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Original Research Article

Evaluating air-blown gasification for energy recovery from wastewater solids: Impact of biological treatment and point of generation on energy recovery

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A B S T R A C T

Decentralized water reclamation is emerging as a new paradigm that pairs local wastewater resources with local users; however, one of the challenges that must be addressed to advance its implementation is the low energy efficiency associated with small treatment plants and the lack of available small-scale energy recovery technologies. Gasification is a technology that could be used to convert wastewater solids to energy at small wastewater resource recovery facilities (WRRF). A model developed for air-blown gasification coupled with internal combustion engine for energy production demonstrated that gasification of wastewater solids could produce up to one third of the electrical demand at a small WRRF. Results based on samples collected from local wastewater treatment plants show that the energy embedded in wastewater solids does not vary substantially with treatment processes implemented or point of solids generation, and thus gasification is feasible for a wide variety of WRRF sizes and processes. Further modeling revealed that feedstocks generated by three different processes have similar power output for one metric ton per day of solids gasified (~20 kW), but the net power produced by a 19 ML/d WRRF varies more substantially (110–140 kW) because the mass of solids produced vary with each treatment scheme.
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Introduction

The need for new water resources is becoming increasingly important as water purveyors across the United States (US) experience increasing water demand that exceeds their procured supply. This was reflected in a recent study of water supply vulnerability in 2103 watersheds throughout the US, which identified 9% as water-stressed [1], and a United Nations study which estimated that 75% of the world's population could face water scarcity in the future [2]. Surface water supplies are expected to continue to decrease [1], and alternate resources are needed to meet increasing demand. An emerging strategy for sustainable wastewater reuse tailors the quality of water produced (e.g., the nutrient and/or total dissolved solids concentrations) to the end use (e.g., irrigation, industrial) using decentralized, or distributed wastewater resource recovery facilities (WRRFs) [2,3]. Decentralized WRRFs may offer substantial advantages over centralized plants because the proximity to end-users reduces the requirements for construction and operation of conveyance infrastructure, and tailoring water quality to the needs of the end-use can help avoid unneeded treatment (e.g., nutrient removal) [3].

However, smaller WRRFs pose new challenges in achieving environmentally and economically sustainable (i.e., energetically favorable) water reclamation. While large WRRFs can realize substantial energy savings, for example by optimizing aeration, small WRRFs do not realize the economy of scale found in large plants and typically use more electricity per gallon of water treated [2,4]. The energy balance is further exacerbated in small WRRFs by the lack of available small-scale technologies for energy recovery. Current practices at large centralized wastewater treatment plants (WWTP) (i.e., those with flows greater than 38 million liters per day (ML/d, or 10 million gallons per day (mgd)) may employ solid treatment processes such as anaerobic digestion to recover energy [5,6]. These technologies are not currently feasible for small WWTPs or WRRFs. Higher power consumption and lower energy recovery opportunities associated with decentralized plants reduce the economic viability, and increase their carbon footprint [2]. These barriers must be addressed for decentralized water reclamation to be sustainable.

The management of solids produced in WRRFs presents the greatest challenge and opportunity for reducing the energy footprint of water reclamation. A decentralized WRRF constructed

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within a sewershed to meet needs of local customers may discharge solids to the existing sewerage for conveyance to the centralized facility; however, discharge of sludge to existing sewer systems is likely to result in accelerated degradation of infrastructure and development of severe odors, making it infeasible in most situations. While energy recovery using anaerobic digestion is generally considered feasible for large centralized WWTPs, fewer than 20% of the WWTPs that utilize anaerobic digestion for solids stabilization generate electrical energy for plant use [7]. Biogas cleaning is required to remove hydrogen sulfide and siloxanes, and although technologies are commercially available, the cost of natural gas and electrical energy must be high enough to make energy recovery economical [8]. If anaerobic digestion processes could be tailored to small flow WRRFs, it may be possible to reduce the energy requirement for solids processing, but unlikely that electrical energy would be generated.

Solids stabilization technologies for facilities with flow less than 19 ML/d (5 mgd) are limited to aerobic digestion and thermal stabilization [8,9], and both are energy intensive, requiring more than ten times the energy used to operate an anaerobic digester. Although energy savings can be realized by optimizing aerobic digestion and thermal stabilization, these technologies are not viable options for recovering energy. New technologies are needed to reduce the carbon footprint of decentralized WRRFs.

Thermochemical conversion (TCC) processes such as gasification may be suitable for treatment of wastewater solids, reducing the energy requirements to treat solids, and potentially enabling energy recovery [10,11]. Gasification converts wastewater solids into heat and a combustible fuel product (syngas) that can be used to both dry solids and generate electricity. Gasification is similar to anaerobic digestion in that the fuel generated can be combusted to produce electricity or burned to produce thermal energy, but there are substantial differences between the two technologies. Gasification provides almost complete conversion of volatile matter [12], while anaerobic digestion converts 20–60% of volatile matter to biogas [5,13]. However, syngas has a lower heating value (LHV) of 4–7 MJ/m^3 (using air-blown gasification) whereas anaerobic digester biogas is reported to have LHV of 19–22 MJ/m^3 [9]. The characteristics of syngas (i.e., corrosive gasses and siloxanes) have not been reported widely in the literature, and the extent of cleaning required for electricity generation has not yet been established [14].

The gasification process has been described extensively in the literature [15–17], and the technology has been commercially developed for biomass feedstocks such as wood and agricultural wastes [18]. Gasification may be suitable for wastewater solids for several reasons. In gasification, volatile matter is converted to syngas (a gaseous mixture composed mainly of hydrogen, carbon monoxide, and methane) and solid/liquid residuals (e.g., inorganic ash and tars), with the residuals typically constituting less than 25% of the original mass of solids. Gasification can be autothermal (self-sustaining) at process temperatures less than 900 °C and operating pressures close to atmospheric pressure [19,20], reducing the complexity of reactor operation. The syngas produced in a gasification system can be used to generate electricity using commercially available generators such as those used for biogas power production [15,20]. Dogru et al. [15] noted that small-scale gasification with heat and power generation could make an important contribution to the economy of rural communities where sewage sludge is adequately produced. Such a contribution could also be realized in urban settings at decentralized WRRFs.

While gasification has been applied to biomass such as agricultural and forestry waste, it has not been widely applied to wastewater solids [13], which are fundamentally different from agricultural and forestry waste biomass. The overriding difference is that solids generated in a WRRF typically have moisture content exceeding 95%, and a substantial amount of energy produced by gasification will be needed to reduce the moisture content [12,19], whereas agricultural and forestry waste have moisture contents of only 10–30% [21]. Another challenge of gasifying wastewater solids is their inorganic constituents, which are reported to be substantially greater in concentration than the ash content of biomass [21].

Several review papers describe the characteristics of sludge or solids collected from residential, industrial, and agricultural processes and discuss the applicability of TCCs [12,19]; however, the source of solids and the wastewater treatment processes by which they were generated are often undefined [22–24]. High heating value of solids have been reported to decrease from 25 MJ/kg for primary clarifier solids (PCS) to 21 MJ/kg for secondary clarifier solids (SCS), and to 12 MJ/kg for anaerobically digested solids (ANS) [5,9]. These sources reference a publication by the United States Environmental Protection Agency (US EPA) from 1979 [25], and the authors note that the data provided in the text was collected before biological nutrient removal was widely incorporated into treatment processes [25]. The existing practice of using anaerobic digestion of solids for energy recovery from wastewater solids shows that increasing the portion of PCS introduced into the digesters increases the mass of biogas produced due to the elevated mass of volatile solids. This same approach might be applicable for increasing the power produced through gasification; however, such data have not been found in the published literature, and there is a lack of data providing a complete and objective evaluation of operating constraints, syngas value, and residuals characteristics for gasification of wastewater solids [12–14,26].

In our previous study a thermodynamic model was developed to evaluate the feasibility of using air-blown gasification to recover energy from wastewater solids [20]. The model results showed that air-blown gasification of solids with ‘typical’ thermochemical properties is both technically and economically feasible for wastewater solids from facilities with flows greater than 8 ML/d (2.1 mgd), producing power sufficient to offset one-third of the requirements of a WWTP [20]. The main objectives of the current study were to evaluate the thermochemical characteristics of solids generated by different wastewater treatment processes and their suitability as gasification feedstock, and to investigate whether energy recovery using gasification could be increased by changing the proportion of primary and secondary solids in the feedstock. We hypothesized that solids generated in treatment processes with long solids retention times would have reduced volatile organic content, which would be detrimental to the energy recovery potential. This would be the most evident in solids from a membrane bioreactor, which is an established technology for WRRFs [3]. To counter the lower energy recovery potential of these treatment processes, a treatment system employing enhanced primary clarification (EPC), which increases the proportion of PCS in the feedstock was modeled. It was hypothesized that gasification of solids from the EPC treatment system would produce more power than solids from conventional and membrane bioreactor treatment, mirroring optimization strategies for anaerobic digestion.

Materials and methods

Wastewater solids included in the study

Solid samples were collected from seven WWTPs, representing a range of plant design flows and biological processes. Samples included biosolids, which are wastewater solids that have been stabilized to reduce pathogens and vector attraction, meeting regulatory requirements of the US Code of Federal Regulations [27],

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