Sustainable Energy Technologies and Assessments 9 (2015) 22–29

Contents lists available at ScienceDirect

Sustainable Energy Technologies and Assessments

journal homepage: www.elsevier.com/locate/seta

Original Research Article

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

Dotti F. Ramey, Nicholas P.G. Lumley, Ana L. Prieto, Jason M. Porter, Tzahi Y. Cath *

Colorado School of Mines, Department of Civil and Environmental Engineering, 1500 Illinois Street, Golden, CO, USA

ARTICLE INFO

Article history:
Received 3 August 2014
Revised 15 October 2014
Accepted 22 October 2014

Keywords:
Thermochemical conversion
Gasification
Energy recovery
Biosolids
Waste to energy
Decentralized water reclamation

ABSTRACT

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.

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

* Corresponding author. Tel.: +1 (303) 273 3402; fax: +1 (303) 273 3413.
E-mail address: tcath@mines.edu (T.Y. Cath).

http://dx.doi.org/10.1016/j.seta.2014.10.003
2213-1388/

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],

and wastewater solids that have not been stabilized. Samples included solids from preliminary treatment operations such as grit chamber (GCS, site 07); fats, oils, and grease (FOG, site 03); primary clarifier solids (PCS, sites 01, 05, and 06); and influent screening (PCS, site 04). Secondary clarifier solids (SCS) were collected from the waste activated sludge lines of a membrane bioreactor and a conventional activated sludge reactor (WAS, sites 01 and 04, respectively) and from the aerobic reactor tank of a Bardenpho treatment system (SCS, site 02). Biosolids samples (stabilized solids (STS)) from aerobic (AES, sites 02, 03, and 06) and anaerobic (ANS, sites 04, 05, 06, and 07) digestion processes were also collected. The facilities' designed flows vary from 0.026 to 832 ML/d (0.007–220 mgd), and each facility has a different treatment train. Two facilities (sites 01 and 05) currently reclaim wastewater for non-potable reuse.

Solid samples preparation and analysis

Samples collected were analyzed for total, suspended, volatile, and fixed solids using Standard Methods 2540 [28], which delineates volatile and fixed solids using an ignition temperature of 550 °C. Samples were analyzed in triplicate and the average results reported. From the total set of samples collected, a subset of 17 samples was chosen for further analysis to characterize their composition and energy content. In preparation for analyses, these samples were dried following procedures outlined in ASTM E1757, using Method B for freeze-drying. Samples that were not dewatered at the WWTP were dewatered in the laboratory prior to freeze-drying using a centrifuge operating at 3500 rpm for 15 min.

Concentrated solids were prepared for freeze-drying by placing samples in a −86 °C freezer (Sanyo Scientific Ultra-Low Temperature VIP Series model DF-U53VC) for a minimum of 24 h. Subsequently, freeze-drying was accomplished using a FreeZone6 lyophilizer (Model 7753020, LabConco Corp., Kansas City, MO) operated at −40 °C and 0.13 mBar for a minimum of 48 h. Dried samples were then shipped to a commercial, certified laboratory for caloric, proximate, and ultimate analysis.

Heating value

The caloric content of the samples was determined using method ASTM D 5865 with results reported as high heating value (HHV) and low heating value (LHV) on dry weight basis (dwb). When reported as dwb, the difference between HHV and LHV represents caloric content lost to the generation of water vapor in the combustion process. The HHV (also referred to as the gross heating value) represents the heat released if the test conditions are returned to 25 °C and energy from condensing the water vapor is recovered, whereas the LHV (net heating value) reports the heat released if the water produced in combustion remains a vapor (i.e., test conditions are returned to 150 °C after combustion and the latent heat of water vaporization is not recovered) [21].

Proximate and ultimate analysis

Methods ASTM D 3172 through 3175 were used for volatile matter (VM), ash, moisture content, and fixed carbon (FC) analyses. Volatile matter was determined by ASTM D 3175, which requires ignition temperatures of 950 °C, while ash content was determined by modified ASTM D 3174, which uses an ignition temperature of 600 °C. Moisture content was determined using ASTM D 3173 with drying temperature ranging from 104 to 110 °C, and FC was found by subtracting the sum, expressed as percentages, of moisture, ash, and VM from 100, per ASTM D 3172.

Although both Standard Methods and ASTM methods use common terms "volatile matter" and "ash", the differences in the temperatures used for determination of these parameters results in values that represent different bulk parameters of the samples, and the terms cannot be used interchangeably. In this study, the results for VM and ash were obtained using the ASTM methods.

The ultimate analyses determine the percentage of major elements (i.e., C, H, O, N, and S) that are part of the gasification reactions. The protocol specified in ASTM D2176e was followed for the ultimate analysis, and according to the methodology the percentage of C, H, N, and S are measured directly, and the oxygen content, expressed as percentage, is calculated by subtracting the sum of the percentages of ultimate analysis elements and the ash content from 100.

Solids mass balance for power production under different treatment scenarios

The power generated by air-blown gasification of WRRF solids was modeled for three scenarios. These include (a) conventional treatment (i.e., primary sedimentation followed by activated sludge biological treatment with nitrogen removal), (b) enhanced primary clarification (i.e., ballasted flocculation followed by activated sludge biological treatment with nitrogen removal, and (c) influent coarse screening followed by sequencing batch membrane bioreactor (SBMBR) with nitrogen removal. A mass balance of solids was conducted for the scenarios to calculate the total mass of solids produced by the three facilities and the proportion of PCS and SCS in the gasifier feedstock using design guidance provided in Tchobanoglous et al. [5] in the Manual of Practice No. 8 [6,9], and removal efficiencies reported by the Electric Power Research Institute [29]. For scenarios (a) and (b) the influent concentrations of total suspended solids (TSS) (260 mg/L) and 5-day biochemical oxygen demand (BOD_5) (240 mg/L) were calculated based on a per capita wastewater flow of 378 L/person/d (100 gal/person/d). Effluent TSS and BOD_5 of 30 mg/L and biological yield (Y) of 0.5 mg/L TSS per mg/L BOD_5 removed were used to estimate the mass of solids produced by an activated sludge treatment system. The removal efficiencies for conventional primary treatment were assumed to be 60% TSS and 35% BOD_5 and for ballasted flocculation were 90% TSS and 60% BOD_5.

The mass balance for solids in scenario (c) was calculated using removal data found in the literature for coarse screening with 12 mm slots [5] and operating parameters recorded in the operation log for Site 01 [3]. Primary solids calculations assumed that the volume of screened sludge produced is 50 L per 1000 m^3 of influent flow, 75% sludge moisture, and specific gravity of 900 kg/m^3. Data from the operating log for the SBMBR for the week the sample was collected showed 6.8 kg/day (dwb) of waste activated sludge (WAS) wasted for an influent flow of 0.026 ML/d.

Using the proportion of PCS and SCS in the treatment scenarios, theoretical profiles of proximate and ultimate parameters for scenarios (a) and (b) were calculated. The average value for each parameter was calculated for a category of solids in the study (i.e., PCS and SCS), then the proportions of PCS and SCS, as defined by the mass balance calculations, were applied to the average values for each proximate and ultimate parameter. For the profile of scenario (c), the proximate and ultimate values for sample WAS-01 were used.

Simulation of power production under differing solids generation scenarios

An ASPEN Plus® model as described in Lumley et al. [20] was used to simulate an air-blown gasification system with electrical energy production using a reciprocating engine generator. The model schematic and brief overview are provided in Fig. S1 of the Supplementary Content (SC), and a brief overview is provided here. Solids enter the system at 80% (wt) moisture from an

upstream centrifuge dewatering process, which is a typical dewatering technology for wastewater solids. Dewatered solids are dried to 10% (wt) moisture in a direct-contact dryer using waste heat recycled from the syngas cooler and engine exhaust. The model results demonstrate that less than 5% of syngas produced in the system will be required to complete the solids drying to 10% moisture. Dried solids are briquetted and fed to the gasifier. The syngas exits the gasifier at 850 °C and cooled by air in a heat exchanger, with the excess heat recycled to the solids dryer. Cooled syngas is cleaned using a bag filter and a wet scrubber to remove particulates and condense tars. The cleaned syngas is used to fuel a reciprocating internal combustion engine to produce electrical energy. Exhaust heat from the engine is recycled back to the solids dryer [20]. The conversion of chemical energy in the syngas to electrical energy by the engine-generator is accomplished with an efficiency of 24%. Overall, the efficiency of the system in generating electrical energy from solids is approximately 17.5%.

The theoretical profiles for each treatment scenario were introduced into the gasification model, which estimates the power produced by each feedstock. The LHV of the syngas produced is calculated in the model for each feedstock, and the power produced is calculated for two conditions: the production of one metric ton per day (mtpd) of solids for each scenario (with varying plant flows), and for the estimated mass of solids that would theoretically be produced by each WRRF scenario treating 19 ML/d (solids mass flow varying).

Results and discussion

At the time of sampling, each WWTP was operating under normal operating conditions (i.e., the plants were not recovering from biological system upsets); thus, the samples are considered to be representative of the solids typically generated at the WWTPs. Information about the WWTPs that were sampled is summarized in Table S1 of the SC, and the results from bulk solid analysis of all samples collected at the WWTPs are summarized in Table S2 of the SC.

Evaluation of solids for energy recovery using gasification

The heating value of syngas and system power production can be estimated from the proximate analysis (i.e., ash, volatile matter, moisture, and fixed carbon content) and ultimate analysis (i.e., feedstock elemental constituents C, H, O, N, and S) of solid samples [16,30]. The ash content and heating values (reported as HHV) of the samples analyzed and of those found in the literature are summarized in Table 1. In general, the HHVs of the samples are within the range of published data, though somewhat lower than most reported HHVs [5,11,19,24,25,31–36]. The HHV of the investigated samples are also within the range of waste wood and agricultural waste biomass currently used in gasification [32].

Ash content for PCS and SCS in the current study was in the lower range for primary, secondary, and combined (primary and secondary) solids found in the literature, and the STS (AES and ANS) in the study were within the median literature range. The higher ash content reported in the literature may be due to different industrial loads to the WWTPs sampled, to differences in preliminary treatment units, including grit separation, or they may be a result of the difference in the methodologies (i.e., ASTM or Standard Methods) used to determine ash content. In the literature, the ash content varied substantially for a point of generation, reflecting the potential differences inherent in WWTP solids; however, the ash content of the samples in this study did not show the same variability for a given point of generation. The ash content for wood biomass (0.3–0.45%) [21], is considerably lower than the WWTP solids sampled, and the ash content of corn stover (9.8–13.5%) [21,32], while higher than in wood, is still lower than the samples investigated here.

The values in Table 1 highlight two important aspects that must be considered when evaluating WWTP and WRRF solids as gasification feedstock. The inorganic content of solids is higher than in biomass feedstocks currently used for gasification, thus the current configurations of biomass gasifiers may need to be modified to accommodate the higher ash residual mass. Also, the inorganic content of solids varies between facilities. The variability of ash content, both in the current study and in the literature, illustrates that, while literature values can be used for preliminary assessment of gasification for energy recovery, site-specific knowledge of solids content and character is needed before reaching a final decision regarding the applicability of gasification.

The results of the bulk solids analysis (Table 2 of SC) are typical of wastewater solids, with moisture content of 75–80% for dewatered samples and greater than 90% for non-dewatered solids. The high moisture content of wastewater solids is one of the most important characteristics when evaluating the feasibility of gasification for energy recovery. Based on modeling results, the energy required to dry solids from 80% to 10% moisture content represents approximately 60% of the energy contained in the solids. Therefore,

Table 1
Comparison of ash content and heating value of WRRF solids and biosolids analyzed in the current study and literature values for similar solids and biosolids. Study values represent the average of values for the solids source if more than one sample was analyzed (e.g., PCS represents the average of four samples). Literature values for heating value and ash content of two different sources of biomass (white oak wood and corn stover agricultural waste) are provided for comparison.

Solids sample[a]	Data source	Ash (%w/w)	HHV[b] (MJ/kg)	HHV[b] (BTU/lb)	Refs.
GCS	Literature	63	9.3	4000	[25,33]
GCS	Study	21.8	17.2	7396	
FOG	Literature	12	38.8	16,700	[25,33]
FOG	Study	11.4	24.1	10,357	
PCS	Literature	16.0–35.0	15.1–27.0	6500–11,000	[5,19,31,34]
PCS	Study	5.7–8.7	19.4–23.4	8345–10,067	
SCS	Literature	23.0–33.0	14.8–20.9	6345–9000	[5,19,34]
SCS	Study	16.7–17.2	9.1–17.1	3909–7359	
PCS + SCS	Literature	15.0–28.0	13.4–19.6	7119–8297	[11,19]
PCS + SCS	Study	19.1–19.7	17.8	7647	
STS	Literature	8.1–65.0	7.0–20.9	3000–8974	[5,24,31,33,35–37]
STS	Study	20.3–23.7	15.1–16.8	6499–7216	
Wood	Literature	0.3–0.45	18.6–21.1	8000–9120	[32]
Stover	Literature	9.8–13.5	17.6–18.5	7585–7967	[32]

Notes: [a] Solids source: GCS: grit chamber solids, FOG: fats, oils & grease, PCS: primary clarifier solids (including thickened primary solids (PTS)), SCS: secondary clarifier solids (including waste activated sludge (WAS)), PCS + SCS = combined primary and secondary solids (including solids thickened by dissolved air flotation (DAF)), STS: stabilized solids (including anaerobically digested (ANS) and aerobically digested (AES) solids).
[b] If the basis of reporting (HHV or LHV) for the heat value was not provided in the literature, HHV was assumed.

use of excess thermal heat from the gasification system is required if electrical energy is to be produced [20].

The results of proximate and HHV are shown on Fig. 1 and summarized in Table S3 of the SC. For comparison, literature values from Tchobanoglous et al. [5] for ash, VM, and HHV of primary, secondary, and anaerobically digested solids are included in Fig. 1 as dataset "LIT". VM and ash contents of the analyzed samples varied with the point of generation in a WWTP. The data show that the VM content decreases as the point of generation proceeds through the treatment train (PCS 85.2 ± 3.6%, SCS 71.8 ± 1.0%, STS 68.63 ± 4.2%), while the ash content increases (PCS 7.5 ± 1.6%, SCS 18.2 ± 1.5%, STS 22.3 ± 1.46%). The literature shows a fairly small difference between the VM and ash of PCS and SCS, and larger difference in those constituents when comparing SCS and STS [5]. The data from this study differs from the literature in that the differences in VM and ash between PCS and SCS were larger than the differences between the SCS and STS values. The lack of substantial decrease in the VM of STS compared to SCS may be due to the changes in the biological treatment processes in recent years. For example, the data in the literature is based on US Environmental Protection Agency studies from 1979 [5], but current treatments plants must meet stricter nutrient removal requirements, and nitrogen and phosphorus removal are typically accomplished using biological treatment, requiring longer solids retention time. The longer solids retention time may result in excess mineralization of organic matter in the aeration basins instead of the solids stabilization process. Additionally, the change of lifestyle and consumer products used by the public have undoubtedly changed the characteristics of wastewater solids in the last 35 years.

Fixed carbon, which does not volatilize at temperatures below 750 °C but reacts in gasification to form components of syngas, varies slightly in samples analyzed in the current study but neither increases nor decreases as the point of solids generation proceeds through the treatment process. Literature reviewed did not consistently report fixed carbon values in solids, but values reported by Dominguez [35] are similar to results obtained in our study for stabilized solids.

Characteristics reflected in the ultimate analysis are shown in Fig. 2, and as with the proximate parameters, there is not a marked difference in the elemental composition of the samples. Carbon concentration slightly decreases when converting from primary solids to secondary solids, and it remains virtually unchanged between secondary solids and stabilized solids. Sulfur concentration remains consistent in all samples with negligibly higher concentrations in secondary and stabilized solids. Nitrogen concentration increases and oxygen concentration minimally decreases as solids turn from primary solids to stabilized solids. Although the range of hydrogen content (%wt) varied only from 5.5% to 7.6% across all solids, it should be noted that a small change in hydrogen content measured by weight represents a larger increase in the molar concentration of hydrogen in a solids sample. A small increase in hydrogen composition will impact the power produced by the solids through gasification, more than other elemental compounds such as oxygen or carbon, because the heating value of H_2 is much higher than other elements.

The secondary solids samples in this study represented processes such as conventional activated sludge, Bardenpho treatment, trickling filter, and SBMBR, and the results show that solids from the various biological processes did not vary greatly in proximate and ultimate composition. The standard deviation of each parameter was less than 8% of the average, with the exception of sulfur, (average 1.22%, SD 0.19%). This lack of substantial difference in thermochemical characteristics indicates that solids generated by a wide variety of biological treatment systems have the potential to successfully recover energy using gasification.

Simulation of power production under differing solids generation scenarios

Based on the mass balance calculations for three feedstocks (i.e., (a) conventional, (b) EPC, and (c) SBMBR treatment schemes), the treatment plant flows required to produce one mtpd were 3.5, 4.0, and 3.7 ML/d, respectively. The solids generated by each scenario for constant plant flows of 19 ML/d were 5.4, 4.8, 5.1 mtpd, for scenario a, b, and c, respectively. The percentage of primary solids in the feedstocks of the three scenarios were 53%, 88%, and 4% for scenarios a, b, and c, respectively.

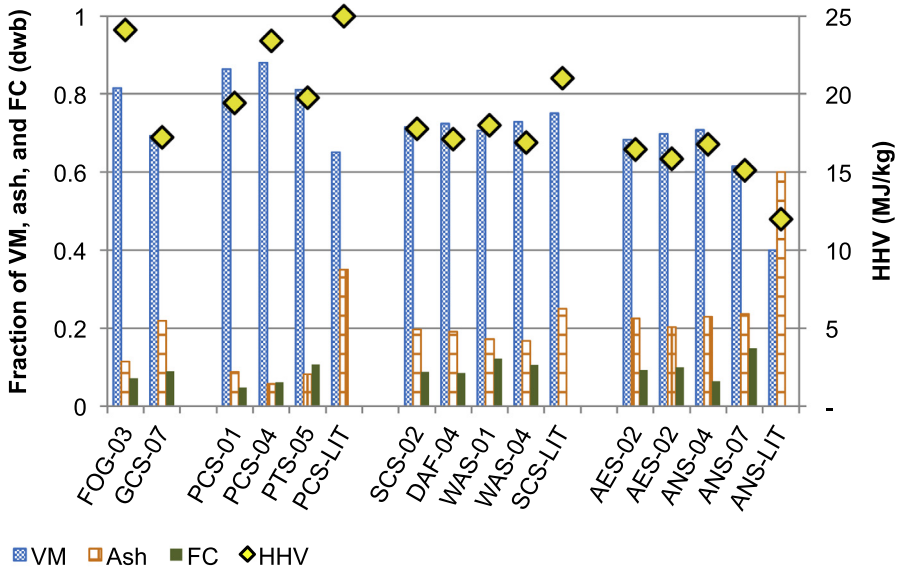

Fig. 1. Proximate and HHV values of WRRF solids with literature values (LIT) provided for reference. VM, ash, and FC contents are reported on dry weight basis (dwb, 0% moisture) and were determined by contract laboratory using ASTM methods, and VM and ash of literature values are based on Standard Methods protocol. Preliminary treatment solids are represented by FOG and GCS; primary solids include PCS and thickened (PTS) solids; secondary solids include solids collected from secondary clarifier (SCS), waste activated sludge (WAS) and WAS thickened using dissolved air floatation (DAF); and stabilized (STS) solids include solids stabilized using aerobic (AES) and anaerobic (ANS) digestion.

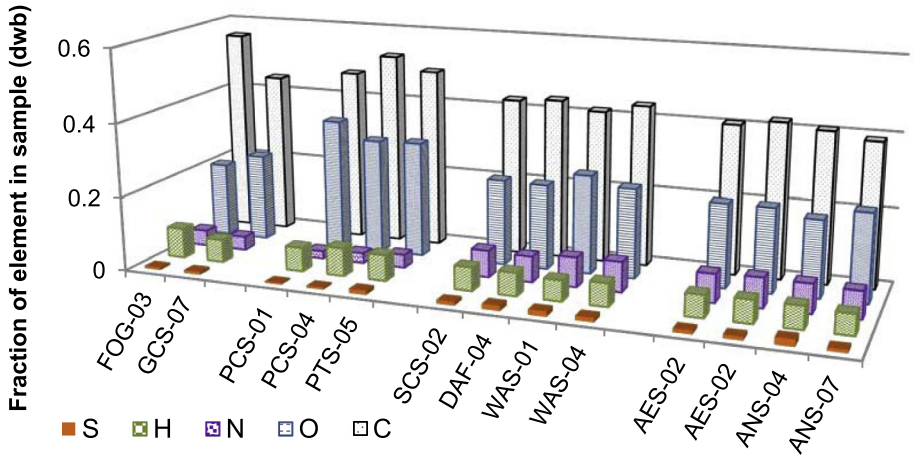

Fig. 2. Comparison of the content (expressed as fraction of total on dry weight basis) of carbon (C), hydrogen (H), oxygen (O), nitrogen (N) and sulfur (S) in solids generated at different points in WRRFs. C, H, N, and S are measured directly, and the O content is calculated based on the measured elements and ash content of the samples.

Results of the model simulations for the three solids feedstocks are summarized in Table 2 and shown graphically in Fig. 3. As with the analytical results from individual samples, the calculated ultimate and proximate values of the solids for each scenario do not vary substantially. The LHV of the syngas produced by EPC treatment was 3% less, and the LHV of SBMBR 3% greater than conventional treatment, and based on variability inherent in the model assumptions, these values are considered to be similar. The results show that the potential power produced for constant mass flow of one mtpd were 24, 22, and 20 kW for scenarios a, b, and c, respectively (▲ in Fig. 3). Solids from EPC treatment produce approximately 8% less power than solids from conventional treatment, and the SBMBR treatment scheme produced 18% less power than conventional treatment. The results reflect the potential energy inherent within each feedstock, and demonstrate that feedstock with higher content of primary solids, which also provide higher VM content, does not ensure greater power produced by gasification compared to power produced by conventional treatment schemes. The model results for the SBMBR, which was comprised of more than 95% secondary solids, indicate that the power produced by gasification of solids from membrane systems with long solids retention times may be substantially lower than conventional treatment systems, which will negatively impact the environmental sustainability of decentralized wastewater resource reclamation.

Table 2
Summary of parameters used to model the power produced by gasification of feedstocks from WRRFs with three treatment schemes: (a) conventional treatment (i.e., primary sedimentation followed by activated sludge biological treatment with nitrogen removal), (b) increased PCS content using enhanced primary clarification (i.e., ballasted flocculation followed by activated sludge biological treatment with nitrogen removal), and (c) influent coarse screening followed by SBMBR with nitrogen removal. The total mass produced in a WRRF with 19 ML/d (approximately 5 mgd) and percentage of PCS and SCS provide the basis for the proximate and ultimate profiles for scenarios a and b.

Parameter	Conventional	EPC	SBMBR
Mass balance results			
Solids produced for a 19 ML/day WRRF (mtpd)	5.4	4.8	5.1
Percent PCS	53	88	4
Percent SCS	47	12	96
Power produced and energy of syngas			
LHV of syngas (MJ/kg)	3.84	3.71	3.92
Net power produced per metric ton dry solids (kW)	24	22	20
Net power produced for a 19 ML/day WRRF (kW)	137	113	109

The net power produced by a plant with 19 ML/d flow was calculated by the model to be 137, 113, and 109 kW for scenarios a, b, and c, respectively. The power produced by EPC treatment was 18% less than conventional treatment, even though the power produced for one mtpd was only 8% lower. The impact of lower solids generation (EPC produces 11% less solid matter than conventional) is reflected in the net power production for a 19 ML/day facility. The SBMBR scenario produced 20% less power than the conventional treatment scheme. The power produced from 19 ML/d flow is impacted by both the power produced per dry metric ton and the mass of solids produced; and because the solids produced by SBMBR is only slightly less than solids produced by conventional treatment (5%), the difference between the power produced per dry metric ton, and that produced by a plant with flow of 19 ML/d is less marked when compared to the EPC solids.

The model results show that, in contrast to anaerobic digestion, power production by air-blown gasification is not enhanced by increasing the content of primary solids in the feedstock. Furthermore, for a specified WWTP flow, the mass of solids generated under different treatment schemes has a larger impact on the power produced than both the LHV of the syngas and the power produced per dry metric ton of solids.

It should be noted that the gasification results from all three scenarios compare favorably to the potential power generation from anaerobic digestion. Based on the values provided in the literature [5,38,39], the estimated gross power production from anaerobic digestion for design flow of 19 ML/d using conventional treatment (scenario a) is 114 kW, with the net electrical power production estimated to range from 5 to 70 kW, depending on the extent to which waste heat is used to provide thermal energy for heating the digesters. In contrast, each of the scenarios for gasification produced greater than 109 kW (net power) for a 19 ML/d plant, which is more than double the power available from anaerobic digestion.

Recovering energy from WWTP solids is the objective of gasification, but the overarching goal of decentralized water reclamation is to develop sustainable systems, and this includes reducing the energy consumption and carbon footprint of wastewater treatment. Based on data provided by a Water Environment Research Foundation factsheet, the electrical energy requirement for a 19 ML/d (5 mgd) WWTP is approximately 1260 kWh per million gallons treated [31], and using this estimate of electrical power requirements, air-blown gasification can supply up to 50% of the power requirement for a 19 ML/d conventional WWTP. Published

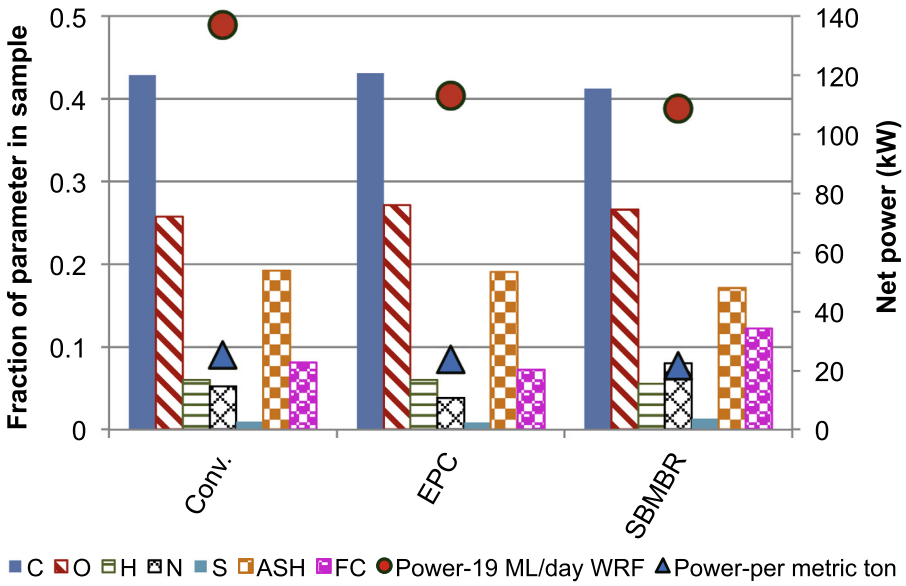

Fig. 3. Model simulation results of net power output for conventional, EPC, and SBMBR WRRFs operating at 19 ML/day (●) and the net power produced by one metric ton of dry solids per day from each WRRF (▲). The proximate and ultimate profiles for each scenario do not vary substantially from each other, and the power produced by gasification of one metric ton of dry solids per day does not vary substantially. The mass of solids generated by the SBMBR WRRF is substantially lower than the other scenarios and results in lower power production for gasification of solids produced by a plant flow of 19 ML/d.

literature notes that EPC could remove more solids and carbon than conventional primary treatment, reducing the aeration requirements for biological treatment [5,38]. Galil and Rebhun [40] found that EPC reduced biological treatment energy requirements by 23%. Thus, although solids from the EPC scenario (scenario b) produced 8% less net electrical power than conventional treatment, a savings of 23% in biological treatment energy requirements is likely to result in a net improvement in the energy footprint compared to a conventional wastewater treatment. In contrast, the SBMBR scenario produced 20% less power than the conventional treatment scheme, and does not provide reduced energy requirements compared to conventional treatment.

Conclusions

This research indicates that energy recovery using air-blown gasification is feasible for a wide variety of wastewater treatment processes. Wastewater solids were shown to have similar thermochemical characteristics regardless of the biological treatment system or plant flow capacity, demonstrating that gasification for energy recovery is feasible for many treatment schemes and merits further research. Although the inorganic content of solids is higher in wastewater solids than in traditional biomass feedstocks, the energy inherent in the solids supports energy recovery via gasification. However, the inorganic content of solids varies between facilities, and site-specific knowledge of the solids produced is needed for detailed design. The variability of ash content, both in the current study and in literature, requires specific knowledge of solids content and character.

The results from this study also show that, in contrast to anaerobic digestion, feedstock with higher content of primary solids does not ensure greater energy production by gasification. While the power produced by alternative treatment schemes such as EPC or SBMBR is lower than the power produced by conventional WWTP solids, the difference is not great enough to preclude considering these treatment schemes as candidates for successful energy recovery via gasification. When other considerations such as energy requirements for biological treatment, solids dewatering, and tertiary treatment are considered, EPC may prove to have a lower overall energy requirement.

Acronym List

Acronym	Full-form
AES	aerobically digested solids
ANS	anaerobically digested solids
APS	acid-phase solids (from anaerobic digester)
ASTM	American Society for Testing Methods
BOD_5	5-day biochemical oxygen demand
C	carbon
CHECRA	Colorado Higher Education Competitive Research Authority
DAF	dissolved air flotation solids
DDS	air-dried solids
dwb	dry weight basis
DWS	dewatered solids
EPC	enhanced primary clarification
FC	fixed carbon
FOG	fats, oils, & grease
FSS	fixed suspended solids
FS	fixed solids
GCS	grit chamber solids
HHV	high heat value
LHV	low heat value
mgd	million gallons per day
MJ/m3	mega joules per cubic meter
MJ/kg	mega joules per kilogram
ML/d	million liters per day
mtpd	metric ton per day
N	nitrogen
O	oxygen
PCS	primary clarifier solids
PTS	thickened primary solids

Acronym List (*continued*)

Acronym	Full-form
ReNUWIt	Reinventing the Nation's Urban Water Infrastructure
S	sulfur
SBMBR	sequencing batch membrane bioreactor
SC	supplemental content
SCS	secondary clarifier solids
SD	standard deviation
STS	stabilized solids
TCC	thermochemical conversion
TS	total solids
TSS	total suspended solids
US	United States
EPA	Environmental Protection Agency
VM	volatile matter
VS	volatile solids
VSS	volatile suspended solids
WAS	waste activated sludge
WRRF	wastewater resource recovery facility
WWTP	wastewater treatment plant

Acknowledgments

This project was supported by the National Science Foundation under Cooperative Agreement EEC-1028968 (ReNUWIt Engineering Research Center), and by the State of Colorado through the Higher Education Competitive Research Authority (CHECRA). The authors wish to express their gratitude to the wastewater facilities that allowed us access to their plants for sampling and information gathering, and to Greta Buschmann, of the Universität Duisburg-Essen, who assisted with sample collection and preparation.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.seta.2014.10.003.

References

[1] Averyt K, Meldrum J, Caldwell P, Sun G, McNulty S, Huber-Lee A, et al. Sectoral contributions to surface water stress in the coterminous United States. Environ Res Lett 2013;8.
[2] Nair S, George B, Malano HM, Arora M, Nawarathna B. Water–energy–greenhouse gas nexus of urban water systems: review of concepts, state-of-art and methods. Resour Conserv Recycl 2014;89:1–10.
[3] Vuono D, Henkel J, Benecke J, Cath TY, Reid T, Johnson L, et al. Flexible hybrid membrane treatment systems for tailored nutrient management: a new paradigm in urban wastewater treatment. J Membr Sci 2013;446:34–41.
[4] Foundation WER. Energy production and efficiency research – the roadmap to net-zero energy. In: Foundation WER. editor. Water Environment Research Foundation: Alexandria, VA, 2011. [Vol. ENER1fs].
[5] Tchobanoglous G, Burton FL, Stensel HD. Wastewater engineering treatment and reuse. 4th ed. McGraw-Hill Education: New York, NY; 2003.
[6] Water Environment Federation. Design of municipal wastewater treatment plants. In: Water Environment Federation, editor. Planning and configuration of wastewater treatment plants, vol. 1. New York: American Society of Engineers; 2010.
[7] McCarty PL, Bae J, Kim J. Domestic wastewater treatment as a net energy producer–can this be achieved? Environ Sci Technol 2011;45(17):7100–6.
[8] U.S. Environmental Protection Agency. Combined heat and power partnership, opportunities for and benefits of combined heat and power at wastewater treatment facilities. Eastern Research Group Inc., Energy and Environmental Analysis, Inc.; 2007. p. 48.
[9] Water Environment Federation. Design of municipal wastewater treatment plants. In: Water Environment Federation, editor. Solids processing and management, vol. 3. New York: American Society of Engineers; 2010.
[10] Hossain MK, Strezov V, Nelson PF. Thermal characterisation of the products of wastewater sludge pyrolysis. J Anal Appl Pyrol 2009;85(1–2):442–6.
[11] Bridle TR, Pritchard D. Energy and nutrient recovery from sewage sludge via pyrolysis. Water Sci Technol 2004;50(9):169–75.
[12] Fytili D, Zabaniotou A. Utilization of sewage sludge in EU application of old and new methods—a review. Renewable Sustainable Energy Rev 2008;12(1):116–40.
[13] Rulkens W. Sewage sludge as a biomass resource for the production of energy: overview and assessment of the various options. Energy Fuels 2007;22(1):9–15.
[14] Furness DT, Hoggett LA, Judd SJ. Thermochemical treatment of sewage sludge. Water Environ J 2000;14(1):57–65.
[15] Dogru M, Midilli A, Howarth CR. Gasification of sewage sludge using a throated downdraft gasifier and uncertainty analysis. Fuel Process Technol 2002;75(1):55–82.
[16] McKendry P. Energy production from biomass (part 3): gasification technologies. Bioresour Technol 2002;83(1):55–63.
[17] Midilli A, Dogru M, Akay G, Howarth CR. Hydrogen production from sewage sludge via a fixed bed gasifier product gas. Int J Hydrogen Energy 2002;27(10):1035–41.
[18] Swanson RM, Satrio JA, Brown RC, Platon A, Hsu DD. Techno-economic analysis of biofuels production based on gasification; NREL/TP-6A20-46587. Golden, CO: National Renewable Energy Laboratory; 2010.
[19] Manara P, Zabaniotou A. Towards sewage sludge based biofuels via thermochemical conversion – a review. Renewable Sustainable Energy Rev 2012;16(5):2566–82.
[20] Lumley NPG, Braun RJ, Cath TY, Prieto AL, Ramey DF, Porter JM. Techno-economic analysis of wastewater sludge gasification: a decentralized urban perspective. Bioresour Technol 2014;161:385–94.
[21] Boundy RG, Diegel SW, Wright L, Davis SC. Biomass energy data book ORNL/TM-2011/446. Oak Ridge, TN: Oak Ridge National Laboratory; 2011. p. 254.
[22] Tsai W-T. An analysis of the use of biosludge as an energy source and its environmental benefits in Taiwan. Energies 2012;5(8):3064–73.
[23] Thipkhunthod P, Meeyoo V, Rangsunvigit P, Kitiyanan B, Siemanond K, Rirksomboon T. Predicting the heating value of sewage sludges in Thailand from proximate and ultimate analyses. Fuel 2005;84(7–8):849–57.
[24] Francisca Gómez-Rico M, Font R, Fullana A, Martín-Gullón I. Thermogravimetric study of different sewage sludges and their relationship with the nitrogen content. J Anal Appl Pyrolysis 2005;74(1–2):421–8.
[25] U.S. Environmental Protection Agency. Process design manual for sludge treatment and disposal EPA 625/1-79-011. In: U.S. Environmental Protection Agency, editor. Center for environmental research information technology transfer. Washington, D.C.: National Service Center for Environmental Publications; 1979. p. 1152.
[26] W.E. Federation, N.B. Partnership. Charting the future of biosolids management: final report. Water Environment Federation, National Biosolids Partnership; 2011.
[27] National Research Council. Biosolids applied to land: advancing standards and practices Grant No. X-82862501. Washington, DC: National Academy Press; 2002.
[28] American Public Health Association (APHA), A.W.A., Water Pollution Control Federation. Standard methods for the examination of water and wastewater. 21st ed. Washington, DC: American Public Health Association; 2005.
[29] EPRI Municipal Water and Wastewater Program High-Rate Clarification for the Treatment of Wet Weather Flows tc-113574, Electrical Power Research Institute: Palo Alto, CA, 1999.
[30] Vaezi M, Passandideh-Fard M, Moghiman M, Charmchi M. On a methodology for selecting biomass materials for gasification purposes. Fuel Process Technol 2012;98:74–81.
[31] Water Environment Research Foundation, Energy production and efficiency research – the roadmap to net-zero energy. In: Water Environment Research Foundation, (Ed.), Water Environment Research Foundation: Alexandria, VA, 2011. [vol. ENER1fs].
[32] Jenkins BM, Baxter LL, Miles Jr TR, Miles TR. Combustion properties of biomass. Fuel Process Technol 1998;54(1–3):17–46.
[33] Lang M, Forste J, Goldstein N, Johnston T, Brandt R. National manual of good practice for biosolids. Water Environment Research Foundation, National Biosolids Partnership; 2005.
[34] Kim Y, Parker W. A technical and economic evaluation of the pyrolysis of sewage sludge for the production of bio-oil. Bioresour Technol 2008;99(5):1409–16.
[35] Domínguez A, Fernández Y, Fidalgo B, Pis JJ, Menéndez JA. Bio-syngas production with low concentrations of CO_2 and CH_4 from microwave-induced pyrolysis of wet and dried sewage sludge. Chemosphere 2008;70(3):397–403.
[36] Werle S, Wilk RK. A review of methods for the thermal utilization of sewage sludge: the Polish perspective. Renewable Energy 2010;35(9):1914–9.
[37] Kim Y-J, Kang H-O, Qureshi TI. Heating value characteristics of sewage sludge: a comparative study of different sludge types. J Chem Soc Pakistan 2005;27(2):124–9.
[38] Water Environment Federation. Design of municipal wastewater treatment plants. In: Water Environment Federation, editor. Liquid treatment processes, vol. 2. New York: American Society of Engineers; 2010.
[39] Pourmovahed A, Opperman T, Lemke B, Performance and efficiency of a biogas CHP system utilizing a stirling engine. European Association for the Development of Renewable Energies, Environment and Power Quality: Las Palmas de Gran Canaria (Spain), 2011.
[40] Galil N, Rebhun M. Primary chemical treatment minimizing dependence on bioprocess in small treatment plants. Water Sci Technol 1990;22(3–4):8.