Journal of Environmental Management 165 (2016) 22–30

Contents lists available at ScienceDirect

Journal of Environmental Management

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

Research article

Energy and carbon footprints of sewage treatment methods

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ARTICLE INFO

Article history:
Received 3 April 2015
Received in revised form
4 September 2015
Accepted 12 September 2015
Available online 23 September 2015

Keywords:
Sewage treatment technologies
Energy consumption
Carbon emissions
Large-scale municipal STPs
Small-scale institutional STPs

ABSTRACT

The paper presents energy and carbon footprints of sewage treatment plants (STPs) operating at different scales and using different technology options based on primary data from 50 STPs operating in India and the UK. The study used a combination of fundamental mass-balance approach for energy consumption and the methodology defined by IPCC for the carbon emissions. Small-scale institutional STPs consume twelve times the energy consumed by large-scale municipal STPs, the corresponding energy intensities being 4.87 kWh/m^3 and 0.40 kWh/m^3 respectively. Embodied energy from construction material and chemicals accounted for 46% and 33% of the total energy intensity of the municipal and institutional STPs respectively. The average carbon footprint of large-scale STPs is 0.78 kgCO$_2$eq/m^3 and for small-scale STPs it is 3.04 kgCO$_2$eq/m^3. However, fugitive emissions from large-scale STPs constituted 74% of the total carbon emissions whereas the figure was only 0.05% for small-scale STPs. Average electrical energy intensity in STPs in India is much lower (0.14 kWh/m^3) than that in the UK (0.46 kWh/m^3). This is due to the reason that STPs in India do not have resource recovery processes and use solar heat for sludge drying. The paper offers information and insights for designing low carbon strategies for urban waste infrastructure.

1. Introduction

Sewage treatment is likely to be one of the major urban infrastructure projects in most of the developing countries in the coming decades for several reasons, namely rapid urbanization (Poumanyvong and Kaneko, 2010), sanitation facilities for the growing population, and large volumes of untreated sewage (UNICEF/WHO, 2012). The efforts of national governments to fulfil the Millennium Development Goals and the growing incidence of health problems related to polluted water will bring to public attention the matter of infrastructure for sewage treatment (Cuppens et al., 2013). Many technologies have been developed for sewage treatment to cater to different requirements ranging from safe environmental disposal standards to recycling and reuse. Sewage treatment requires energy, the magnitude of which varies with the treatment system and several other factors. Most of the studies related to the water-energy-carbon nexus have been carried out in developed countries (Table 1).

The studies reported in Table 1 mainly considered electrical energy. Other than electricity, the energy embodied in the chemicals used for the treatment can claim up to 14% share in the total energy consumption (Pan et al., 2011). Energy consumption

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Abbreviations: AF, Anaerobic fermentation; ASP, Activated Sludge Process; AD, Anaerobic digester; AC, Activated carbon; BT, Biological treatment; BS, Bar screen; BFP, Belt filter press; BOD, Biological oxygen demand; CF, Clariflocculation; CAACO, Chemo-autotrophic activated carbon oxidation; CL, Chlorination; Cf, Centrifuge; CO$_2$, Carbon emission; CH$_4$, Methane emission; DAF, Dissolved air flotation; ET, Equalization tank; EA, Extended aeration; E$_n$, Net energy; E$_l$, Electrical energy; E$_d$, Diesel energy; E$_B$, Biogas energy; E$_{mt}$, Embodied energy of construction material; E$_{ch}$, Embodied energy of chemicals; FST, Final settling tank; FM, Flash mixer; FBR, Fluidized bed reactor; FM, Flash mixer; G$_e$, Carbon emission from use of electricity; G$_d$, Carbon emission from use of diesel; G$_{fugitive}$, Carbon emission due to fugitive gases; G$_{biogas}$, Carbon emission due to biogas flaring; G$_{mt}$, Emissions embodied in construction materials; G$_{ch}$, Emissions embodied in chemicals; GC, Grit chamber; I1 to I8, Small-scale institutional sewage treatment options; LCA, Life cycle analysis; M1 to M6, Large-scale municipal sewage treatment options; MGF, Multi grade filter; MLD, Million litres per day; MB, Membrane bioreactor; N$_2$O, Nitrous Oxide emission; NT, Not-for-treatment; OD, Oxidation ditch; OT, Ozonation tank; PT, Primary treatment; PST, Primary settling tank; RCC, Reinforced cement concrete; RBC, Rotating biological contractor; SC, Screen chamber; STP, Sewage treatment plant; SAGBR, Submerged attached-growth biological reactor; ST, Secondary treatment; Sld. H, Sludge treatment; SF, Sand filter; SDB, Sludge-drying beds; TT, Tertiary treatment; TSD, Treated sewage disposal; TF, Trickling filter; UASB, Up-flow anaerobic sludge blanket; WSP, Waste stabilization pond.

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http://dx.doi.org/10.1016/j.jenvman.2015.09.017

Table 1
Energy and carbon footprints of various processes used in sewage treatment plants.

Process	Energy use kWh/m^3	Emission kgCO$_2$e/m^3	Source	Country
Pumping raw sewage	0.048	–	Venkatesh and Brattebø 2011	Norway
	0.14	0.15	Friedrich et al., 2009	South Africa
	0.04	0.19	Plappally and Lienhard 2012	(Analysis of different countries)
Treatment of sewage	0.19–0.86	–	Gilbert et al., 1986	USA
	–	0.03–0.17	Gori et al., 2011	USA
	0.48–1.6	–	Hernández-Sancho et al., 2011	Spain
	–	0.54–0.61	Flores-Alsina et al., 2011	USA
	1.108	2.1	Fine and Hadas 2012	Israel
	1.69	0.47	Stokes and Horvath 2010	USA
	–	0.112	Friedrich et al., 2009	South Africa
	0.2–0.3	–	Yerushalmi et al., 2009	Canada
	0.18–0.78	–	Stillwell et al., 2010	USA
	0.28–0.89	–	Lorenzo-Toja et al., 2015	Spain
	–	2.0	Cornejo et al., 2013	USA
Handling sludge		0.23–0.25	Flores-Alsina et al., 2011	USA
	0.034–0.94		Houillon and Jolliet 2005	France
	0.4	0.34	Fine and Hadas 2012	Israel
Recycling of treated sewage	–	0.191–0.27	Flores-Alsina et al., 2011	USA
			Muñoz et al., 2008	Spain

estimates varies widely because of the differences in the system boundary, treatment technology, estimation method, scale of the process, and the extent of treatment required. Fig. 1 shows the variation in electrical energy used within and across different methods of sewage treatment such as trickling filter (TF), lagoon, oxidation ditch (OD), membrane bioreactor (MB), activated sludge process (ASP), extended aeration (EA), rotating biological contractor (RBC), and waste stabilization pond (WSP). The variation within a given technology varies by a factor of about 10 for ASP, OD, and MB.

Similarly, the methods of estimating energy and carbon footprints vary from simple spread sheet-based models (Préndez and Lara-González, 2008) to life cycle analysis (LCA) (El-Sayed Mohamed Mahgoub et al., 2010; Foley et al., 2010; Friedrich et al., 2009; Gallego et al., 2008; Lim et al., 2008; Meneses et al., 2010; Pan et al., 2011; Pasqualino et al., 2011; Zhang et al., 2010). Commonly used LCA-based methods for water-related infrastructure are *CML 2000* (Pasqualino et al., 2011), *Eco-Indicator 99 assessment model* (Mohamed et al., 2010), *96 and 97 Environmental design of industrial products* (EDIP 96 and 97) (Muñoz et al., 2008), *Environmental priority strategy in product design* (EPS), and *Eco-points 97* (Renou et al., 2008). In addition, depending on the objectives (such as energy efficiency, environmental impacts, cost effectiveness, and choice of technology), some studies have estimated the energy and carbon footprints of only a small part of a treatment system (Bani Shahabadi et al., 2010; Keller and Hartley, 2003; Yerushalmi et al., 2009). Therefore, choice of the method for analysis depends on the objectives and the boundary conditions for system analysis. LCA methods are mostly used for a wider system boundary conditions and it consider the long-term impacts of energy use and carbon emissions. Amongst various LCA approaches, process-based LCA approach is very similar to spread sheet-based models where system boundary for analysis is narrow and it uses time and site specific data.

IPCC Tier 3 described a method to estimate carbon emissions from water-related infrastructure (Gupta and Singh, 2012; Préndez and Lara-González, 2008), which considers emissions only during the operating phase and includes direct carbon emissions from the biochemical process and indirect emissions from electricity consumption. A few years later, the United States Environmental Protection Agency improved on this method by incorporating specific values for methane recycling (USEPA, 1997). Recently, the International Water Association *Benchmark Simulation Model No. 2* (Flores-Alsina et al., 2011) has been used for assessing changes in carbon emissions due to changes in parameters that influence *effluent quality index*, *operational cost index*, or the *time in violation* in

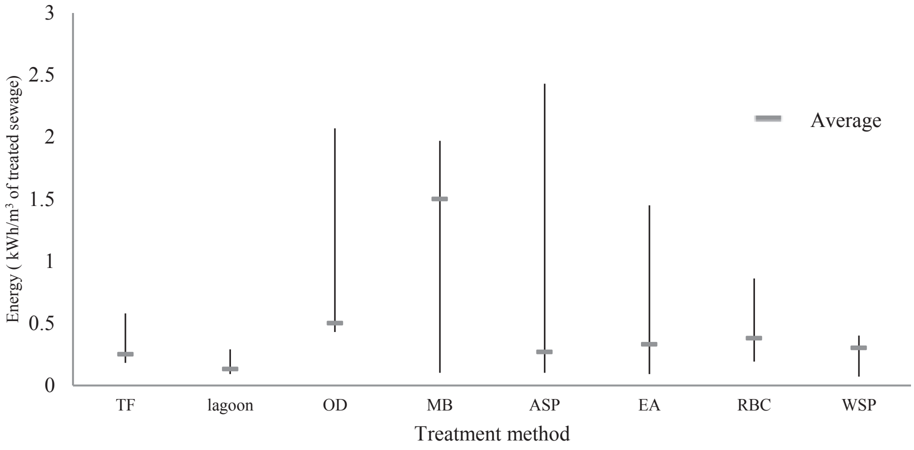

Fig. 1. Electrical energy use of various biological sewage treatment methods (Gilbert et al., 1986; EPRI, 2002; Plappally and Lienhard, 2012; Stillwell et al., 2010; Siddiqi and Anadon, 2011; Molinos-Senante et al., 2013).