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Green Production of Hydrogen from Excess Biosolids Originating from Municipal Waste Water Treatment

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Abstract: Technical and economic aspects of equivalent hydrogen (moles of H_2 + moles of CO potentially converted to H_2) production from biosolids produced in wastewater treatment are evaluated in this paper. ASPEN+ simulation of the gasification of biosolids and coal provides the basis for the analysis of the technical performance of a gasification process. The General Electric (GE, formerly Texaco) Gasifier was chosen for the study. The solids are assumed to be slurried as 50 wt% or 70 wt% solids (typical and maximum attainable) as feed streams for the gasifier with water.

In this study, the incremental raw material costs (feed + oxygen) for gasification plants producing the same annual quantity of H_2 from coal and/or biosolids are compared. It may be seen that under the conditions of this study, the estimated cost of H_2 production may be significantly reduced when biosolids are included in the feed materials to gasification, but only when the avoided disposal costs of the biosolids are considered.

Keywords: Biomass gasification, hydrogen production, green energy

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INTRODUCTION

Gasification is an important technology for developing green chemical processes for the future. Gasification provides integrating and robust capability for recovering and converting low-value carbonaceous materials to synthesis gas (syngas), from which a variety of chemicals may be made: sulfur to products such as H_2SO_4, and energy, in the form of steam and electricity. Utilization of gasification technology for the production of H_2 from wastewater treatment biomass is consistent with green engineering goals for future processes and is the focus of the current study. Such an integrated approach whereby all materials are converted to products is implicit in the 1990 Pollution Prevention Act which provides the current United States waste management hierarchy. Other benefits of the proposed use of gasification are the beneficial use of a non-fossil carbon feed stock, thus eliminating the net emission of CO_2 for that portion of H_2 produced from biosolids and enabling a beneficial use of materials now requiring disposal.

This work seeks to estimate the incremental raw material costs (coal and/or treated biosolids + O_2) for gasification plants using biosolids feedstock from wastewater treatment and comparing them with similar processes utilizing coal as a feed material. An entrained-flow gasifier was selected for this study for the following reasons:

1. Water separated from biosolids may be beneficially used to slurry the gasifier feed;
2. The ability to produce a slag waste form;
3. It is being cited as having a relative high capacity per gasifier volume (1).

This paper examines the raw material cost of substituting biosolids for all or part of a coal feed stream to an entrained-flow gasifier. The cost of the biosolids as used in this paper is that estimated for pretreatment to free the bound water in sludge from wastewater treatment, producing a biosolid-water slurry suitable to feed (with or without coal) to an entrained flow gasifier. The results of this study should be useful for determining potential values of biomass feed stocks.

Biosolids from waste water treatment, commonly called sludge, are one component of municipal waste and amounts to a production of about 5.6 million dry tons per year (ton = 2000 lb) in the United States (US) (2). Biosolids may be envisioned as containing up to 50% carbonaceous materials (depending on extent of treatment) with the balance as water. About 61% of the total biosolids currently produced is disposed of through land farming, 17% disposed of in licensed municipal solid waste landfills, 20% incinerated, and about 1% disposed of in surface disposal units (2). Disposal in East Tennessee is typically by landfill disposal and currently cost about $20/wet ton, not including transportation costs. Due to the high water content, incineration tends to be the most costly alternative. Biosolids have a large percentage of carbon and hydrogen and hence a fuel value of about 7,000 to 10,000 BTU/(lb of dry solids) for activated sludge (3). At a fuel value of 10,000 Btu/lb of dry solids, the potential energy value of US biosolids is about 112 trillion Btu/yr. Typically biosolids from wastewater treatment are available at 10% solids concentrations, 25% solids is breakeven from an energy standpoint in a combustion process.

One of the proven technologies for upgrading the value of carbonaceous feed stocks is gasification. Gasification is a process which operates at high temperatures (up to 2,700°F) and breaks down carbon-based feedstock into its basic constituents and converts them into useful gases. Any solid residues left behind (typically 10–20%) are converted to glassy slag which can be safely disposed of in a municipal landfill. The gaseous effluent from gasification is called syngas and typically contains high concentrations of H_2 and CO; the syngas may be used to produce electricity, steam, chemicals and fuels. Thus, the biosolids may be upgraded to many useful products. The gaseous pollutants may be conveniently utilized or disposed of. Sulfur dioxide (air blown gasifier) or H_2S (O_2 blown) from gasification can be converted into saleable H_2SO_4; the concentrated CO_2 produced during syngas purification can be sold or easily captured, for example, as ammonium carbonate. The ability to convert waste materials from gasification to useful products reduces the load on waste treatment and disposal capability as well as reducing fossil-based raw material usage. The gasification process, as used in the current application, nearly eliminates the impact of biosolids on the environment, instead producing clean products such as H_2.

BACKGROUND

Overall Process Description

The present study seeks to utilize biosolids, including water (it is assumed in this study that the biosolids will be lysed prior to gasification). A catalyst, such as a strong acid or base, is necessary for this lysing operation so that its recovery and recycle provides another motivation for feeding the entire effluent of the dewatering step to the gasifier. Such a process is presented in Fig. 1. The dry composition of a typical biosolid and coal (Pittsburgh No. 8) is presented in Table 1. As may be seen from Table 1, biosolids contain less C than coal and somewhat higher percentages of N and H with much higher percentages of O_2. Biosolids from wastewater treatment contains up to approximately 90 wt% or higher bound water depending on the extent of processing (3), while raw anthracite or bituminous coal may contain up to approximately 12 wt% water (Perry's Chemical Engineering Handbook).

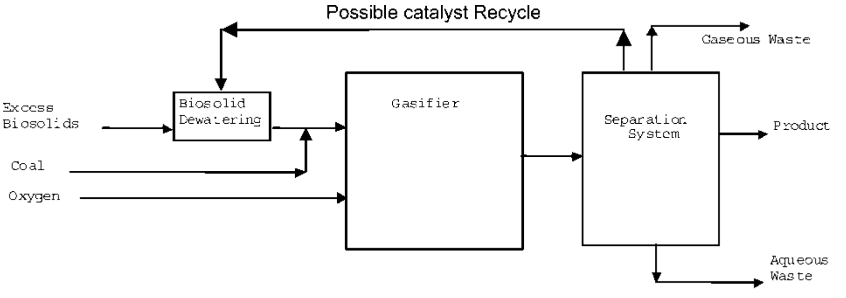

Figure 1. Schematic of gasification process with excess biosolids and coal as possible feedstocks.

Typical coal/biomass slurries contain 50–70 wt% solids with the water mostly derived from the lysed biomass.

Lysing of Biosolids

The lysing of biosolids is currently under investigation using H_2SO_4, HNO_3 and NaOH as possible catalysts. Work by Perkins et al. (4) addressed the hydrolysis of biosolids with HNO_3 as a catalyst; in the course of that work the lysing performance of the hydrolysis reaction was recognized. This work is being pursued further with an emphasis on catalytic lysing (5). The lysing process breaks down the biomass structure freeing the bound water and converting the feed from essentially a solid to a slurry with a low viscosity (5 cp).

Chemistry of Gasification

In the gasification reactions, gases with high H_2 and CO content are produced (1); Gasification is currently accomplished by several processes at temperatures up to 2700°F and pressures up to 4 MPa (40 atm). The reactions

Table 1. Composition (wt%) of dry excess biosolids and dry Pittsburgh No. 8 coal

Component	Dry excess biosolids (12)	Coal (11)
Carbon	41.14	76.52
Nitrogen	16.72	1.58
Oxygen	21.45	5.91
Hydrogen	12.37	4.90
Inerts	8.32	9.14

sequence may be envisioned with the first step being the exothermic reaction of C with O_2 to CO_2, according to

$$C + 1/2\,O_2 \Leftrightarrow CO \tag{1}$$

$$CO + 1/2\,O_2 \Leftrightarrow CO_2 \tag{2}$$

The CO_2 may react endothermally with C to produce CO as per

$$C + CO_2 \Leftrightarrow 2CO \tag{3}$$

The CO may in turn exothermally react with H_2O (steam) producing CO_2 and H_2,

$$CO + H_2O \Leftrightarrow CO_2 + H_2 \tag{4}$$

Carbon monoxide and H_2 may also be produced by the endothermic reaction of H_2O and C, as per

$$C + H_2O \Leftrightarrow CO + H_2 \tag{5}$$

The above reaction sequence may be manipulated by the O_2 input to provide the adiabatic temperature of choice. The typical effluent from gasification of carbonaceous material is CO, CO_2, H_2, H_2O, CH_4; any S present in the feed (coal) will be converted to reduced sulfur compounds such as H_2S for an O_2 starved process. These reactions are modeled as a set of equilibrium reactions by the Aspen Plus simulation.

Review of Alternative Gasification Technologies

There are four broad types of gasification reactors; these reactors are usually distinguished based on the method of contacting solid and gaseous reactants: moving fixed bed, fluidized bed, entrained flow, and molten bath.

In moving fixed bed gasifiers the fuel is fed at the top as granules or lumps and is contacted with the gasifying mixture passing up through the bed (usually air, O_2, and/or steam). As the fuel descends, it is dried, gasified, and combusted, leaving a dry ash or a slag. Slagging occurs when the exit solid phase is in the range of 1500 to 2000°C and results in the ash melting and exiting in the molten state (1). If waste material is utilized as a feed stock, then pretreatment to convert the waste material into pellet is usually recommended. The moving fixed bed technology is especially efficient in achieving high C utilization and coping with high ash-content feed materials. The limitations are mechanical complexity and inability to handle fine feed materials.

Fluidized beds for gasification of solids utilize velocities of the gasification medium sufficient to fluidize the solid particles. Thus, smaller particles are required then for moving bed processes. The solid particles move about randomly so that a perfectly mixed reactor performance is approached. The maximum temperature is determined by the ash softening and melting behavior. Caking feedstocks require special operation and the C conversion of this technology is limited by a continuous loss of carbon to the ash effluent. This technology is less complex than that of moving beds. Limitations include entrainment of fine material in the effluent gas and loss of carbon in the effluent ash. Fluidized bed technology is frequently selected as a high-ranking choice for biomass feedstock (1, 6).

In entrained-flow gasifiers, solid particulates are generally entrained by the gasification medium; the flow of all materials is in the same direction (usually down). The solids must in general be smaller that of moving fixed beds or fluidized bed gasifiers. The gasification medium is usually injected through nozzles or burners. The particulate may be fed as slurry or as dry particles. High temperatures coupled with small particle size provide high carbon conversion in short residence times. The ash usually melts and is removed as a slag. The entrained-flow gasifier has no moving parts and accepts a wide variety of particulate feed stocks. Commercial designs are readily available and it is reported to be superior to other concepts when considering the capacity per gasifier volume (1); a disadvantage includes higher O_2 consumption than other technologies. In the molten-bath gasification process, a hot liquid bath of molten slag, metal or salt, receives an injected solid feedstock and gasifying agents. The high temperature of the bath promotes fast reaction rates. Advantages of this concept include any grade of solids in a wide range of sizes which may be utilized, no pretreatment of the feedstock is typically required, and sulfur from the feedstock is retained in the bath. Limitations of the process include bath cleanup and the corrosive nature of the bath.

Related Experience

Experience with blended fuels has been cited by Tampa Electric Company (NETL, 2004), which utilizes a GE Gasifier; the blended fuel feed consisting of 40% petroleum coke and 60% Pittsburgh coal with about 30% fly ash recycle. Hamelinck and Faaij (6) studied gasification concepts for converting biomass to methanol and hydrogen; they conclude that biomass-derived methanol and hydrogen are likely to become competitive fuels in the future. Several studies provide estimates of the cost of producing hydrogen by gasification (6–9). The reader should note that these estimates may have a different basis from each other and usually provide estimates of amortized capital as an included cost.

Narrowing the Focus

The GE (formerly Texaco) gasification process was selected for the current study. This gasification process uses a pressurized version of an entrained-flow reactor and a slurry feed system.

Path Forward

In the current paper, the costs of substituting biosolids for all or part of a coal feed stream to an entrained flow gasification process is studied. The results will be expressed as percent change in the cost of raw material in a particular case as compared to the base case. The base case is feeding coal alone to the gasifier as a 70 wt% slurry. No capital costs and operating costs are considered in order to simplify the study. Operating costs in all cases are assumed to be equal and hence will nullify when compared.

METHODS AND PROCEDURE

The current study involved two types of calculation activities. A model of the adiabatic gasifier was developed using ASPEN+ (see Fig. 2); the inputs and assumptions as listed in Table 2a for gasifier simulation calculations. ASPEN+ runs the gasifier as an adiabatic Gibbs reactor. The gasifier is simulated at 2300°F and 35 atmosphere pressure based on suggestions in Ullmann's Encyclopedia (1). Table 2b contains important economic assumptions.

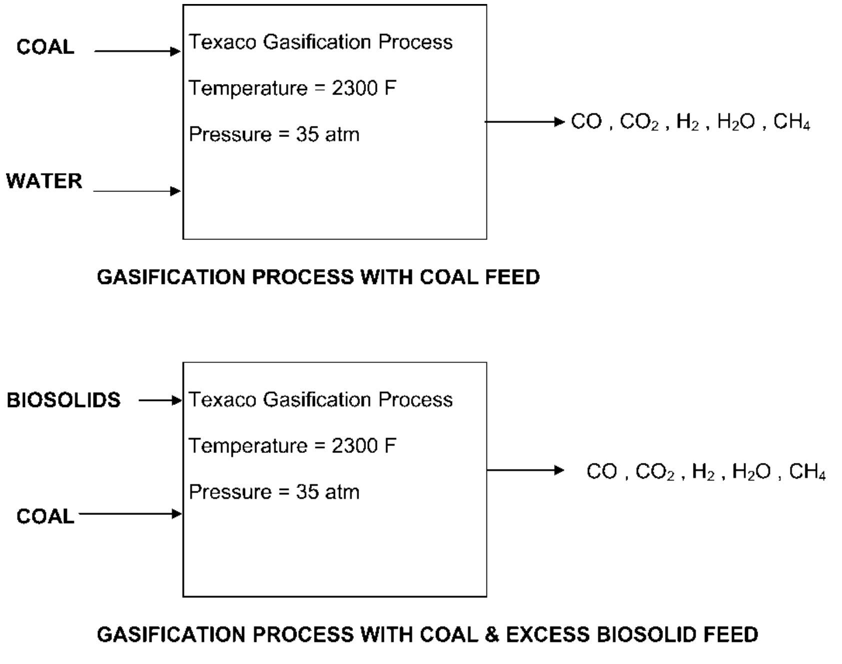

Figure 2. Block diagrams for major input/output streams to/from gasifier for two cases considered.

Table 2a. Basis and assumptions for ASPEN simulation

1	The carbon in the feed is completely gasified
2	The amount of steam and oxygen fed to the gasifier is sufficient for complete conversion of the carbon
3	Excess biosolids contains 40 wt% solids and 60 wt% water in material supplied from waste water treatment
4	Coal contains 11% moisture
5	Feed to gasifier is 50 or 70 wt% solid assuming biosolids can be dried from 40% solid to 50 or 70%
6	No energy integration of the whole process is considered. The gasifier is modeled adiabatically, which means that the heat required to heat feed from room temperature to the gasifier temperature is supplied by burning carbon in the gasifier
7	H_2 losses from sulfur recovery are neglected

Table 2b. Basis and economic assumptions for economics

1	Coal cost is \$50/ton as received (1 ton = 2000 lbs)
2	Biosolids disposal credit is \$100/dry ton (refer appendix 1)
3	All costs for transporting the biomass from Waste Water Treatment Plant to the biomass preparation and gasification plant is not considered
4	Estimated cost of lysing and drying sludge is \$54.7/dry-ton
5	Oxygen from oxygen plant costs \$20/ton at 95% purity
6	Fresh water cost (required for gasification) is \$10/ton
7	Water recycle cost (from biomass drying) is \$20/ton

GASIFIER SIMULATION

Table 3 shows some details of the ASPEN simulation run at various inlet flow rates of coal or biosolids or a mixture of both. This is done to highlight the difference in composition of the product gas with changing feed constituents, especially the O_2 requirement and the equivalent H_2 produced. Biosolids are an important potential source of O_2 to the gasifier and have been assumed to reduce the O_2 required from the O_2 plant for this study. Another important observation is significantly more H_2 is produced per mole of carbon in biosolids as compared to that of coal. The estimated higher H_2 production per mole of C is consistent with the higher H content of the biomass than that of coal. An important assumption in these results is the water in the excess biosolids is completely available to slurry the feed to the gasifier. In Cases 5 and 6 of Table 3, it is thus assumed that the biosolids are available at 50 wt% and 70 wt% respectively; this is done to permit a simple comparison of the two feed materials over the range of expected slurry feeds to the gasifier. The cost of drying the biosolid material to the required solid water ratio is taken into consideration in the biosolid pretreatment cost. From Table 3, it

Table 3. Characterization of product gas streams from Texaco gasifier

	Case-1	Case-2	Case-3	Case-4	Case-5	Case-6
Description	Coal + biosolids fed to the gasifier	Coal + biosolids fed to the gasifier	Only coal fed to the gasifier	Only coal fed to the gasifier	100 % biosolids	100 % biosolids
Amount of water fed with solids	50 wt%	30%	50%	30%	50%[a]	30%[b]
Inlet temp.	90°F	90°F	90°F	90°F	90°F	90°F
Gasification pressure	35 atm	35 atm	35 atm	35 atm	35 atm	35 atm
Gasification temperature	2300°F	2300°F	2300°F	2300°F	2300°F	2300°F
Mass of biosolids in feed, kg/hr	12649	10909	0	0	20558	17617
Mass of coal in feed, kg/hr	7517	6483	19750	18917	0	0
Mass of water in feed, kg/hr	20166	7454	19750	8105	20558	7549
Composition of product gas, mol%[c]						
CO	19.9 (1.58)	31.8 (1.99)	29.9 (1.59)	49.5 (2.04)	14.6 (1.57)	22.9 (1.97)
CO_2	9.5 (1.19)	5.4 (0.52)	14 (1.17)	6.9 (0.45)	7.1 (1.2)	4.2 (0.57)
CH_4	48 PPM	414 PPM	50 PPM	439 PPM	41 PPM	348 PPM
H_2	29.1 (.177)	40.1 (0.18)	23.9 (0.09)	30.1 (0.09)	31.8 (0.25)	45 (0.28)

(*continued*)

Table 3. Continued

	Case-1	Case-2	Case-3	Case-4	Case-5	Case-6
H_2O	37.9 (1.93)	18.4 (0.74)	30.4 (1.04)	11.5 (0.3)	42 (2.9)	22.4 (1.24)
NH_3	60 PPM	105 PPM	30 PPM	44 PPM	78 PPM	143 PPM
Mass of hydrogen equivalent ($CO + H_2$) Produced, kg/hr	3032.42	3032.79	3065	3033.2	3031.15	3031.6
Oxygen from oxygen plant, kg/hr	16560.84	10900.755	20655	16263.4	14142.95	8614.725
Oxygen from other sources, kg/hr[d]	31432.4	19660.72	29519	19088	24698.47	16528.03
Mol of H_2 Eqvt/mol of carbon	1.67	1.94	1.23	1.27	2.152	2.512
Mol of O_2 from oxy plant consumed/mol of carbon	0.57	0.43	0.52	0.43	0.63	0.45

[a]Assuming biosolid water content is 50%.
[b]Assuming biosolid water content is 30%.
[c]The number inside parenthesis is kg product per kg of carbon.
[d]Oxygen from sources like water, intrinsically contained in coal, biosolids, etc.

may be noted that gasification of biosolids at comparable conditions to coal produce less H_2 but does so with less O_2 supplied from the O_2 plant. Also, biosolids produce more H_2 per mol of C in the feed. The reduced O_2 demand and higher H_2 production per mole of C is consistent with the higher O_2 and H_2 content of the biomass than that of coal as reported in Table 1. The quantity of solids that must be handled does increase and the ratio of biosolid to coal increases.

ECONOMIC RESULTS

In Table 4, the incremental raw material costs are compared with respect to the base case for gasification plants producing the H_2 equivalent in an entrained–flow gasifier operating at the conditions of Table 3. The base case is the case in which only coal is fed with 30% water to the gasifier. All the other cases are a combination of coal, biosolids, and water in a different ratio. These costs do not include capital amortization but does include a credit for avoiding the disposal and transportation of biosolids at \$100/dry ton; this is discussed further in the Appendix 1. While comparing the five cases with the base case the other costs (labor, maintenance, etc.) are not included in the calculation as it is assumed they are the same for all the cases. The estimated cost of lysing and drying biosolid has been estimated to be \$54.7/dry ton (10). Coal is assumed to cost \$50/ton and O_2 is valued at \$20/ton at 95% purity. It may be observed from Table 4 that the use of 70% solid slurry to the gasifier shows improved cost benefits over the corresponding case of 50% slurry feed. The assumption that all the O_2 fed to the gasifier (in any form) is available results in lower O_2 costs when biosolids are fed due to higher O_2 content of the biosolids over coal; this is speculative but does not significantly effect the conclusions presented here. It may be seen that under the conditions of this study, the estimated cost of H_2 production is significantly reduced when biosolids are included in the feed materials to gasification. The hydrogen cost can be as low as −29% with only biosolids fed in as 50% slurry as compared to 100% assigned to the base case. The negative value indicates that biosolids disposal credit is more than the total amount spent on raw material. Figure 3 is the pictorial representation of Table 4. Figure 3 signifies that, if it costs \$100 for raw materials to gasify the coal under process conditions of case-4 (base case), one would receive a credit of \$29 if one gasified biosolids with 50% water as in case 5. The "Approximate Breakeven Point" in the last row of Table 4 implies the amount of money that can be further spent on biosolids treatment to make the raw material cost (with disposal credit) of any case equal to that of base case (Case 4). For instance, besides spending \$54.7 on biosolids lysing and drying \$99.79 can be further spent on biosolids treatment, handling, etc., to make the total raw material cost of Case 1 equal to that of Case 4 (= \$1609.15).

Table 4. Economic calculation

	Units	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
Slurry preparation operating costs							
Bone dry biomass slurry prep	kg/hr	12649	10,909	0	0	20558	17617
	lb/hr	27,828	24,000	0	0	45,228	38,757
Bone dry coal to slurry prep	kg/hr	7517	6,483	19750	18917	0	0
	lb/hr	16,537	14,263	43,450	41,617	0	0
Solids concentration in slurry	%	50	70	50	70	50	70
Total dry solids to slurry prep	lb/hr	44,365	38,262	43,450	41,617	45,228	38,757
Coal cost	$/hr	$465	$401	$1,221	$1,169	$0	$0
Biomass treatment cost	$/hr	$761	$656	$0	$0	$1,237	$1,060
Biomass disposal credit	$/hr	−$1,391	−$1,200	$0	$0	−$2,261	−$1,938
Biomass freight cost[a]	$/hr	$0	$0	$0	$0	$0	$0
Water requirement							
Total water required (to mills)	lb/hr	44,365	16,398	43,450	17,836	45,228	16,610
Total water from wet biomass	lb/hr	41,742	36,000	0	0	67,841	58,136
Total water from coal	lb/hr	2,044	1,763	5,370	5,144	0	0
Total water available in feed	lb/hr	43,786	37,762	5,370	5,144	67,841	58,136
Water recycle to WWT	lb/hr	0	21,364	0	0	22,614	41,526
Fresh water to mills	lb/hr	580	0	38,080	12,692	0	0
Fresh water costs	$/hr	$3	$0	$190	$63	$0	$0
Water to WWT costs	$/hr	$0	$214	$0	$0	$226	$415
Total slurry cost	$/hr	$1,229	$1,271	$1,411	$1,232	$1,463	$1,475
Total slurry cost with credit	$/hr	−$163	$71	$1,411	$1,232	−$798	−$463

Oxygen requirement							
O_2 from ASU	kg/hr	16561	10901	20655	16265	14143	8615
	lb/hr	36434.2	23982.2	45441	35783	31114.6	18953
O_2 cost	\$/hr	\$383.52	\$252.44	\$478.33	\$376.66	\$327.52	\$199.51
Total raw material pricing (gross)	\$/hr	\$1,612.04	\$1,523.12	\$1,889.23	\$1,609.15	\$1,790.63	\$1,674.78
Total raw material pricing (w/credit)	\$/hr	\$220.65	\$323.13	\$1,889.23	\$1,609.15	−\$470.75	−\$263.09
Hydrogen equivalent produced	kg/hr	3032	3033	3065	3033	3031	3032
	lbmole/hr	3335.2	3336.3	3371.5	3336.3	3334.1	3335.2
H_2 equl cost (gross raw material)	\$/kg	\$0.53	\$0.50	\$0.62	\$0.53	\$0.59	\$0.55
H_2 equl cost (with credit)	\$/kg	\$0.07	\$0.11	\$0.62	\$0.53	−\$0.16	−\$0.09
Relative raw material costs							
Total slurry costs		99.7%	103.1%	114%	100%	119%	120%
Total slurry costs with credit		−13.2%	5.7%	114%	100%	−65%	−38%
Total raw materials (gross)		100.2%	94.7%	117%	100%	111%	104%
Total raw materials (with credit)		13.7%	20.1%	117%	100%	−29%	−16%
Approximate breakeven point							
Credit required for all cases to equal 100%							
Total slurry costs with credit	\$/dry ton	\$100.29	\$96.82			\$89.80	\$87.47
Total raw materials (with credit)	\$/dry ton	\$99.79	\$107.17			\$91.97	\$96.61

[a]All costs for transporting the biomass from Waste Water Treatment Plant to the biomass preparation and gasification plant is not considered at this stage, as it is difficult to figure out the cost without knowing the actual site distance and other conditions.

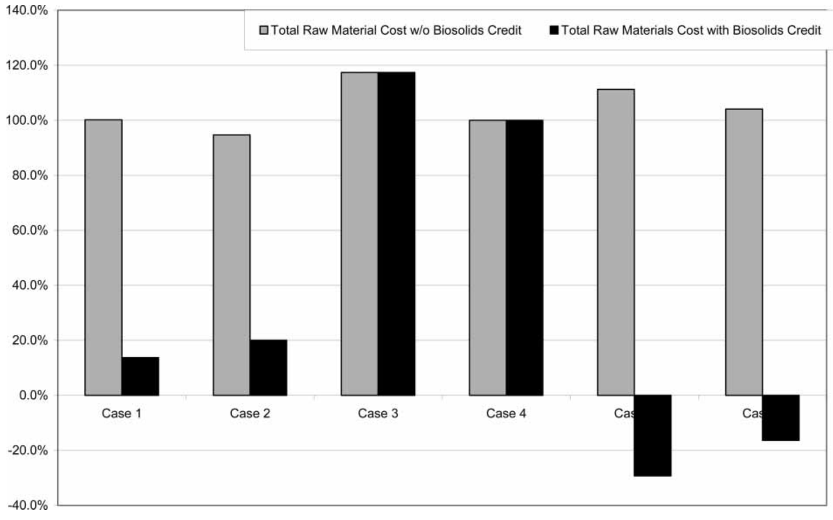

Figure 3. Cost of raw material with respect to base case cost (= 100%).

DISCUSSION AND CONCLUSION

Under the conditions of this study, the estimated cost of H_2 production is significantly reduced when biosolids are included in the feed materials to gasification. The external oxygen requirement from oxygen plant is also reduced when co-feeding biosolids and coal, although this is speculative. The added advantage of co-feeding biosolids with coal to the gasifier is that it effectively accomplishes disposal and reduces reliance on fossil fuels for energy. The rational of this study is to put forward the above economic advantage of co-feeding biomass with coal as feed stock in a gasification process.

APPENDIX 1

1. Knoxville sludge disposal cost = \$20/wet ton Basis: According to Joshua (13) \$20 per wet ton of biosolids (dry sludge with 62% water) is spent on transportation and disposal of municipal sludge.
2. Nashville sludge disposal cost = \$26/wet ton Basis: According to Ron (14) \$26 per wet ton of sludge is spent on transportation and disposal of sludge.
3. Chattanooga sludge disposal cost (15) = \$11.92/wet ton.
4. According to Damon S. Williams Associates (16), biosolids disposal costs ranged from \$47.14/dry ton to \$235.50/dry ton with an average of \$114.15/dry ton. The study was conducted for seven different

participating municipal agencies on the west coast (typically higher costs than around Tennessee).

5. According to EPA report (17), the average tipping fee (disposal only) for facilities in the U.S. in the mid to late 1990's was \$35–\$38/dry ton with a range of \$15/dry ton in Texas to over \$100/dry ton in New Jersey. Transportation costs will be in addition to the tipping fee and will vary depending on the distance between generation site and the disposal site.
6. Biosolids Disposal credit fee considered in the paper = \$100/dry ton Basis: According to the EPA report mentioned above (17), the tipping fee was around \$38/dry ton till late 1990's. So with inflation it will be around \$50/dry ton. In the opinion of various experts working in this field, the transportation cost is often equal to or greater than the tipping fee. So, combined cost of transportation and tipping fee should be \$100/dry ton.

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