Techno- Economic Analysis of Wastewater Biosolids Gasification

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I. Introduction

Wastewater treatment biosolids, commonly referred to as sludge, is a dilute suspension of micro-organisms, noxious organic matter, and mineral species in up to 99% water. Sludge is produced at about 250 mg/L of mixed municipal and light industrial wastewater treated[1]. Management of this process stream can present a financial and environmental challenge for wastewater treatment plants (WWTPs), accounting for up to 15% of plant energy consumption[2]. Operators of small urban WWTPs see the greatest challenge as their operations do not benefit from economies of scale, which permit larger facilities to absorb the costs or footprint of anaerobic digestion. This work considers small scale urban WWTPs, which serve sewage flows of up to 5 million gallons per day (MGD) (0.22 m^3/s).

A contemporary approach to sludge management considers sludge to be an income-generating, recoverable resource[3]. On a dry basis, sludge has a lower heating value (LHV) similar to that of low- rank coal, about 15 MJ/kg (6449 Btu/lb). This suggests that the value of sludge might best be recovered as a fuel for on-site cogeneration of electricity and heat, with heat being used internally (i.e. for thermal drying). Thermochemical conversion (TCC) technologies subject sludge to chemical processes at high temperatures to convert the chemical energy in sludge into heat, more useful fuels, or both. Four candidate TCC technologies were looked at in this study. These include wet oxidation, direct combustion, pyrolysis, and gasification (air blown, steam blown, and supercritical water). Air and steam blown gasification were determined to be the most appropriate TCC technologies and were studied in depth. The present work intends to determine whether sludge fueled cogeneration is technically and economically feasible for decentralized urban WWTPs. We have reviewed the four TCC technologies, designed and simulated the performance of a cogeneration system, and evaluated the systems for technical and economic feasibility.

Sewage Sludge Characteristics

The composition of sewage sludge used in this study is summarized in Table 1 alongside other common biomasses. The most noticeable differences are fuel moisture and ash content. A great challenge in exploiting sludge as a fuel is the energy demand to remove moisture content, which can exceed 95 wt% prior to dewatering. Up to 60% of the fuel energy, , is required to thermally dry sludge from a post-centrifuge moisture content of 80 wt% to 10 wt% needed for most TCC processes. Ash presents other challenges to TCC systems. Ash is corrosive at high temperature, and can agglomerate at temperatures higher than 850 ºC (1562 ºF). Ash also catalyzes hydrocarbon cracking reactions, which can be beneficial depending on the TCC technology used. A further challenge of sewage sludge not represented by proximate and ultimate analyses is management of heavy metals and Resource Conservation and Recovery Act metals content, including Cd, Hg, Pb, Zn[4].

Table 1. Sludge and Biomass Analyses

Analysis	Yield (dry wt% unless otherwise indicated)			
	Sewage Sludge[5]	**Wood, Pine**[6]	**Corn Straw**[7]	**Municipal Solid Waste**[8]
Initial Moisture (wet basis)	80 (dewatered)	12	6.17	8.8
Fixed Carbon	9.03	16	13.75	11.79
Volatile Matter	71.3	71.5	75.95	82.8
Ash	19.67	0.5	5.93	5.93
C	42.92	51.6	43.83	51.81
H	6.04	4.9	5.95	5.76
O	24.51	42.6	45.01	30.22
N	5.91	0.9	0.97	0.26
S	.95	Not Detected	0.13	0.36
LHV [MJ/kg]	16.7	20.2 (HHV)	17.75	21.3

Thermochemical Conversion Technologies

A TCC process appropriate for sewage sludge-fueled cogeneration must be able to accommodate a wet fuel (either directly or by supplying waste heat for drying), with a composition that may change in time. Furthermore, the TCC process must support simple, economical, on-site electricity production. From these criteria, wet oxidation can be immediately excluded. Wet oxidation contacts sludge with oxygen saturated water at elevated temperatures of 150-600 ºC (302-1110 ºF) and pressures of 5-30 MPa (725-4350 psi). Organic species are exothermically oxidized in solution, yielding a product stream of H_2O, CO_2, NH_3, volatile fatty acids, and solvents[9]. The process produces no fuel species and only low temperature heat. A wet oxidation plant processing sludge was able to deliver only 115.5 ºC (240 ºF) process steam[10]. Direct combustion is eliminated due primarily to emissions considerations, but also due to low efficiency. Sludge combustion generates emissions, including fly ash, SO_x, NO_x, HCl, Cd, Hg, Pb, dioxins, furans, and others, which require extensive flue gas cleaning facilities[11]. Direct combustion is suitable only to medium and large size WWTPs[12] which are outside the scope of this study. Furthermore, small-scale sludge-fired Rankine cycle steam generating systems are expected to be <15% efficient[13]. Fast pyrolysis partitions initial sludge energy into three phases: gas, oily water- miscible liquid, and ash laden solid char[14]. None of the phases can be selectively optimized with great efficiency for sewage sludge[15]. Moreover, pyrolysis oil from wastewater sludge is corrosive, water- miscible, viscous, and difficult to reliably ignite[16]. Once refined, pyrolysis oil is easily stored and transported[17], making pyrolysis more attractive for biofuel production than cogeneration. Supercritical water gasification must be excluded mostly due to its state of development. The anticipated difficulties in reactor design, pumping, and heat recovery still require substantial development effort[18].

Air and steam blown gasification both produce a single fuel stream, generate no direct emissions, and are well developed. Gasification processes have been demonstrated for numerous biomass sources, including sludge[19]. No immediate advantage is seen between air and steam blown gasification processes. The greater LHV of steam-processed syngas may be outweighed by the increased heating duty required to raise additional water to reactor temperature. Thus both processes are simulated to compare net electrical output.

II. Methods

Effective thermal system design must consider process energy consumption, energy recovery, and cost. In the case of wastewater sludge, it is expected that the energy requirement to dry sludge and heat it to reactor temperature will constitute the bulk of process energy demands. Up to 75% of the energy as is required to dry sludge from 80 wt% to 10 wt% moisture in a convective dryer and heat it to 800 ºC (1472 ºF). Thus, heat recovery is of primary importance to system design. Environmental concerns add to the complication of using sewage sludge as a fuel. Char combustion approaches to gasifier heating, such as chemical looping combustors, present the same stack gas challenges as direct combustion[20]. We developed a model system composed of four process areas, including convective drying, gasification, gas cooling and cleaning, and a spark-ignition engine. The system recovers heat by recycling all exhaust gas and hot gas from the syngas cooling heat exchanger into the convective dryer.

Assumptions

This investigation is intended to determine the electrical and thermal performance of a model system from a high level, thermodynamic perspective. A system boundary crosses sludge influent, gas vent, ash waste, and electrical work streams. Sludge enters the boundary at 80 wt% water post- centrifuge. The analysis does not consider component geometry, performance characteristics, or piping and conveyance. A 10% plant backwork factor is used to estimate plant electrical demands not specifically modeled. It is further assumed that the system represents real components, which are optimized for the chemistry and flow rate at every point of analysis. Surface heat losses are modeled only for the gasifier and engine. All processes are considered at steady state.

ASPEN Plus Model

A model of the system shown in Figure 1 was implemented in the chemical engineering process simulator ASPEN Plus®. The dryer model assumes the energy needed to evaporate water is simply [21]. Gasifier modeling is based on a restricted equilibrium method[22], with $T_{equilibrium} = T_{reactor} + \Delta T_{approach}$ applied to a linearly independent set of reactions,

(1)
(2)
(3)

Heat for the gasification reactions is satisfied by an energy balance across the reactor. For the air process, a *Design Spec* block admits air into the gasifier simulating partial combustion of the fuel. Heat for the steam process is satisfied by a similar *Design Spec* block diverting some of the product syngas to a burner exchanging heat at 20 ºC (68 ºF) above the reactor temperature. The internal combustion engine model is constructed of a reciprocating compressor (*Compr*), an adiabatic combustor (*RGibbs*), and an expander (*Turb*). The model accounts for the performance of a real spark ignition engine by calibrating its efficiency to experimental data[23].

The gasifier model is semi-empirical and must be calibrated against experimental measurements. $\Delta T_{approach}$ was varied iteratively for each reaction until model gas compositions converged to experimental data. A sum of error-squared method was used to evaluate results. Error for a set of N data points is defined as

(4)

where *e* and *m* refer to experimental and model data respectively and is the mole fraction. Mean relative error is found by .

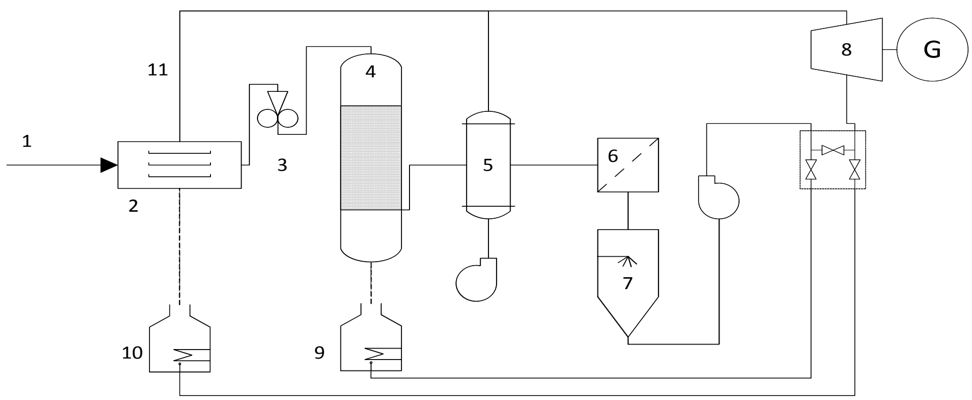

Figure 1. System Flowsheet. 1: sludge feed, 2: dryer, 3: briquetter, 4: gasifier, 5: syngas HX, 6: filter, 7: water scrubber, 8: engine- generator, 9: gasifier heating burner, 10: dryer heating burner, 11: recycled gas streams

Economics

Economic viability is evaluated by a present worth (PW) calculation. PW discounts net cash flows over the plant lifetime to some specified point, taken to be analysis year 2010. Positive PW suggests an economically viable business case. Net annual cash flow is calculated by considering the cost and revenue difference between the gasification plant and a base case, thermal stabilization in a natural gas fired dryer. We choose thermal stabilization over other options, such as anaerobic digestion, as the footprint and odor limitations of urban wastewater treatment may preclude such schemes. Net annual cash flow, F_n, is given by Equation 5:

(5)

where R is a positive valued revenue, C a negative valued cost, *elec* is electricity revenues, *fuel* is natural gas cost, *capital* is the cost of financing, and *mfg* is manufacturing costs. Manufacturing costs for both the gasification plant and base case include labor, landfill disposal, and maintenance supplies, and are not necessarily equal. Gasifier plant revenues are saved electrical utility purchase costs and saved natural gas utility costs, which would otherwise be incurred by a thermal dryer (required for thermal stabilization). On an annual compounding basis, PW is calculated as[24]

(6)

For a project evaluated every year *n* for *k* years. Plant operating life is expected to be 20 years. *i* is the minimum acceptable rate of return (MARR). Publicly owned treatment works are expected to be financed solely with municipal debt. A mean average of 20 year AA-rate municipal bonds from 2000-2012 is 4.62 %[25]. In order to provide for unseen costs and to take a generally conservative approach, we assume a MARR of 10%.

Cost Estimation

Costs are estimated according to the percentage of delivered equipment method, typically accurate to ±30%[24]. This method assumes the total cost of building and commissioning a process plant can be determined by multiplying the total purchased equipment cost (TPEC) by empirically determined factors. Purchased equipment is taken to be major process components such as reactors, engines, compressors, etc. The total cost to build and commission a process plant is the total capital investment (TCI) and is the sum of direct, indirect, and working costs:

(7)

Direct costs are those construction costs directly related to equipment installation including construction materials, labor, and ancillary equipment. Indirect costs do not contribute directly to equipment installation and commissioning and include engineering, supervision, contingency, legal, etc. Working costs account for capital held in the production process; items such as raw and finished material in stock and cash on hand. Operating costs reflect costs incurred in regular operation of the plant such as labor, maintenance, and overhead. These are calculated separately from TCI and used in calculating net annual cash flow.

Costing begins with the cost factors given by Peters and Timmerhaus[24]. The factors are slightly modified to reflect the costs of a waste to energy plant instead of a process plant and given in Table 2. Neither the base case nor gasification plant operate on salable product or purchased raw material. Working capital is assigned a low value. It is assumed that the building facilities needed for the base case will satisfy the gasification plant with limited additional work. A low cost factor for buildings is assigned. No laboratory work is expected. Commercial experience with a highly automated wood-fired, small-scale gasification plant suggests operating labor of less than 1 hour/ shift is appropriate. Thus, labor costs are based on 3 hours of operator time

per day. Publicly owned treatment works in the United States are generally exempt from sales and income tax. Neither tax nor depreciation are applicable.

Major equipment costs for all components except the gasifier were determined from literature sources[26] and supplier quotations. Costing a small-scale downdraft gasifier is challenging because little literature exists on the techno-economics of small-scale biomass power. The literature found to date is vague in regards to component costing, perhaps reflecting limited industrial experience with small scale TCC. No definite costs could be found for the gasifier. This analysis estimates gasifier cost from a large scale atmospheric fluidized bed reactor[17]. A fluidized bed reactor is more expensive than a downdraft reactor, making this substitution conservative. Costs are scaled by capacity via Eqn. 8[17], where is the scaled cost, is quoted cost, is the quoted capacity and is the capacity the cost is scaled to:

(8)

Table 2. Cost Factors

Direct Costs	Cost Factor (*TCI)
Installation	0.39
Instrumentation, Control	0.2
Piping	0.25
Electrical	0.15
Buildings	0.05
Yard Improvements	0
Indirect Costs	**Cost Factor (*TCI)**
Engineering	0.32
Construction	0.15
Legal	0.4
Contractor's Fee	0.19
Contingency	0.2
Working Capital	0.05
Fixed Operating Costs	**Cost Factor (*Labor)**
Maintenance	0.04
Laboratory	0
Supervision	0.2 * Labor
Overhead	0.25
Insurance	0.0125
General Expenses	0.15

III. Results

Modeling results

A parametric study in sludge flow rate was used to determine net electrical output and component mass flows as a function of raw sludge flow rate. Both sets of data are input to the economic model to determine component cost and electrical revenue. Optimized gasifier operating temperature and fuel moisture were determined by parametric studies maximizing net electrical output. The conditions were found to be 850 ºC (1562 ºF) for both systems and moisture concentrations of 10 wt% (air process) and 28 wt% (steam process.) System performance indicators are given in Table 3. Both models agree well with syngas LHV data where the error, given by (Eqn. 4), indicates that the syngas LHV is within 6.7% for the air process and 6.0% for the steam process. As this work is a systems-level feasibility analysis, 6-7% deviations between model and data are sufficient as LHV is the most salient property of the syngas[22]. Thermal performance of the systems was analyzed by considering the energy balance around the dryer. Both processes were found to satisfy dryer heating demands solely with recycled heat streams. Within the simplified assumptions of a thermodynamic model, effective heat recovery is possible.

Table 3. System Modeling Results

Process	Specific Output kWh/kg	Max Net Output 5.5 MGD (0.241 m^3/s)	Electrical Efficiency	Cold Gas Efficiency	Syngas LHV Error
Air	0.788	150 kW	17.10%	75%	6.7%
Steam	0.586	111 kW	12.70%	86%	6.0%

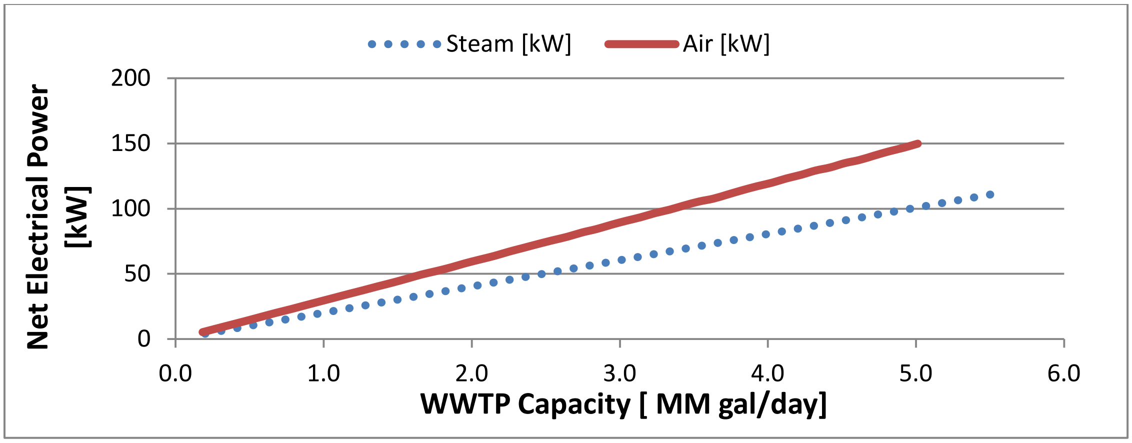

Figure 2. Net power output

Net electrical output for both processes is linear in wastewater supply rate as shown in Figure 2. This is expected as the model assumes components are optimized for their flow rates. The air process outperforms the steam process by 35%. This difference is greater than the modeling error in syngas LHV suggesting that this conclusion is robust. System efficiencies, also shown in Table 2 are less than 20%. Nonetheless, the air process efficiency is about 5% greater than small-scale steam Rankine cycles[13] and about triple the performance of energy recovery from anaerobic digester gas. The low steam process efficiency is partially due to the thermodynamics of indirect heating. The model assumes heat from a syngas burner is transferred at 20 ºC (68 ºF) above reactor temperature. This process is inherently inefficient as heat exchange with a body at 850 ºC (1562 ºF) produces a flue gas stream of temperature higher than 850 ºC (1562 ºF). Calculating burner efficiency as ,
where is heat transferred to the reactor and refers to gas mass flow delivered to the burner, reveals a burner efficiency of only about 56%.

Technical feasibility

This analysis has determined that sewage sludge cogeneration based on gasification is energetically feasible. In order to support the thermodynamic conclusions we further evaluated whether our system design is technically feasible to construct and operate. Sewage sludge properties are variable, with organic and inorganic compositions that depend upon numerous factors, including WWTP process design, geography, time of day and year, upstream plant conditions, etc. An additional complication comes from limited commercial experience with sewage sludge TCC, especially at a small scale. Where sludge specific components were not available, the analysis used data from general biomass sources with the assumption that this technology is likely adaptable to sludge service.

Sludge drying and conveyance are expected to be the greatest technical challenges to system design. Sludge must be dried to less than 28 wt% moisture. Mechanical drying methods cannot achieve design moisture levels[20] and thus thermal drying methods are used in conjunction with initial mechanical dewatering to 80 wt% moisture. Two general classes of thermal dryers are available, which can readily dry sludge to less than 10% water. Direct or convective dryers contact sludge with hot drying gas. Direct dryers can accept drying gas streams of relatively low temperatures, even below 200 ºC (392 ºF)[27], allowing for large mass flows of drying gas. This is useful where low temperature waste heat sources are available. Indirect dryers operate in the 300-400 ºC (572-752 ºF) or greater temperature range by circulating a heat transfer fluid through a jacketed chamber. Conduction from the chamber wall raises the temperature of sludge, thermally evaporating water.

Sludge conveyance after the dryer is influenced by final moisture. Sludges of moisture concentration below 15 wt% can be considered granular solids and are easily handled[21]. Discussion with sludge conveyance equipment vendors, including Andritz, Komline-Sanderson, and RUF suggest that sludges above 15 wt% moisture may not be conveyable. Redesigning the steam process to dry sludge to dry to 15 wt% moisture and supply the necessary steam from a utility boiler reduces net electrical output further below the air process. The final components involved in sludge handling are the briquetter (for fixed bed gasifiers) and gasifier charging equipment. The dry, granular solids required by the air process are readily briquetted by available equipment. Gasifier charging equipment design depends upon the type of reactor. Downdraft gasifiers may be gravity fed by simple metering hoppers or conveyors. Charging downdraft gasifiers should be simple and robust for briquettes of dry fuel[28]. Fluidized bed gasifiers operate on small particulate fuel; usually no briquetting is necessary. However fluidized beds require more sophisticated charging apparatus[28]. The technical challenges and mechanical complexity of charging fuel to fluidized bed reactors suggests that these systems will be more expensive and require more operator attention than mechanically simpler fixed bed reactors.

Numerous gasifier designs have been developed for biomass processing[29]. This analysis considers the fixed-bed downdraft gasifier to be the most economical option. The fixed bed downdraft gasifier supports a continuously replenished fuel pile on top of an ash grate. Combustion air is drawn through the bed and usually also injected via controlled tuyeres in the combustion zone. Syngas contact with charcoal on the ash grate acts to filter many contaminants, producing a low tar syngas with limited heavy metal entrainment. Hot ash additionally serves to catalyze tar cracking reactions[30].

Processes downstream of the gasifier are not expected to be unusually challenged by sewage sludge fuel in comparison to common biomass fuels. However, such equipment may necessarily be specialized and costly. For example, the syngas heat exchanger and associated piping must be constructed of 300- series stainless steels to accommodate high temperature hydrogen and the possibility of water condensation during startup and shutdown. Also, special consideration must be given to the internal combustion engine to ensure its compatibility with low LHV syngas. Nevertheless, equipment for all processes downstream of the gasifier is found to be commercially available from process equipment suppliers.

Economic Feasibility

This analysis shows that it is technically and energetically possible to produce net electrical power from the air blown gasification of wastewater sludge. Whether this technology can be successfully applied in decentralized urban wastewater treatment plants depends upon economic considerations. In order for a gasification plant to be economically viable, the savings from generated electricity and reduced disposal cost must offset the capital investment and manufacturing costs incurred from the plant. WWTP capacities are investigated in the rage of 0.5-5 dry metric tons of sludge per day. A benchmarking analysis compares the major equipment costing method to a commercially available wood-fired, small-scale gasifier platform manufactured by a Colorado-based biomass energy company[31].

Net Present Worth

Table 4. Present Worth Results

Capacity MGD	Present Worth $1000x	Cost per kWe $/kW
0.55	-2585	32600
1.1	-2271	24400
2.2	-1247	18400
3.3	147	15500
4.4	1536	13800
5.5	3022	12600

Table 4 shows the results of the economic evaluation. PW of the gasification plant, in comparison to the base case, becomes economically viable at a plant capacity of about 3.3 MGD (0.145 m^3/s). Over a plant lifetime of 20 years, the 3.3 MGD plant will earn about $147,000 over the base case. Profit margins at this level allow for some confidence in covering unanticipated costs. To benchmark this cost analysis, the TCI of the modeled gasifier plant is compared to a highly automated, turnkey biomass gasification platform produced by Community Power Corporation (CPC). The CPC system delivers 100 kWe from wood fuel at a cost of $1.2 million commissioned. Small-scale gasifier plants are available from companies including Gasek and All Power Labs however the sophisticated CPC system is a closer match to our system design. The modeled sludge gasification system at capacity equivalent to the CPC system is expected to cost $ 1.1 million. The close agreement between modeled costs and the commercial system supports the validity of this economic model. Further engineering effort will likely increase the range of economic feasibility for decentralized WWTPs. A concern in this analysis is the effect of historically low natural gas prices in the United States at the time of this study. A decrease in natural gas cost of 30% results in only the 5.5 MGD (0.241 m^3/s) system showing economic viability. As in any waste cogeneration scheme, good predictive models of local utility costing should be included in a detailed economic analysis.

IV. Conclusion

The results from this study suggest that decentralized, urban WWTPs with plant flows of about 3.3 MGD (0.145 m^3/s) can successfully recover value and energy from sludge using air blown gasification. The conclusions reached herein have added to the knowledge base of small biomass cogeneration system design and simulation. In particular, we have analyzed small-scale sewage sludge cogeneration on a systems level, a topic which until this work had no literature support. The fact that this analysis concludes that wastewater sludge cogeneration at small scale is economically feasible should motivate academic and industrial development. Application of this technology promises to reduce operating costs of wastewater treatment plants, carbon emissions from fossil-fired electricity, and the quantity of sludge requiring land disposal.

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