Journal of Environmental Management 197 (2017) 673–680

Contents lists available at ScienceDirect

Journal of Environmental Management

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

Research article

Municipal wastewater sludge as a sustainable bioresource in the United States

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ARTICLE INFO

Article history:
Received 7 January 2017
Received in revised form
3 April 2017
Accepted 9 April 2017
Available online 20 April 2017

Keywords:
Bioenergy
Renewable energy
Waste to energy
Wet waste
Biosolids

ABSTRACT

Within the United States and Puerto Rico, publicly owned treatment works (POTWs) process 130.5 Gl/d (34.5 Bgal/d) of wastewater, producing sludge as a waste product. Emerging technologies offer novel waste-to-energy pathways through whole sludge conversion into biofuels. Assessing the feasibility, scalability and tradeoffs of various energy conversion pathways is difficult in the absence of highly spatially resolved estimates of sludge production. In this study, average wastewater solids concentrations and removal rates, and site specific daily average influent flow are used to estimate site specific annual sludge production on a dry weight basis for >15,000 POTWs. Current beneficial uses, regional production hotspots and feedstock aggregation potential are also assessed. Analyses indicate 1) POTWs capture 12.56 Tg/y (13.84 MT/y) of dry solids; 2) 50% are not beneficially utilized, and 3) POTWs can support seven regions that aggregate >910 Mg/d (1000 T/d) of sludge within a travel distance of 100 km.

1. Introduction

The U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE) Bioenergy Technology Office (BETO) is working to accelerate the adoption of technologies that convert wet and gaseous renewable biomass into high-performance biofuels compatible with today's transportation infrastructure. In support of this effort, the Pacific Northwest National Laboratory (PNNL) assessed whether municipal wastewater sludge merits further consideration as a wet waste feedstock for biofuels production.

Within the 50 United States, the District of Columbia, and Puerto Rico, publicly owned treatment works (POTWs) process 130.5 Gl/d (34.5 Bgal/d) of wastewater, generating millions of tons of sludge annually, which must be treated for disposal or beneficial reuse.

Many established pathways exist for handling, treating, disposing, and utilizing sludge waste (Oleszkiewicz and Mavinic, 2001). However, sludge management continues to present major environmental, technical, financial, and regulatory challenges for system owners. Emerging commercial technologies are providing an additional energy pathway through the whole conversion of wet wastewater sludge into a bio-crude oil that can be upgraded and fractionated to various liquid fuels, including diesel, kerosene and gasoline (Elliott et al., 2015; Vardon et al., 2011; WERF, 2016), thereby expanding waste-to-energy conversion options beyond generating heat and power (Fonts et al., 2012), while still recovering nutrients and sterilizing bioactive contaminants (Pham et al., 2013).

Diverting wet sludge waste from further treatment to produce biofuels could substantially reduce 1) non-beneficial sludge disposal at landfills and incinerators; 2) residual management costs, which account for 40–50% of total wastewater treatment costs (Gebreeyessus and Jenicek, 2016; Turovskiy and Mathai, 2006); 3) energy use, as 30% of the 30.2 BkWh/y of electricity consumed for wastewater treatment is used for biosolids processing (Pabi et al., 2013), and 4) greenhouse gas emissions, mostly from energy displacement, as biosolids treatment and disposal accounts for up to 40% of total wastewater treatment emissions (Brown et al., 2010).

The technical feasibility and relative environmental and economic tradeoffs of various sludge management and waste-to-energy opportunities are difficult to assess in the absence of highly spatially resolved estimates of total sludge production. Production estimates for treated biosolids are often used to represent the municipal sludge feedstock. However, from a waste-to-energy perspective, these are two distinct material streams. Sewage sludge describes the "solid, semi-solid, or liquid residue generated during the treatment of domestic sewage in a treatment

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http://dx.doi.org/10.1016/j.jenvman.2017.04.032
0301-4797/

works" (EPA, 1999b). Whereas, biosolids is an industry term that describes the material produced after sludge has been properly treated to meet U.S. Environmental Protection Agency (EPA) standards for beneficial use or disposal. Biosolids are therefore a reduced form derivative of raw sludge solids and do not represent the total bioresource.

Historical national estimates of municipal sludge and treated biosolids are presented in Table 1. The prevalence of biosolids estimates is attributed to historic emphasis on managing treated sludge as municipal solid waste, which requires an understanding of the quantity of residual material to be disposed rather than the amount of sludge initially produced. The emergence of novel waste-to-energy pathways is shifting the focus from managing treated biosolids for disposal or reuse to evaluating the parent sludge material as a wet bioresource (McCarty et al., 2011; Peccia and Westerhoff, 2015).

The 1992 Regulatory Impact Analysis (RIA) of the then proposed Part 503 regulation was the last time the entire sludge feedstock inventory was reviewed. The RIA analysis was based on data from 1988, and does not reflect the pattern, scale, or practices of modern wastewater treatment. None of the previous works evaluate the spatial distribution and availability of sludge as sustainable bioresource.

Although there are no contemporary estimates of annual sludge production, modeled estimates can be compared to engineering factors based on average solids density in wastewater. Turovskiy and Mathai (2006) reported solids production rates ranging from 0.2 to 0.3 kg/m^3 (0.8–1.2 T/Mgal) of treated wastewater with an average rate of 0.24 kg/m^3 (1 T/Mgal).

The quantity of sludge produced during treatment is dependent upon the composition and volume of incoming wastewater, the type of treatment processes used, and generally increases with increased levels of treatment (Lee et al., 2014). The quantity of wastewater, and therefore sludge production and management challenges are expected to rise with increases in population, regulation, wastewater treatment coverage and treatment effectiveness. According to the EPA Clean Watersheds Needs Surveys (CWNS), the total number of residential customers served by wastewater treatment could increase by 17.8%–292 M people, if all identified wastewater infrastructure needs are implemented in the next 20 years (EPA, 2016a).

The objectives of this study are to 1) estimate site specific annual sludge production in total and by treatment phase for POTWs in the U.S.; 2) provide updated insights regarding national sludge resources for waste managers, policy makers, regional planners, and modelers; and 3) connect ongoing dialogue in the fields of wastewater treatment, renewable energy, resource recovery, and water quality regarding sustainable pathways for managing municipal wastewater sludge.

2. Materials and methods

To achieve the objectives of this study, a simplified assessment model with conservative parameterization using generally accepted literature values is used to estimate primary, secondary, and total annual sludge production on a dry weight basis at facility, state, and national scales. Sludge requirements for major current beneficial uses are estimated to provide insight into feedstock availability. Finally, regional sludge production hotspots and candidate centralized feedstock aggregation locations are identified to help focus future assessments of biofuels production potential and feedstock blending.

2.1. Facility inventory

An inventory of 15,014 POTWs was developed by synthesizing facility data catalogued in the EPA 2008 and 2012 CWNS (EPA, 2010, 2016a) and the EPA Integrated Compliance Information System National Pollutant Discharge Elimination System (ICIS NDPES) (EPA, 2016b). The composite dataset includes facilities from all 50 states, the District of Columbia, and Puerto Rico. Influent flow values are assumed to represent average flow exclusive of any combined sewer overflow (CSO) discharges, which are estimated to generate 3.22 Tl/y (850 Bgal/y) of untreated storm and wastewater (EPA, 2004).

A total of 14,354 POTWs were selected from the CWNS 2012 database, which had an existing influent flow value greater than zero and a "resident population actually receiving treatment" greater than zero. The latter constraint helps to avoid double counting influent flow from facilities that are passing collected water onto downstream facilities for treatment.

The state of South Carolina (SC) did not participate in the 2012 CWNS survey. Therefore, data for 175 facilities in SC were extracted from the 2008 CWNS dataset using similar criteria, except for the constraint on "resident population actually receiving treatment", which could not be applied because the attribute was not included.

The CWNS is a voluntary survey and not all states or facilities participate. The ICIS NPDES database was used to represent additional POTWs with a daily average flow ≤3.8 Ml/d (1.0 Mgal/d) and a permit status of "effective, administratively continued, pending, or none required". ICIS NDPES records were cross referenced with CWNS by NPDES permit number, city, and facility name to remove any duplicate facilities. Several ICIS facilities were also removed due to apparent misclassification as POTWs. A total of 485 POTWs were added from ICIS NPDES. Due to concern regarding the data quality of the design and actual flow attributes included in ICIS NDPES, these attribute values were replaced, to the extent possible, with average daily influent flow values reported either in the Water Environment Federation (WEF) Biogas Data (WEF, 2015) or information gathered from facility websites.

Procedures were also developed to ensure acceptable spatial accuracy of POTW locations that balanced attention given to the largest facilities and facilities with most egregious spatial errors. Errors included missing coordinates, transcription, reversed coordinates, reversed signs (e.g. negative latitude), and truncation, as well as more difficult problems such as erroneous coordinates, mixed coordinate systems, outfall or administrative building coordinates being assigned to treatment facilities, duplicate

Table 1
Historic estimates of wastewater sludge and biosolids production in the U.S.

Source	Tg/y (MT/y)	Material	Description
(NEBRA, 2007)	6.51 (7.18)	Biosolids	Used or disposed in 2004
(EPA, 1999a)	6.90 (7.61)	Biosolids	Used or disposed in 1998
(Bastian, 1997)	6.22 (6.86)	Biosolids	Used or disposed in 1997
(EPA, 1992)	7.05 (7.77)	Sludge	Generated in 1988
(EPA, 1992)	5.36 (5.91)	Biosolids	Used or disposed in 1988
(EPA, 1988)	4.56 (5.03)	Biosolids	Used or disposed in 1988, (secondary)