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COMPARATIVE CARBON FOOTPRINT STUDY FOR ALTERNATIVE WASTEWATER TREATMENT TECHNOLOGIES

Debashis Raha and P. C. Mishra

C arbon Footprint

Wastewater

Water Treatment

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DEBASHIS RAHA* AND P. C. MISHRA
Department of Environmental Science, Sambalpur University,
Jyoti Vihar, INDIA
E mail: debashis_raha@yahoo.com.au

ABSTRACT

Water is both life and livelihood and is vital to economy, development, society and natural environment. Water is the principal medium through which climate change will affect economic, social and environmental conditions. Access to water and sanitation is a human right under the UN Charter. Currently 884 million people lack access to safe drinking water and more than 2.6 billion people do not have access to basic sanitation in developing countries. Wastewater without treatment is causing one-tenth of the global burden of disease. As a consequence, treatment of wastewater and recycling and reuse of effluent from wastewater treatment plant (WWTP) is becoming a priority that will provide both sanitation and reduce pressures on limited and increasingly scarce fresh water resources. However, wastewater treatment consumes significant amount of energy and emits greenhouse gases (GHG). It demands for wastewater treatment with lowest energy intensity and greenhouse gas (GHG) emission and ecological footprint. This study investigates energy- intensity and carbon footprint of alternative wastewater treatment (WWT) processes applying Australian National Greenhouse and Energy Reporting (NGER) framework. This will help water utilities in selecting appropriate WWT technologies that have minimum energy intensity and carbon footprint, as part of their climate change mitigation and adaptation program. This study shows that energy intensity (GJ/ ML), carbon footprint (kg CO_2-e/ ML) and carbon cost (US$/ML) for each mega litre (ML) wastewater treated, increase from primary to conventional activated sludge (CAS) to sequential batch reactor (SBR) to intermittently decanted aerated lagoon (IDAL) biological nutrient removal (BNR) treatment technologies. Carbon cost for primary treatment US$7.3/ ML, CAS of US$13.6/ ML, SBR of US$22.8/ML and IDAL BNR of US$27.3/ ML. Grid electricity and fugitive nitrous oxide emission contribute between 59% to 94% of total GHG emissions for WWTPs.

*Corresponding author

INTRODUCTION

Anthropogenic emission of greenhouse gases has caused to increase earth's surface and ocean temperature and climatic change (IPCC, 2007; CSIRO, 2007). The main impacts of climate change on humans and the environment is likely to occur through water (UNESCO, 2009). Currently 884 million people lack access to safe drinking water and more than 2.6 billion people do not have access to basic sanitation (UNGA, 2010). One-tenth of the global burden of disease can be attributed to water, sanitation, hygiene and environmental factors (UNESCO, 2009).

Pressure on freshwater supplies is increasing dramatically worldwide (UNESCO, 2009). United Nations (UN) General Assembly (GA) by majority votes of members has declared access to water and sanitation is a human right on 28 July 2010 (UNGA, 2010). As a consequence, treatment of wastewater and recycling and reuse of effluent from WWTP is becoming a priority that will provide both sanitation and reduce pressures on limited and increasingly scarce freshwater resources (NRMMCEPH Australia, 2006). As wastewater treatment processes involves significant quantity of energy consumption and GHG emissions, therefore selecting low energy and GHG emission- intensive wastewater technology, is an important step in climate change mitigation, adaptation and water security strategies for water utilities.

The first step in reducing carbon footprint (CFP) for a wastewater utility is to measure, monitor and evaluate energy and GHG intensity of alternative WWT technologies. This paper endeavors to study this topic.

Waste water treatment technologies

A variety of treatment technologies are applied in municipal wastewater treatment, ranging from primary treatment to conventional biological activated sludge (CAS), sequential batch reactor (SBR) to intermittently decanted aerated lagoon (IDAL) advanced tertiary biological nutrient removal (BNR) process. Selection of treatment process technology depends upon, among other things, on the daily flow, diurnal inflow pattern and composition of wastewater, wastewater networks and treatment plant's infrastructure, operations and maintenance costs; effluent end uses (for residential, commercial, industrial and irrigation), receiving environment of effluent and exposure routes and economics and social costs and benefits. Effluent recycling, energy conservation and demand management and fugitive GHG emissions reduction from WWTP are becoming key mitigation and adaptation strategies for water security world- wide in the face of global warming and climate change. In this research, primary, CAS, SBR and IDAL BNR WWTPs' energy and carbon footprint (CFP) is studied.

Dunlop primary WWTP

Dunlop WWTP is a primary wastewater treatment plant that serves an urban residential population of 164,000 and discharges effluent to ocean. It generates biogas in anaerobic digesters that is used to cater a significant portion of its energy demand. A simplified process flow diagram (PFD) for Dunlop WWTP is given in Fig. 1.

Meadow CAS WWTP

Meadow WWTP is a CAS plant that serves a residential semi- urban population of 45,400 and discharges treated effluent to ocean. It generates biogas in anaerobic digesters that is used to cater a portion of its energy demand. A simplified PFD for Meadow WWTP is given in Fig. 2.

Centennial SBR WWTP

Centennial WWTP is a SBR biological treatment plant that serves a country town's residential population of 13,700 and discharges effluent to ocean. Biological sludge generated in the plant is anaerobically digested in a lagoon system that emits uncontrolled methane (GHG), causing its CFP to increase significantly. A simplified PFD for Centennial WWTP is given in Fig. 3.

Jubilee BNR WWTP

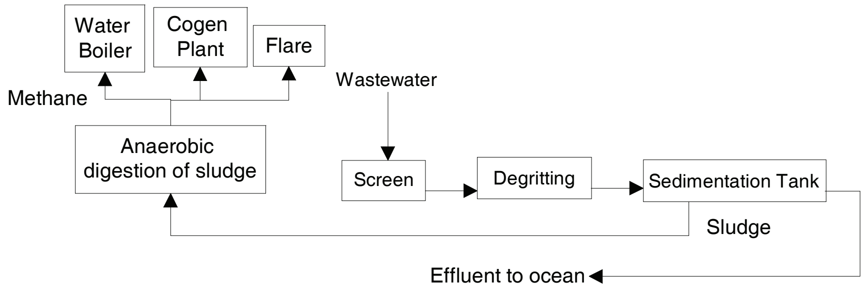

Figure 1: Dunlop WWTP process flow diagram

Jubilee WWTP is an IDAL BNR plant that serves a rural residential population of 40.400. Its effluent is beneficially reused in agriculture and remaining excess is discharged to inland river. It generates biogas in anaerobic digesters that is used to cater a portion of its energy demand. A simplified PFD for Jubilee WWTP is given in Fig. 4.

Carbon footprint accounting (CFA)

Scope of CFA

In this study Scope 1 and 2 CFA are included. Scope 1 GHG emission means emissions from fuel combusted, energy generated and used at WWTP facility sites. Scope 2 GHG emission means energy produced by other corporation outside WWTP facility sites and used by WWTPs e.g. grid electricity.

For WWTPs, 'production of energy' (Scope 1) normally means generation of renewable energy (gigajoule, GJ) from biogas cogeneration plants, water boiler, hydro- electric plants, wind turbine and solar panel and non- renewable energy from diesel generator (back- up electricity).

For water utilities, 'consumption of energy' normally means use or disposal of energy for operation of the facility (e.g. grid electricity), transport fleet, on- site renewable energy source (biogas cogeneration, hydro electricity, solar panel and wind turbine) and losses in extraction, production and transmission.

Exemption from CFA for WWTPs

In this study, following the Commonwealth of Australia NGER legislation, the following WWT activities are exempted from CFA:

1. large infrastructure project contractors for WWTPs that are independent corporations and hold full operational control including environmental, health and safety policies for projects at WWTP'sites.
2. Transporters, handler and processor for by- products for WWTPs, such as grit, screenings and sewer miners that are independent private corporation.
3. Scope 3 GHG emissions that are generated in the wider economy as a consequence of WWTP facility's activities but that are physically produced by another facility, such as processing of biosolids (composting).

Methodology and legislative framework for CFA study

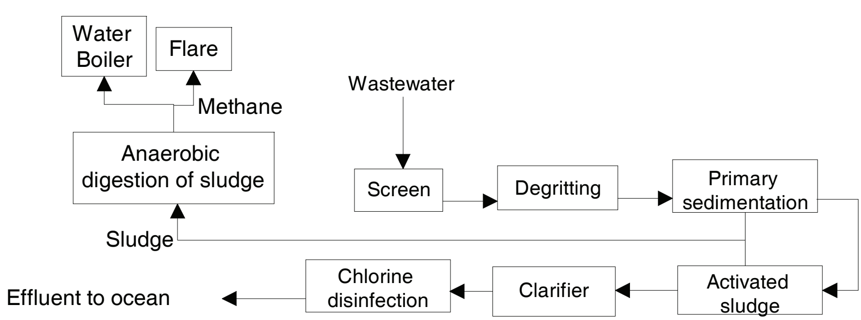

Figure 2: Meadow WWTP process flow diagram

In Australia, the National Greenhouse and Energy Reporting Act 2007 (NGER Act, 2007), NGER Regulation 2008 (NGER Regulation, 2008) and NGER (Measurement) Determination (MD) 2009 (NGER MD, 2009) provide the legal framework, technical guidelines and governance requirements for CFA. These legislation, regulation, protocols and technical guidelines are applied for CFA study for WWTPs in this paper.

Carbon footprint report (CFR) preparation steps

To describe in simple terms, compilation of CFR is a six- step process as explained in Table 1.

Energy consumption and greenhouse emission estimation for CFR

WWTPs in this study consume grid electricity, gaseous fuel (natural gas), liquid fuel (gasoline, diesel, LPG and ethanol). Energy content factor, GHG emission factor and the formula used to compile GHG inventory (Tier 1 and 2) for WWTPs is summarized in Table 2.

CFA research and ananlysis for WWTPs

For the reporting year, grid electricity (scope 2) and fuel (diesel, gasoline, LPG, natural gas, E10 and sludge biogas) consumption (scope1) and production of sludge biogas and electricity (cogeneration plant) is provided in Table 3. Emission of greenhouse gases in carbon dioxide equivalent (CO_2-e) resulting from fuel and electricity consumption, and fugitive methane and nitrous oxide from wastewater treatment, are also provided in Table 3.

Energy consumption in wastewater treatment

WWTPs use grid electricity and internally generated biogas to meet majority of its energy demands. It uses small amount of diesel, gasoline, LPG, natural gas and E10 fuel for stationary engines (e.g. back- up generator, water boiler) and transport (e.g. fleet, forklift, backhoe). In this study, it has been demonstrated that the energy intensity of wastewater treatment process depends upon:

1. Level of technology: Dunlop WWTP with primary treatment has lowest energy intensity and IDAL Jubilee BNR WWTP has the highest intensity. CAS Meadow WWTP and SBR Centennial WWTP's energy intensity lie in between (Fig. 5).
2. Economies of scale: Higher daily inflow to a WWTP such as Dunlop WWTP, helps to achieve economies of scale in energy efficiency (Fig. 5) and the opposite is true with Centennial WWTP.

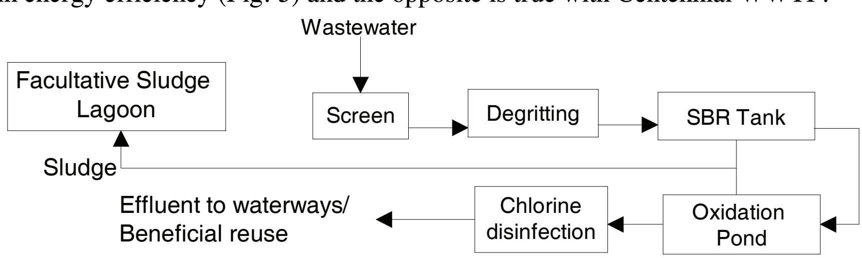

Figure 3: Fairy WWTP process flow diagram

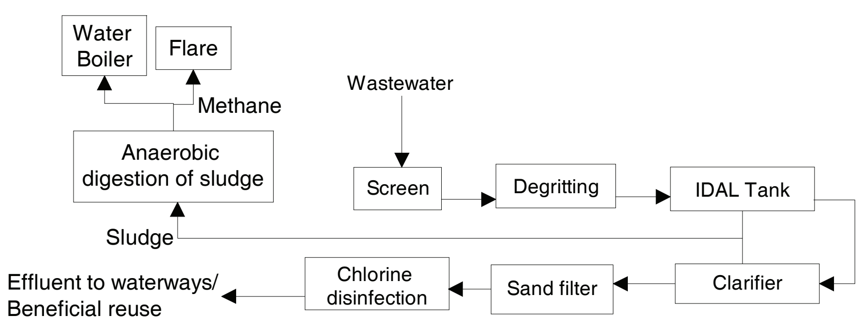

Figure 4: Jubilee WWTP process flow diagram

Table 1: Process steps in preparing CFR

Step	Task	Explanation
1	Identifying key GHG sources	To focus effort, resources and priority for GHG sources that contributes most to the overall inventory or inventory uncertainty. 1. Scope 2 grid electricity consumed 2. Scope 1 Fuel e.g. diesel, gasoline, E10, natural gas, LPG, biogas consumed; and fugitive methane and nitrous oxide emission
2	Determining appropriate GHG inventory estimation methodology	Estimation methodology depends upon whether the source is 'key' or 'not key' and by data and resources available. Tier 1 is the basic method. Tier 2 intermediate and Tier 3 most demanding in terms of complexity and data requirements. They are more accurate.
3	Data collection activities or Measurement and Monitoring (MandM) Program	Focus on the collection of data needed to improve estimates of key GHG · establish and maintain good verification, documentation and checking procedures (QA/QC) to minimize errors· Develop comprehensive Annual Energy and GHG MandM program
4	GHG emission estimation	Emissions are estimated for GHG sources in Step 1 applying methodology chosen in Step 2
5	Estimation uncertainty and key GHG sources	Estimates of uncertainty are needed for all relevant source and sink categories, greenhouse gases, inventory totals and their trends.
6	Report inventory	Present the inventory in an as concise and clear way as possible to enable users to understand the data, methods and assumptions used in the inventory.

Table 2: CFR formulas and important parameters (NGER MD, 2008)

Energy/ Fuel consumed	Energy content factor	Emission factor (Scope 1and 2), EF_i ($CO_2+CH_4+N_2O$), Kg CO_2e/ GJ	GHG emission calculation formula
Gaseous fuels (i)			
Natural gas (pipeline) for stationary engine	39.3 X 10-3 GJ/m³	51.33	$$Eij = \frac{Q_i \text{ x } EC_i \text{ x } EF_{ijoxec}}{1000}$$
Natural gas (light duty transport)	39.3 X 10-3 GJ/m³	57.0	
Natural gas (heavy duty transport)	39.3 X 10-3 GJ/m³	53.6	E_{ij} is the GHG emission in CO_2 -e ton type from each gaseous fuel type (*i*) in CO_2 -e ton Q_i is the quantity of fuel type (*i*) combusted standard cubic metre, m³ or gigajoules. EC_i is the energy content factor (gigajoules per standard cubic metre) of fuel type
	(*i*)EF_{ijoxec} is the GHG emission factor		
(kilograms CO_2e per gigajoule)			
Liquid fuels			
Gasoline (stationary engine)	34.2 GJ/ kL	67.10	$$Eij = \frac{Q_i \text{ x } EC_i \text{ x } EF_{ijoxec}}{1000}$$
Gasoline (transport)	34.2 GJ/kl	66.92	
Diesel oil (stationary engine)	38.6 GJ/kl	69.50	E_{ij} is the GHG emission in CO_2 -e ton type from each liquid fuel type (*i*) in CO_2 -e ton
Diesel oil (transport)	38.6 GJ/ kL	69.81	
Liquefied petroleum gas (stationary engine)	25.7 GJ/ kL	59.9	Q_i is the quantity (kilolitres, kL/ yr) of fuel type (*i*) combusted
Liquefied petroleum gas (transport)	26.2 GJ/ kL	60.2	EC_i is the energy content factor (gigajoules per kilolitre) of fuel type
Biodiesel (stationary engine)	34.6 GJ/ kL	0.26	(*i*)EF_{ij} is the GHG emission factor (kilograms CO_2 e per gigajoule)
Biodiesel (transport)	34.6 GJ/ kL	3.4	
Ethanol (stationary engine)	23.4 GJ/ kL	0.26	
Ethanol (transport)	23.4	3.4	

Coun….Table 2: CFR formulas and important parameters (NGER MD, 2008)

Energy/ Fuel consumed	Energy content factor	Emission factor (Scope 1and 2), EF_i $(CO_2+CH_4+N_2O)$, Kg CO_2e/ GJ	GHG emission calculation formula
Grid electricity		089kg CO_2e/kWh	Y = QXEF/100 Q = quantity of electricity purchased from the electricity grid during the year (kilowatt haur). EF - Scope 2 emission factor (kilogram CO_2e emissions per kilowatt hour) = 0.89 kg CO_2e/ kwh in NSW
Fugitive methane emission from wastewater treatment	CH_{4gen} = [$(COD_w$ - COD_{sl} - $COD_{eff})$X F_{wan} X EF_{wij}] + [$(COD_{sl}$ - COD_{trl} - $COD_{tro})$ X F_{slan} X EF_{slij}] where COD_w = COD of raw wastewater, ton; COD_e = COD of effuent, ton; COD_{sl} = COD of sludge, ton; COD_{trl} = COD of sludge transferred to landfill, ton; COD_{tro} = DOD of sludge transferred to other site, ton; F_{slan} is the fraction of COD in sludge anaerobically treated by the plant during the year; EF_{slij} is the default methane emission factor for sludge COD		
Fugitive nitrous oxide emission from wastewater treatment	= $(N_{in}$ - $N_{BOut})$ x 4.9 where N_{in} = Ton of total nitrogen in wastewater entering the WWTP; N_{BOut} = Ton of total nitrogen in biosolids sludge leaving the WWTP		

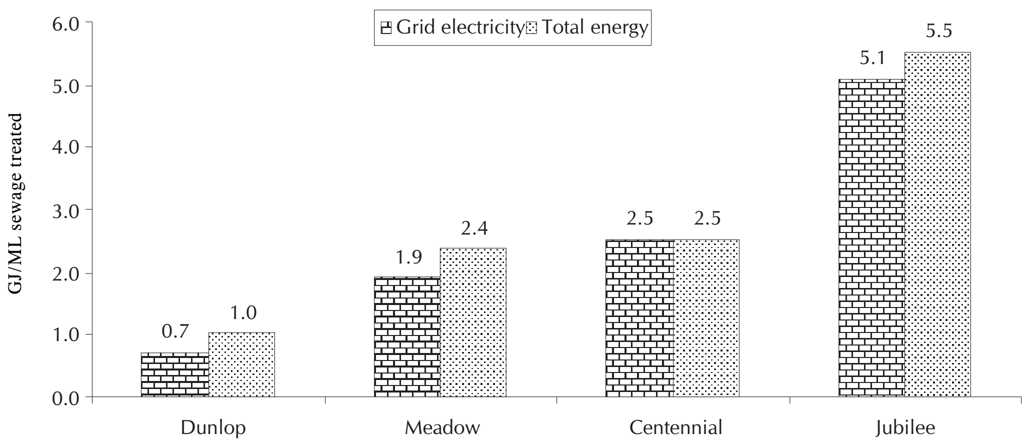

Figure 5: Energy intensity (including grid electricity) for wastewater treatment

3. Biogas generation potential of WWTPs with anaerobic digester (e.g. Dunlop, Meadow and Jubilee) and particularly for primary WWTP (Dunlop) assisted in meeting a portion of the energy demand of wastewater treatment (Fig. 6).

4. Advanced tertiary IDAL BNR WWTP such as Jubilee, consumes five times and secondary biological ASP (Meadow) and SBR (Centennial) two- and- half time more energy (GJ/ ML) than a primary WWTP (Dunlop) (Fig. 5).

5. For WWTPs with lagoon such as Centennial WWTP, 100% of its energy demand is met by grid electricity (Fig. 6). On the other hand, for primary Dunlop WWTP, 31% of its energy demand is met by internally produced biogas in anaerobic digester.

6. ASP Meadow WWTP generates more biogas per ML of wastewater treated, compared to tertiary advanced Jubilee WWTP (Fig. 6). This is due to the raw sludge from primary sedimentation process at Meadow WWTP produces more biogas per tonne of COD, compared to microbiological sludge from ASP and IDAL processes at Jubilee and Meadow WWTPs.

Greenhouse gas (GHG) emission from wastewater treatment

In WWTPs, GHG are emitted indirectly from consumption of significant amount of coal- based grid electricity (Scope 2) and directly from combustion of fuels (e.g. diesel, gasoline and biogas) for stationary and transport energy purposes, fugitive methane emission from anaerobic sludge treatment and fugitive nitrous oxide emission from wastewater treatment and effluent disposal into environment.

This study shows that GHG emission from WWT can vary from 430 kg CO_2-e/ ML for primary treatment (Dunlop WWTP) to 1603 kg CO_2-e/ ML for advanced tertiary IDAL BNR treatment (Jubilee WWTP). Secondary biological ASP Meadow and SBR Centennial WWTP lies between them. Considering a price of carbon of US$ 17 per tonne CO_2-e as per the latest US Environmental Protection Agency (USEPA)'s economic analysis of Kerry-Lieberman Climate and Energy Bill (USEPA, 2010), carbon pollution cost per ML of sewage treated ranges from US $7 for primary Dunlop WWTP to US $ 27 for IDAL BNR Jubilee WWTP (Fig. 7). Analysis shows that grid electricity is the major contributor to GHG emission for biological WWTPs (e.g. Meadow, Centennial and Jubilee WWTP) followed by fugitive nitrous oxide and methane emission respectively (Fig. 8). However, fugitive methane emission from Centennial SBR WWTP's sludge lagoon is very significant.

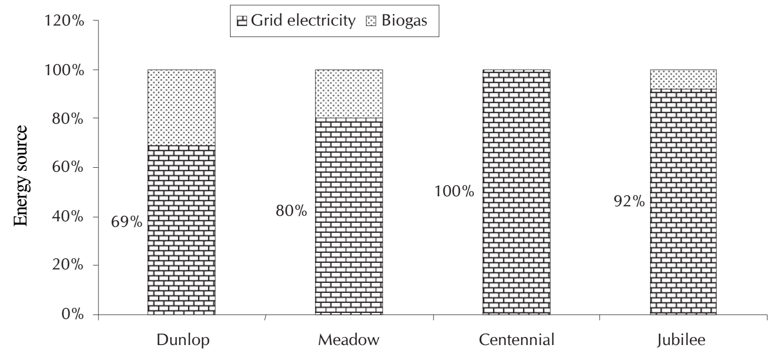

Figure 6: Sources of energy for wastewater treatment

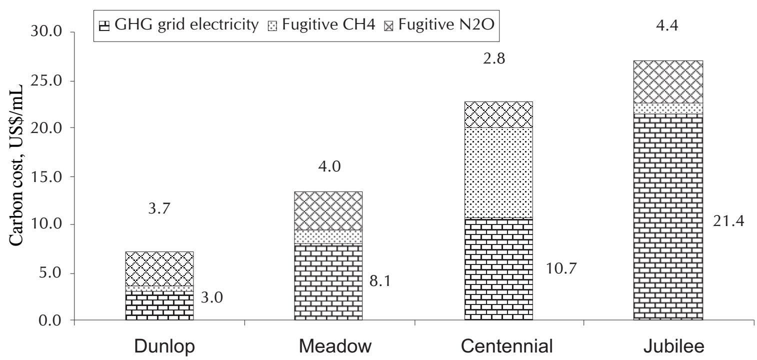

Figure 7: Carbon cost for wastewater treatment

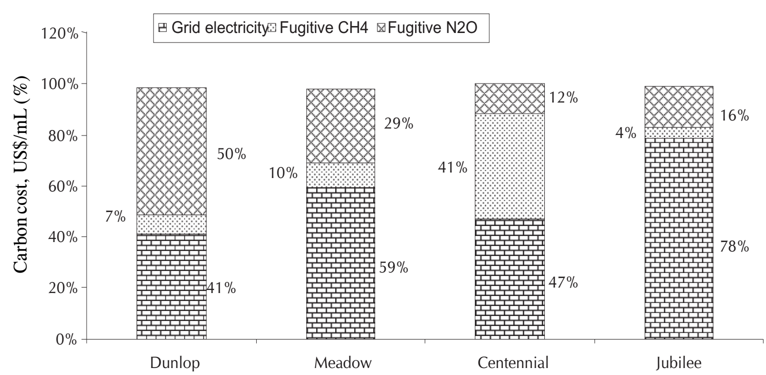

Figure 8: Sources of greenhouse gas emission in wastewater treatment

Opportunities for improvement for CFA for WWTPs

CFA methodology for WWTPs, particularly fugitive GHG emission estimation methodology, is in its early development stage. Following improvement opportunities have been identified for CFA of WWTP:

1. Nitrous oxide (N_2O) emission: There is widespread uncertainty about the existing N_2O emission estimation methodology for WWTPs (Foley *et al.,* 2008). Latest research has shown that N_2O emission inventory from WWTPs could be much lower (Ahn *et al.,* 2010).

Table 3: Energy consumption (GJ) and GHG emissions (ton) from WWTPs

Parameter	Dunlop	Meadow	Centennial	Jubilee
Wastewater treated, ML/ yr	27,230	4,159	1,205	2,852
Grid electricity consumption, GJ/ yr (scope 2)	19,460	7,962	3,051	14,492
Internally generated biogas, cogeneration electricity and other fuels consumption, GJ/ yr (Scope 1).	8,823	1,944	0	1,287
Total energy consumption, GJ/ yr	28,283	9,906	3,051	15,780
Total renewable cogeneration electricity production from biogas, GJ/ yr	2,430	0	0	0
Greenhouse gas emission from grid electricity, ton CO_2-e	4,815	1,970	755	3,586
Greenhouse gas emission from fuels combustion in stationary engines and biogas combustion in cogeneration plant, water boiler and flare, ton CO_2-e	169	65	0	46
Total fugitive methane emission, ton CO_2-e	841	322	666	197
Total fugitive nitrous oxide emission, ton CO_2-e	5,895	969	195	743
Total fugitive methane and nitrous oxide emission, ton CO_2-e	6,736	1,291	861	940
Total Scope 1and2 greenhouse gas emission, ton CO_2-e	11,720	3,326	1,616	4,572

2. Data accuracy and reliability: A large number of parameters such as hydraulic flow, temperature, pressure, chemical oxygen demand (COD), BOD, volatile solids %, total solids %, total nitrogen, etc for wastewater, effluent, biosolids, biogas, raw and biological sludge are involved in fugitive emission estimation. Many of these parameters are determined based on grab samples and numbers of such measurement samples are also often limited. Continuous monitoring of these parameters, wherever feasible, otherwise increasing frequency of statistically appropriate grab sampling would improve fugitive emission estimation.

3. Calibration, operation and maintenance of gauges: Often some of the instruments and gauges such as biogas, thickened biological and raw sludge flow meters are not regularly calibrated and maintained.

4. Methane and sludge concentration meters: On- line digital methane concentration meter for biogas and concentration meter for thickened raw and biological sludge on the WWTP's SCADA system would help in calculating accurate fugitive emission.

5. Thermal mass flow meters for biogas: Mass of biogas generated from the anaerobic digester in a WWTP depends at least upon its pressure and temperature, which keep on changing depending upon the health, operation and maintenance of the digestion system. Thermal mass flow meters would directly calculate mass of biogas produced in tonnes.

6. WWTP Operators awareness and training would greatly help in developing their knowledge, understanding and ownership in GHG emission and CFA parameters monitoring, measurement and control.

7. Covering sources of fugitive emissions may improve measurement and quantification as well as providing greater options for control, odour reduction or capture.

8. Anthropogenic carbon in wastewater: Currently, NGER legislation considers that all constituents in wastewater are of biogenic origin and get exempt from carbon dioxide emission in the NGER. However, latest research applying radiocarbon (^{14}C) age technique has shown that up to 25% of wastewater dissolved organic carbon (DOC) could be fossil carbon, likely derived from petroleum- based household products e.g. detergents (Griffith *et al.,* 2009). This has the potential to increase GHG intensity of wastewater treatment.

9. Fugitive methane and nitrous oxide emission in the wastewater networks: Currently, GHG emission

from sewerage networks is out of scope. However, research findings showed that there significant amount of methane and nitrous oxide emission in the sewerage networks (Foley *et al.,* 2009, 2008).

10. Inclusion of Scope 3 GHG emissions (e.g. water conservation and demand management) and life cycle CFA for water services is planned for future study.

CONCLUSION

Greenhouse gas emission from fossil fuel burning is causing global warming and climatic change, whose negative impact on economy, human development, environment and society will be manifested through water. CFA is an important key step for developing WWTPs' climate change mitigation and adaptation strategies. CFA calculation process steps, methodology and assumption, are explained for primary (Dunlop), CAS (Meadow), SBR (Centennial) and IDAL BNR (Jubilee) WWT. It is revealed from this study that fossil fuel- based grid electricity and fugitive N_2O emission from WWTPs are the major contributors to greenhouse gas emission. Once implemented, the carbon pollution reduction scheme (CPRS) (Commonwealth of Australia, 2008) or carbon emission trading (CET) or a carbon tax, is likely to increase prices of carbon and wastewater services in the future, if the current trend in energy consumption at WWTP utilities continues. The challenges are to minimize the energy and carbon intensity of WWT through, for example:

1. using leading edge anaerobic digester technology to maximize production of biogas, cogeneration electricity and heat energy and sourcing energy from other renewable sources, such as wind, solar.
2. using low carbon intensity fossil fuels (natural gas, LPG, ethanol).
3. optimizing energy consumption in wastewater transmission, treatment, reuse and disposal.
4. other innovative, reliable and cost- effective processes, technologies, operations and practices in wastewater services delivery.

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