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Techno-economic analysis of wastewater sludge gasification: A decentralized urban perspective

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HIGHLIGHTS

- Evaluate potential technologies for conversion of waste water sludge to energy.
- Thermal systems analysis of air-blown and steam gasification of waste water sludge.
- Techno-economic analysis of electricity generation from sludge at small-scale plants.
- Air-blown gasification converts sludge to electricity with an efficiency greater than 17%.
- Favorable economics for energy recovery from sludge using air-blown gasification.

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ABSTRACT

The successful management of wastewater sludge for small-scale, urban wastewater treatment plants, (WWTPs), faces several financial and environmental challenges. Common management strategies stabilize sludge for land disposal by microbial processes or heat. Such approaches require large footprint processing facilities or high energy costs. A new approach considers converting sludge to fuel which can be used to produce electricity on-site. This work evaluated several thermochemical conversion (TCC) technologies from the perspective of small urban WWTPs. Among TCC technologies, air-blown gasification was found to be the most suitable approach. A gasification-based generating system was designed and simulated in ASPEN Plus® to determine net electrical and thermal outputs. A technical analysis determined that such a system can be built using currently available technologies. Air-blown gasification was found to convert sludge to electricity with an efficiency greater than 17%, about triple the efficiency of electricity generation using anaerobic digester gas. This level of electricity production can offset up to 1/3 of the electrical demands of a typical WWTP. Finally, an economic analysis concluded that a gasification-based power system can be economically feasible for WWTPs with raw sewage flows above 0.093 m^3/s (2.1 million gallons per day), providing a profit of up to $3.5 million over an alternative, thermal drying and landfill disposal.

1. Introduction

Wastewater treatment sludge is a dilute mixture of microorganisms, suspended and dissolved organic matter, and mineral species in up to 99% water. Sludge is produced at a concentration of about 0.25 kg/m^3 of solids in mixed municipal and light industrial wastewater treated (Metcalf et al., 2010). In 2005, about 8.2 million dry metric tons of sludge was produced in the United States (Biosolids Generation, 1999). Sludge production was seen to increase 29% faster than the U.S. population growth from 1972 to 1998 (Biosolids Generation, 1999). Management of this process residual can present financial and environmental challenges for wastewater treatment plants (WWTPs). Operators of small urban WWTPs face the greatest difficulties as their operations do not benefit from the economies of scale which permit larger facilities to absorb the costs and plant footprint of anaerobic digestion. This work considers urban WWTPs serving sewage flows of up to 5.3 million gallons per day (MGD) (0.23 m^3/s).

A contemporary approach to sludge management considers sludge to be an income-generating recoverable resource (Murray et al., 2008). In analyzing thermochemical conversion (TCC)

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technologies, it is often useful to know the fuel's heating value, which is the amount of heat released during combustion. The higher heating value (HHV) treats water in the combustion products as a liquid, while the lower heating value (LHV) treats water in the combustion products as a vapor. On a dry basis, sludge has a LHV of about 15 MJ/kg, which is similar to that of a low-rank coal. For a 5.3 MGD plant, up to 825 kW_{th} would be available for conversion to electricity. This suggests that the value of sludge might best be recovered as a fuel for on-site electricity generation. TCC technologies subject sludge to chemical processes at high temperatures to convert the chemical energy in sludge into heat, more useful fuels, or both. However, no small scale (<100 kW_e) techno-economic analyses of TCC-generating systems have been found in the literature.

The objective of this research effort was to estimate the minimum WWTP capacity for which electric power generation by TCC of sludge may be feasible. Feasibility of a process was defined as the ability to produce electrical power on-site using currently available technology while creating a net present worth greater than zero. Four candidate TCC technologies were considered in this study. These include wet oxidation, direct combustion, pyrolysis, and gasification (air blown, steam blown, and supercritical water). The TCC technologies were evaluated with a focus on the unique demands of small-scale, decentralized WWTPs. A sludge fired generating system incorporating the most appropriate TCC process was simulated using the process modeling software ASPEN Plus®. The system was then analyzed for technical feasibility with currently available technology. Data from the simulations were used to inform an economic model that compared the generating system to a base case of thermal drying and landfill disposal, to determine at what scale the TCC-based generating system would be economically feasible.

1.1. Sewage sludge chemical characteristics

Technical fuels are commonly described by their proximate analyses (percentages of moisture, volatile matter, sulfur, fixed carbon, and ash, as well as HHV) and ultimate analyses (percentages of elemental carbon, elemental hydrogen, elemental nitrogen, sulfur, elemental oxygen, ash, and moisture). The composition and properties of the sludge used in this study along with several other resource streams commonly considered as gasification feedstocks are summarized in Table 1. These include wood (pine), corn straw, and municipal solid waste. The most notable differences between sludge and other resource streams are initial moisture, oxygen, and ash content. One challenge in exploiting sludge as a fuel is the need to remove substantial quantities of water. For example, simulations conducted in the course of this study predict that up to 60% of the chemical energy in dried sludge is required for thermal drying. Ash presents other challenges to TCC of sludge, particularly corrosion. The ash compositions of sludges from several different municipal wastewater treatment processes in the Denver, Colorado, area were studied and found to contain 1,830 mg/kg of Na, 5350 mg/kg of K, and 19,600 mg/kg Ca (averaged between all samples) (Ramey et al., 2014). Ash can be aggressively corrosive at high temperature (Cummer and Brown, 2002); however, ash high in Na and K salts may provide a benefit to the system by catalyzing tar cracking reactions at temperatures above 500 °C (Fonts et al., 2012). A further complication of sludge not represented by proximate and ultimate analyses is heavy metals content, including Cd, Hg, Pb, and Zn. At flame temperatures achieved during sludge or char combustion, metals may vaporize and be entrained with the exhaust gas stream. Metals remaining in ash and char may also be leached by acidic water if disposed of in a landfill (Fytili and Zabaniotou, 2008). Furthermore, due to the presence of fats, oils, and greases, the mass fraction of oxygen in sludge is somewhat lower than other biomass materials, which partially offsets the reduction in mass-basis heating value caused by high ash content.

1.2. Thermochemical conversion processes

TCC processes are routinely used to transform solid fuels into heat or a more valuable technical fuel such as synthesis gas or bio-oil (Fytili and Zabaniotou, 2008; Werther and Ogada, 1999; Bridgwater, 2003). For consideration in this study, candidate TCC technologies were required to be at least in the pilot plant stage of development and able to support the production of electricity on-site. TCC technologies considered in this study include wet oxidation, direct combustion, pyrolysis, and gasification. Selection of the most appropriate TCC process was also based on process energy efficiency, environmental considerations, and applicability to small scale installations. A short summary of these technologies with a view to decentralized WWTPs is presented in the following paragraphs.

1.2.1. Wet oxidation

Wet oxidation is an exothermic process which takes place in an oxygenated aqueous phase at pressures ranging from 5 to 30 MPa (725–4350 psi) and temperatures from 150 to 600 °C (Khan et al., 1999). Organic species are oxidized to H_2O, CO_2, volatile fatty acids, and simpler organic compounds such as formaldehyde (Khan et al., 1999). The effluent solution must be recycled to the WWTP headworks to treat the reaction products (Khan et al., 1999). Wet oxidation in wastewater treatment is used to decompose organic materials which are resistant to biological treatment processes.

Table 1
Chemical composition of sludge compared to other common waste streams. Data are dry wt.% unless otherwise indicated

Analysis	Wastewater sludge[a]	Pine wood[b]	Corn straw[c]	Municipal[d] solid waste
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	5.98
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	0.95	Not detected	0.13	0.36
LHV [MJ/kg]	16.7	20.2 (HHV)	17.75	21.3

[a] Ramey et al. (2014).
[b] Franco et al. (2003).
[c] Gai and Dong (2012).
[d] He et al. (2009).