). Thus the objective of this study is to develop an economic model for evaluation and assessment of  syngas production costs of micro-scale syngas facility using a modeling approach.

## Materials and Methods

A general procedure of the micro-scale bio-gasification facility is presented (Fig. 1), which consists of three units: feedstock preparation, gasification, and syngas cleaning (Wei et al., 2009a). The pilot micro-scale bio-gasification system was installed at the Mississippi State University (MSU), Department of Agricultural and Biological Engineering's Research Building in 2003. It was centered on an atmospheric, downdraft, and a fixed-bed gasifier system (BioMax Renewable Fuel Gas Generator, Community Power Corporation (CPC) of Littleton, CO). The full-load capacity of the gasifier system was designed by CPC to produce syngas at a 60 $Nm^3$ $h^{-1}$ rate.

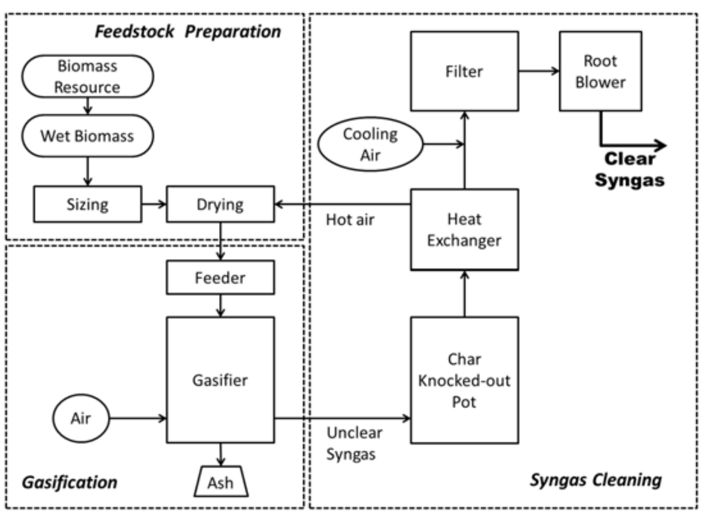



Figure 1. Micro-scale bio-gasification system.

### *Syngas Production*

Syngas production in the micro-scale gasification facility starts with the receipt of raw biomass feedstock. In this study, the hardwood chips were used as raw biomass feedstock. These chips were of red oak, with a length usually less than 75 mm (Wei et al., 2009b). The carbon content, the nitrogen content, and the density of the used hardwood chips were 51% (wt), 0.3% (wt), and 0.2 g $cm^{-3}$, respectively (Wei et al., 2009b). Raw biomass feedstock for gasification may have moisture content (MC, wet basis) ranging from 5% to 50%. Thus, some feedstock may need sizing and/or drying. The prepared feedstock is then fed into the gasifier, the control system is initialized, and an internal heater is turned on to warm up the system and then ignite the feedstock. The heater takes 30 to 40 minutes to warm up the system. After the system warms up to a set temperature, the heater is automatically turned off. At that point, the system is under fully automated control for syngas production (Wei et al., 2009a; Wei et al., 2009b).

The feedstock loaded into the gasifier undergoes four stages of chemical reaction in the process of being converted into syngas: drying, pyrolysis, oxidation, and reduction. The syngas produced in this study from wood chip air gasification (air used as oxidant) with a downdraft gasifier contained about 22% CO, 12% $CO_2$, 3% $CH_4$, and 18% $H_2$, with the balance being $H_2O$ and $N_2$ (Wei et al., 2009a; Wei et al., 2009b). In this study, the syngas was designated for fueling internal combustion engines in a CHP application. It was assumed that the syngas was compressed in storage tanks or delivered directly to an engine or gas turbine for power generation without those operations being considered in the study. More literature for this section can be found in Wei et al (Wei et al., 2009a; Wei et al., 2010).

### *Economic Model Description*

An economic model was developed using a $C^{++}$ computer programming language, which was based on several mathematical equations, calculations, and assumptions. The economic evaluation of the bio-gasification system has been carried out on the basis of capital cost, operating cost, and revenue from sale of the recovered heat. Total capital cost was calculated by adding the fixed capital cost to the working capital cost. The fixed capital costs were determined as the sum of direct project costs, indirect project costs, and other costs. Total operating cost consisted of direct operating costs, fixed operating costs, and general expenses. Total annual production cost was calculated by subtracting the by-product credit from the sum of the total annual capital charge and the total annual operating costs. Finally, syngas production unit cost was calculated by dividing the total annual production cost by the total annual syngas yield. All the considered items and equations used to calculate the composition of production costs are summarized in Table 1. Numerical values for such factors used in this study were derived from other previous studies (Turton et al., 1998; Wei et al., 2009a; Choi et al. 2010). Based on these calculations, All costs were adjusted to be in U.S. dollars, year 2008 basis.

The total capital costs have been evaluated as the sum of the fixed capital cost and the working capital cost. A fixed capital cost represents all the costs associated with constructing a new facility. It consists of three parts: the direct project cost, the indirect project cost, and other costs. Total direct project costs include the equipment cost, materials required for installation, and all labor costs associated with installing the equipment and materials.

The new equipment purchase cost of an existing similar facility can be calculated by the relationship between the purchased cost and an attribute of the equipment related to units of capacity (Turton et al., 1998; Wei et al., 2009a; Wei et al., 2010). The relationship is given by

$$\frac{C_a}{C_b} = \left(\frac{A_a}{A_b}\right)^n \tag{1}$$

where *A* is equipment cost attribute, *C* is purchased cost, *n* is costs exponent, a refers to equipment with the required attribute, b refers to equipment with the base attribute. The exponent value of 0.6 is often used for new micro-scale gasification facilities (Wei et al., 2009a; Wei et al., 2010).

Other expenses, such as materials cost, building and construction costs, indirect project costs, other costs, and working capital cost were calculated individually and multiplied by related factors, as shown in Table 1.

Annual capital charge can be calculated using the following equation with a capital recovery factor (Turton et al., 1998; Klonsky et al., 2009; Choi et al., 2010).

$$C_{AC} = C_{TC} \times \frac{i(1+i)^n}{(1+i)^n - 1} \tag{2}$$

where $C_{TC}$ is the annual capital charge, $C_{TC}$ is the total capital cost, *i* is the interest rate, and *n* is the loan life.

The annual operating cost of the bio-gasification system was calculated as the sum of all the annual costs, including both direct and indirect operating expenses, and by-product credits. Direct operating costs represent operating expenses that vary with production rate. These costs include the raw materials costs, waste treatment cost, utilities costs, operating labor cost, supervisory and clerical labor cost, maintenance and repair expenses, and operating supplies costs, laboratory charges, and patents and royalties costs.

Table 1. Equations for calculating syngas production cost.

| Cost factor | Equation | References |
|---|---|---|
| • Total capital cost ($C_{TC}$) | $C_{FC}$+$C_{FC}$ | |
| o Fixed capital cost ($C_{FC}$) | | |
| 1. Direct project costs ($C_{DC}$) | | |
| (a) Equipment (f.o.b) ($C_{EQ}$) | $C_{EQ}$ | Wei et al. (2009a) |
| (b) Materials for installation ($C_{MI}$) | $0.2C_{EQ}$ | Wei et al. (2009a) |
| (c) Building and construction ($C_{BC}$) | $0.35C_{EQ}$ | Wei et al. (2009a) |
| 2. Indirect project costs ($C_{IC}$) | | |
| (a) Freight, insurance, and taxes ($C_{FIT}$) | $0.08C_{EQ}$ | Choi et al. (2010) |
| (b) Construction overhead ($C_{CO}$) | $0.05C_{EQ}$ | Wei et al. (2009) |
| (c) Contractor engineering costs ($C_{CE}$) | $0.15(C_{EQ}+C_{MI})$ | Choi et al. (2010) |
| 3. Other costs ($C_{OT}$) | | |

| | | |
|---|---|---|
| (a) Contingency and fee cost ($C_{CF}$) | $0.18(C_{DC}+C_{IC})$ | Choi et al. (2010) |
| (b) Auxiliary facilities cost ($C_{AF}$) | $0.3(C_{DC}+C_{IC}+C_{CF})$ | Choi et al. (2010) |
| o Working capital cost ($C_{WC}$) | $0.13C_{FC}$ | Choi et al. (2010) |
| • Annual capital charge ($C_{AC}$) | $C_{TC}$ ×Capital recovery factor | Choi et al. (2010) |
| • Total Operating cost ($C_{AO}$) | $C_{DO}+C_{FO}+C_{GC}$ | |
| 1. Direct operating costs ($C_{DO}$) | | |
| (a) Raw materials ($C_{RM}$) | $C_{RM}$ | Wei et al. (2009a) |
| (b) Waste treatment ($C_{WT}$) | $C_{WT}$ | Wei et al. (2009a) |
| (c) Utilities ($C_{UT}$) | $C_{UT}$ | Wei et al. (2009a) |
| (d) Operating labor ($C_{OL}$) | $C_{OL}$ | Wei et al. (2009a) |
| (e) Supervisory and clerical labor ($C_{SC}$) | $0.15C_{OL}$ | Choi et al. (2010) |
| (f) Maintenance and repairs ($C_{MR}$) | $0.06C_{FC}$ | Choi et al. (2010) |
| (g) Operating supplies ($C_{OS}$) | $0.15C_{MR}$ | Choi et al. (2010) |
| (h) Laboratory charges ($C_{LC}$) | $0.15C_{OL}$ | Choi et al. (2010) |
| (i) Patents and royalties ($C_{PR}$) | $0.03C_{AO}$ | Choi et al. (2010) |
| 2. Fixed operating costs ($C_{FO}$) | | |
| (a) Local taxes ($C_{LT}$) | $0.15C_{FC}$ | Choi et al. (2010) |
| (b) Insurance ($C_{IS}$) | $0.005C_{FC}$ | Choi et al. (2010) |
| (c) Overhead cost ($C_{OH}$) | $0.6(C_{OL}+C_{SC}+C_{MR})$ | Choi et al. (2010) |
| 3. General costs ($C_{GC}$) | | |
| (a) Administration costs ($C_{AD}$) | $0.15(C_{OL}+C_{SC}+C_{MR})$ | Choi et al. (2010) |
| (b) Distribution and selling costs ($C_{DS}$) | $0.10C_{AO}$ | Choi et al. (2010) |
| (c) Research and development ($C_{RD}$) | $0.05C_{AO}$ | Choi et al. (2010) |
| • By-product credit ($C_{PC}$) | $C_{PC}$ | Wei et al. (2009a) |
| • Annual production cost | $C_{AC}+C_{AO}-C_{PC}$ | |

In this study, the feedstock cost was calculated by multiplying the feedstock consumption amount required by the feedstock price, which included considerations for quality, transportation, and storage (Wei et al., 2009a). Waste treatment cost is determined by the amount of waste produced multiplied by the price of waste treatment. The costs of utilities are directly influenced by the cost of fuel or electric power. The power demand for the bio-gasification facility was estimated by equation 3.1 with a 0.6 scaling factor (Wei et al., 2009a). Labor cost was determined by the number of operators needed multiplied by the pay rate of operators. The downdraft fixed-bed gasifiers were designed to enable running automatically with a computer control system, which can significantly reduce operators needed for micro-scale gasification facilities. Considering the characteristics of biomass feedstock and operating safety, operators were necessary for starting up the system at the beginning of a working day, monitoring and controlling the gasifier system during syngas production, and shutting down the facility at the end of a working day (Wei et al., 2009a). Working hours of operating mode were set at 52 weeks per year, 5 days per week, and 8 h per day. One hour was needed for starting up and shutting down a gasification facility in each working day (Wei et al., 2009a). Supervisory and clerical labor fees, maintenance and repair expenses, and operating supplies costs, laboratory charges, and patents and royalties costs were calculated individually and multiplied by related factors, as shown in Table 1.

Fix operating costs are independent of changes in production rate. They include property taxes, insurance, and overhead cost that are charged at constant rates even when the facility is not operation (Turton et al., 1998). The fixed operating costs were calculated as percentages of the total cost or capital costs (Table 1). General costs represent an overhead burden that is necessary to carry out business functions. They include management, sales, financing, and research functions. General costs are obtained via multiplication with various constant factors, as shown in Table 1.

Working condition and economic assumption for the micro-scale gasification facility applied in the economic model were based on those described in a previous study by Wei et al. (2009a).

### *Sensitivity Analysis*

The sensitivity analysis was conducted to identify the impact of individual model parameters on the syngas unit cost of the bio-gasification system. This procedure involved multiple model simulations by changing parameter values, and then observing the effects on particular output variables. The procedure modified one model parameter at a time while all other parameters kept unchanged. For each model parameter an arc-elasticity metric was calculated by the following equation (Mckenney et al., 2011).

$$AE = \left| \frac{\Delta C / C}{\Delta P / P} \right| \quad (3)$$

where $C$ is a output metric in the scenario with unchanged parameter (baseline), $\Delta C$ is the relative metric change in the altered vs. baseline scenario, $P$ is a parameter value in the baseline scenario, and $\Delta P$ is the parameter change in the altered vs. baseline scenario. Elasticity values approaching zero indicated that the model outputs do not correlate with given model parameter (Mckenney at al., 2011).

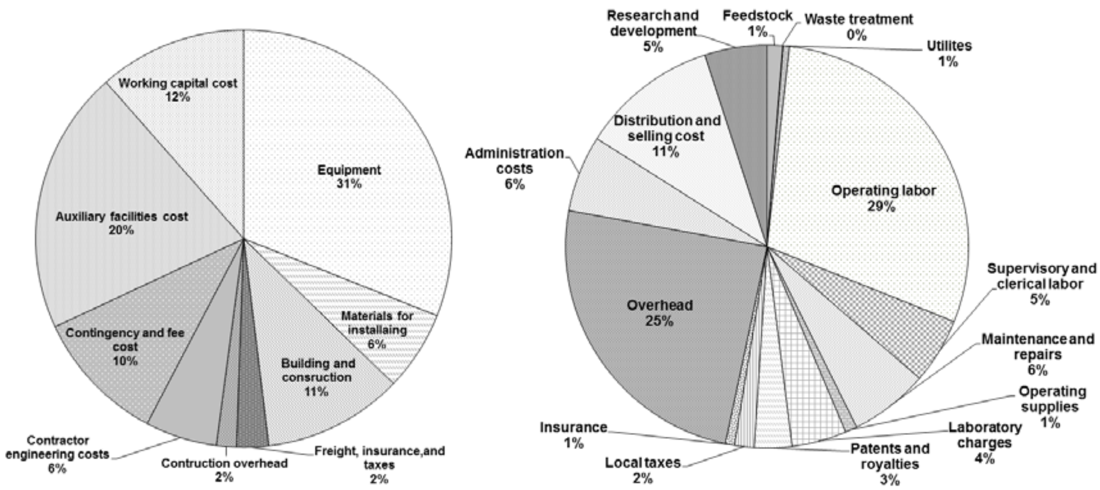
## Results and Discussion

The estimated results showed that the total annual production cost of syngas was $119,630 and the unit production cost of syngas was $1.22 Nm$^{-3}$(Table 2) The cost of this system is higher than the results provided by Li et al. (2010) and Wei et al. (2009a). This is because the costs such as working capital cost, supervision, patent, royalty, and overhead cost were not considered in their study, which is included in this study. The total annual capital, operating, and byproduct cost were $9,964, $113,628, and $3,962, respectively. The total annual operating cost is the largest part of the total annual production cost for a 60 Nm$^3$ h$^{-1}$ capacity bio-gasifier. The cost components of the capital and operating cost for a 60 Nm$^3$ h$^{-1}$ are shown in Fig. 2(a) and 2(b), respectively.

Table 2. Modeling results for the bio-gasification at 60 Nm$^3$ h$^{-1}$

| Calculation items | Unit | Value |
|---|---|---|
| Annual running hours | h | 1,820 |
| Annual woodchip consumption | kg | 17,522 |
| Annual syngas yield | Nm$^3$ | 109,200 |

| | | |
|---|---|---|
| Sub-total annual capital costs | \$ | 9,964 |
| Sub-total annual operating costs | \$ | 113,628 |
| By-product credit (revenue) | \$ | 3,962 |
| Total annual production cost | \$ | 119,630 |
| Syngas unit cost | \$ $Nm^{-3}$ | 1.22 |




(a) Capital cost (b) Operating cost

Figure 2. Cost components of the capital and operating cost for a 60 $Nm^3$ $h^{-1}$

The equipment cost and auxiliary facilities accounted for 31% and 20% of the total capital costs, respectively. Since each component cost included in the capital cost was calculated by the function or equation based on the equipment cost, selecting an appropriate gasifier system is very important in order to reduce total capital cost. The direct operating cost represents 51% of the total annual operating cost and should be the focus of efforts to minimize the total annual operating cost. Labor cost was 29.3% of the total annual operating cost. This was the largest part of the total annual operating cost, followed by overhead cost (24.5%), distribution and selling costs (11.0%), and maintenance and repairs (6.3%).

## ***Effect of Production Capacity***

The effect of gasification facility capacity on the annual costs associated with syngas production was analyzed. As the bio-gasification capacity increased, all costs are also increased (Fig. 3). The increase rate of total annual production cost was lower compared to that of annual operating cost since the cost of byproduct heat produced from gasification linearly increased when the gasification capacity was scaled up.

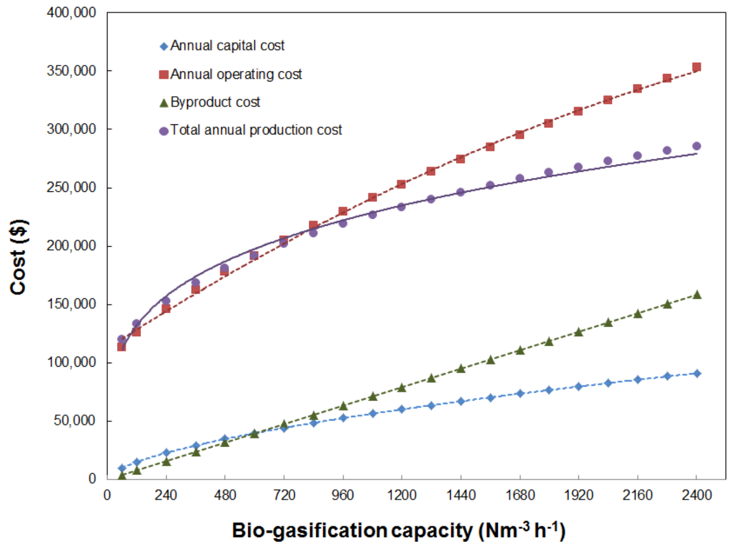



Figure 3. Annual production costs for gasification facilities of different capacities

The operating cost composition for syngas production changed significantly with the increase of the gasification capacity (Fig. 4). In case of items related to feedstock, waste treatment, utility, maintenance and repairs, operating supplies, local taxes, and insurance, the percentage of the total annual production cost was continually increasing, while labor cost, supervisory and clerical cost, laboratory charges, overhead cost administration costs was steadily decreasing with the increase of the gasification capacity. Patrent and royalty, distribution and selling costs, and research and development cost was not changed. These results indicate that cost factors such as feedstock, waste treatment, utility, maintenance and repairs, operating supplies, local taxes, and insurance have a relatively large impact on the production cost when improving the economic feasibility at a higher-capacity facility.

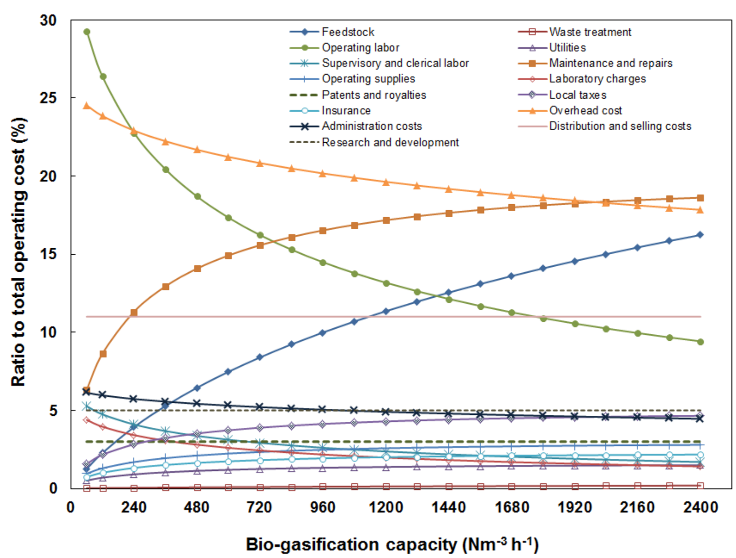



Figure 4. Cost composition in different gasification capacities

The unit cost of syngas production continually decreased with the increase of the capacity (Fig. 5). The reason is that the increase rate of syngas yield is higher than that of total annual production cost. The average retail price for industrial natural gas in the U.S. in 2008 was $0.41 Nm$^{-3}$ (USEIA, 2008). Comparing natural gas to syngas, the unit cost of syngas production was close to the price of natural gas when the syngas production capacity was scaled up to 230 Nm$^3$ h$^{-1}$.

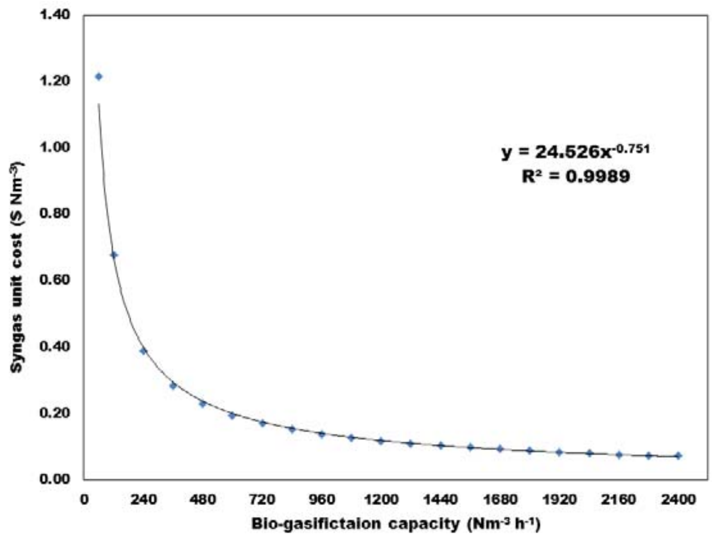



Figure 5. Syngas unit costs for gasification facilities of different production capacities

### *Sensitivity Analysis*

The sensitivity analysis in study is based on average elasticity values from -30% to 30% changes in the mean model parameter. These changes are intended to represent both changes in the underlying knowledge of a particular parameter and the possibility of technical change that might arise from, for example, research activities. The impact of parameter changes was examined in relation to the unit syngas production costs.

Labor and equipment costs have the greatest impact on the unit syngas production costs compared to other model parameters (Table 3).

Table 3. Sensitivity analysis for the economic model parameters.

| Variables | Initial value | Average elasticity value over all scenarios | Average rank over all scenarios |
|---|---|---|---|
| Labor cost | \$33,280 year$^{-1}$ operator$^{-1}$ | 0.433 | 2 |

| | | | |
|---|---|---|---|
| Equipment cost | $42,000 for 60 $Nm^3\ h^{-1}$ | 0.726 | 1 |
| Loan life | 20 year | 0.167 | 3 |
| Feedstock cost | $35 $ton^{-1}$ FOB | 0.144 | 4 |
| Interest rate | 4% | 0.085 | 5 |
| Utility cost | $0.0718 $kwh^{-1}$ | 0.017 | 6 |
| Waste treatment cost | $40 $ton^{-1}$ | 0.002 | 7 |

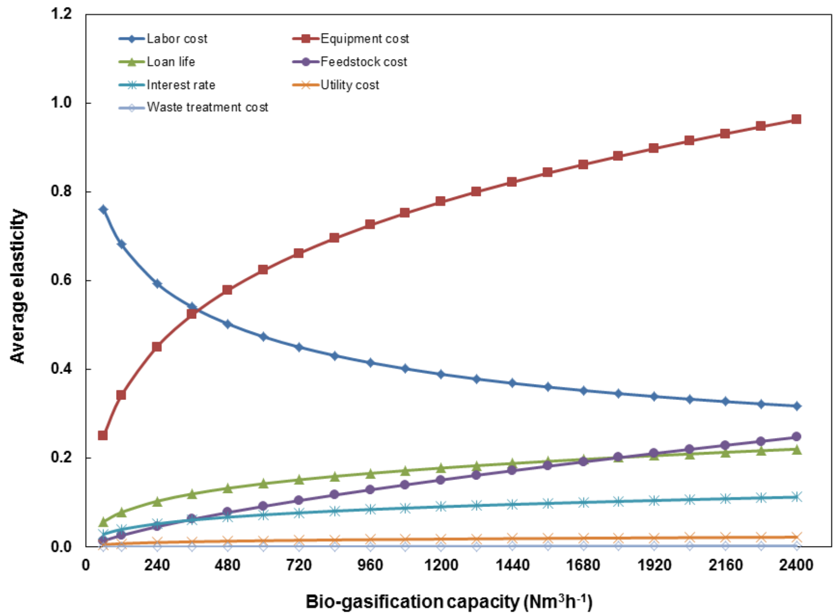



Figure 6. Average elasticity for different bio-gasification capacities.

Waste treatment costs had the lowest elasticity values. Equipment cost ranked first in overall model parameters, followed by labor cost, loan life, feedstock cost, interest rate, utility cost, and waste treatment cost. Average elasticity for different bio-gasification capacity was shown in Fig. 7. As the facility capacity increased, the elasticity of equipment cost, loan life, feedstock cost, interest rate, utility cost, and waste treatment cost increased, while that of labor cost decreased. The drastic change of the elasticity was seen in equipment, labor, and feedstock cost. This result indicates that equipment cost, labor cost, loan life and feedstock cost are the factors to affect syngas production cost significantly. The others changed slowly.

## Conclusion

In this study, an economic model was developed to evaluate the unit cost of syngas production. The sensitivity analysis was performed to identify the major factors affecting the economic

feasibility of the syngas production cost. The unit cost of syngas for a 60 $Nm^3\ h^{-1}$ capacity bio-gasifier in Mississippi determined \$1.22 $Nm^{-3}$, which was greater than the \$0.41 $Nm^{-3}$ average natural gas retail prices in the U.S. in 2008. Syngas production cost from bio-gasification facility was significantly affected by the facility's production capacity. As the capacity increased, the total annual production costs are also increased, while the syngas unit costs are decreased. The unit cost of syngas would be lower than the market price of natural gas if the bio-gasification capacity level is selected higher than 230 $Nm^3\ h^{-1}$. Among the variables related to the syngas production costs, equipment cost, labor cost, loan life and feedstock cost were found to be the most significant variables affecting the economic viability of the bio-gasification system. Therefore, selecting the suitable bio-gasification facility, stabilizing the labor and feedstock, and providing reasonable subsidy are helpful to reduce the cost of syngas production. These results provided the useful information for the economic evaluation of the syngas production from a bio-gasification system, and an appropriate indication for the promotion of syngas production in the future, targeting the reduction of the syngas production with reasonably bio-gasification system capacity.

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## References

Boerrigter H. and R. Rauch. 2006. Review of applications of gases from biomass gasification. Energy Research Centre of the Netherlands. Available at: http://www.ecn.nl/docs/library/report/2006/rx06066.pdf. Accessed 15 September 2010.

Borjesson M., and E. O. Ahlgren. 2010. Biomass gasification in cost-optimized district heating systems- A regional modeling analysis. *Energy Policy* 38(1):168-180.

Choi D., D. C. Chipman, S. C. Bents, and R. C. Brown. 2010. A techno-economic analysis of polyhydroxyalkanoate and hydrogen production from syngas fermentation of gasified biomass. *Appl. Biochem. Biotechnol.* 160(4):1032-1046.

Craig K. R., and M. K. Mann. 1996. Cost and performance analysis of biomass-based integrated gasification combined-cycle (BIGCC) power system. National Renewable Energy Laboratory. Available at: http://www.nrel.gov/docs/legosti/fy97/21657.pdf. Accessed 15 September 2010.

Dowaki K., S. Mori, C. Fukushima, and N. Asai. 2005. A comprehensive economic analysis of biomass gasification system. *Electrical Engineering in Japan* 153(3):52-63.

Dysert  L. R. 2003. Sharpen your cost estimating skills. *Cost Engineering* 45(6):22-50.

Jin H. , E. D. Larson, and F. E. Celik. 2009. Performance and cost analysis of future commercially mature gasification-based electric power generation from switchgrass. *Biofuels, Bioproducts and Biorefining* 3:142-173.

Klonsky K. , J. Thompson, J. Grant, J. Hasey, and R. Elkins. 2009. Sample costs to hull and dry walnuts. University of California Cooperative Extension. Available at: http://coststudies.ucdavis.edu/files/huller-dryerstudy2009.pdf. Accessed 15 September 2010.

Larson, E. D. 1998. Small-scale gasification-based biomass power generation. Paper prepared for the Biomass Workshop, held in Changchun, China, 12-13 January 1998. Available at: http://www.princeton.edu/pei/energy/publications/texts/Small_scale_-gasification.pdf . Accessed 15 September 2010..

Li L. , Z. Song, C. Ma, and X. Zhao. Technical and economic analysis on syngas production from biomass gasification. Paper prepared for Power and Energy Engineering Conference; held in Chengdu, China; 28-31 March 2010. Available at: http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=5448387&tag=1. Accessed 15 September 2010.

Mago P. J. , L. M. Chamra, and A. Hueffed. 2009. A review on energy, economical, and environmental benefits of the use of CHP systems for small commercial buildings for the North American climate. *Int. J. Energy Res.* 33(14):1252-65.

McKendry P. 2002. Energy production from biomass (part 2): conversion technologies. *Bioresource Technology* 83(1):47-54.

McKenney D. W., D. Yemshanov, S. Fraleigh, D. Allen, and F. Preto. 2011. An economic assessment of the use of short-rotation coppice woody biomass to heat greenhouses in southern Canada. *Biomass and Bioenergy* 35(1):374-84.

USEIA, 2008. Mississippi Natural Gas Industrial Price in 2008.  United State Energy Information Administration. Available at: http://tonto.eia.doe.gov. Accessed 15 December 2010.

Mitchell C. P., A. V. Bridgewater, D. J. Stevens, A. J. Tof, and M. P. Waters. 1995. Technoeconomic assessment of biomass to energy. *Biomass and Bioenergy* 9(1-

5):205-26.

Stassen H. E. H., and H. A. M. Knoef. 1995. Small scale gasification systems. Biomass Technology Group BV. Available at: http://www.iafbc.ca/funding_available/programs/livestock/documents/LWTI-1_FR_App3.pdf. Accessed 15 September 2010.

Turton R., R. C. Bailie, W. B. Whiting, and J. A. Shaeiwitz. 1998. Analysis, Synthesis, and Design of Chemical Processing. Upper Saddle River: Prentice Hall.

Wei L., S. D. Filip To, L. Pordesimo, and W. Batchelor. 2010. Evaluation of micro-scale electricity generation cost using biomass-derived synthetic gas through modeling *Int. J. Energy Res.* in press. doi: 10.1022/er.1749.

Wei L., L. O. Pordesimo, S. D. Filip To, C. W. Herndon, W. D. Batchelor. 2009a. Evaluation of Micro-scale syngas production costs through modeling. *Trans. ASAE* 52 (1):1649-59.

Wei L., J. A. Thomasson, R. M. Bricka, R. Sui, J. R. Wooten, E. P. Columbus. 2009b. Syngas quality evaluation for biomass gasification with downdraft gasifier. *Trans. ASABE* 52 (5):21-37.