Supplementary Materials

This file contains life cycle inventory data of the three wastewater sludge treatment scenarios (Multiple Hearth Incineration, Fluid Bed Incineration, Anaerobic Digestion) used in this paper: ***Impact of Subjective Choices on Life Cycle Assessment of Wastewater Sludge Treatment Processes***

Table of Contents

Table S1: Inventory Data for Multiple Hearth Incineration Scenario **2**

Table S2: Emissions to Air and Water from the Treatment of 1 Dry Kg of Solids in Multiple Hearths Incinerator. All Data have Lognormal Distribution **4**

Table S3: Inventory Data for Fluid Bed Incineration Scenario **7**

Table S4: Emissions to Air and Water from the Treatment of 1 Dry Kg of Solids in Fluid Bed Incinerator.All Data have Lognormal Distribution..... **9**

Table S5: Inventory Data for the Anaerobic Digestion Scenario **12**

Table S6: Emissions to Air and Water from the Treatment of 1 Dry Kg of Solids in Anaerobic Digestion. All Data have Lognormal Distribution..... **15**

References..... **17**

LIST OF ABBREVIATIONS

Abbreviation	Description
BFP	Belt Filter Press
BOD	Biochemical Oxygen Demand
BPWWTP	BP Wastewater Treatment Plant
BTU	British Thermal Unit
COD	Chemical Oxygen Demand
DT	Dry Ton of solids
DS	Dry Solids
FBI	Fluidized Bed Incineration
LCIA	Life Cycle Impact Assessment
MHI	Multiple Hearth Incineration
NMVOC	Non-Methane Volatile Organic Compounds
WWTP	Wastewater Treatment Plant

Table S1: Inventory Data for Multiple Hearth Incineration Scenario.

Inventory	Units/	Typical	Distribution	Uncertainty[a]	Data Source[b]
Inputs*					
Polymer to BFP	Kg/dry ton	1.51	Lognormal	3.31	Provided from the plant
Electricity (entire solids handling unit)	KWh/dry kg	0.353	Lognormal	6.16	Provided from the plant
Land occupied by BFP	m^2	1394	Normal	269	Measured onsite
Steel materials for BFP	Kg	125872	Normal	10206	Measured onsite
Concrete for stands	Kg	82871	Normal	8287	Measured onsite
Steel for stands	Kg	2858	Normal	285	Measured onsite
Steel for scum concentrator	Kg	11197	Normal	215	Measured onsite
Steel for piping	Kg	9385	Normal	905	Measured onsite
Fuel for incinerators (natural gas)	MJ/dry kg	3.49	Lognormal	4.79	Provided from the plant
Land occupied by incinerators	m^2	883	Normal	46	Measured onsite
Steel for incinerators.	Kg	1378059	Normal	235278	Measured onsite
Brick for stock	Kg	506113	Normal	27311	Measured onsite
Aluminum for venting	Kg	11499	Normal	2300	Measured onsite
HH Alloy for incinerators	Kg	85284	Normal	6560	Measured onsite
Concrete for incinerators	Kg	4933	Normal	980	Measured onsite
Concrete for ash slurry holding tank	Kg	108862	Normal	4536	Measured onsite
Steel for ash slurry holding tank	Kg	3629	Normal	227	Measured onsite
Polyurethane used for slurry ash piping	Kg	16556	Normal	675	Measurement onsite
Land occupied by ash slurry pond	m^3	20100	Normal	980	Measured onsite
Stones used for constructing the pond	Kg	10061150	Normal	453592	calculated onsite
Bricks for pond's floor	Kg	5755905	Normal	131542	Measured onsite
Concrete used for walk way	Kg	479864	Normal	22680	Measured onsite
Steel used for walk way	Kg	16547	Normal	453	Measurement onsite
Steel used for walk way hand rail	Kg	680	Normal	69	Measurement onsite
Steel for piping	Kg	9385	Normal	725	Measurement onsite
Steel for pumps	Kg	4890	Normal	685	Measurement

					onsite
Transportation of ash to landfill	Kg.km/ dry kg	(0.23 kg dry ash produced per dry kg of solids) * 9.65 km the distance to landfill			EPA (1979) [c]
Outputs					
Wash water from BFP	L/dry kg	18	Lognormal	1.59	Calculated from data given by plant
Heat from incineration	MJ/dry kg	7.52	lognormal		Calculated based on Stillwell et al., 2010[d]
Dry ash produced	Kg/dry kg	0.23	lognormal	1.46	EPA (1979)

*For construction materials and equipment, service life for all mechanical equipment was assumed to have an average of 40 years, and the service life for building materials was 70 years as recommended by plant's engineers.

aIn a 95% confidence interval, the materials that have normal distributions, the uncertainties reported are the double arithmetic standard deviations.While for the materials that have lognormal distributions, the uncertainties reported are the square geometric standard deviations. The method used for uncertainty calculation was described by Frischknecht and Jungbluth (2007). The calculation of uncertainties for this case study can be found in (Alyaseri, 2014).

bData collected from BP WWTP for construction materials were collected by measurements onsite. Data for electricity, natural gas, dry tons incinerated, heat produced, polymers, and dewatering wash water were provided by the plant for the year 2011.

cAsh from incineration was calculated based on the criteria provided by EPA (1979) to be 0.23 kg of bottom ash/kg of solids incinerated. This value was consistent with range of 20 to 30% of solids in slurry ash from incineration reported by Metcalf and Eddy (2003). The unit kg.km is the weight of ash in kg multiplied by the distance to the landfill in km. This unit is required by SimaPro to calculate the environmental burdens associated to the transportation.

dThe heat waste from incineration was calculated based on Stillwell et al., (2010) equation:

$$ER = \frac{(DFR * CS * HV)}{(HR * DSB)}$$

Where *ER* is the heat generated from incineration (MJ/kg of solids). This heat is released to the atmosphere. *DFR* is the daily flow rate in MGD. *CS* is the dry solids content in the wastewater, kg of solids per million gallon. *HV* is the solids heating value, kJ/kg of solids. *HR* represents the steam electric heat rate, kJ/KWh. DSB represents the daily solids burned in the plant (average of 106 dry ton of solids/day).

The wastewater dry solids content ranges between 680 to 1020 kg per million gallon (Metcalf and Eddy, 2003) and the average in this study was taken as 730 kg/MG. The solids heating value has a wide range depend on the type of sludge. Primary sludge may have a higher heating value of up to 29000 KJ/dry kg (Metcalf and Eddy, 2003) while anaerobically digested sludge has a lower heating value of no more than 7500 KJ/dry kg (Murray et al., 2008). However, because the secondary sludge is returned to the primary clarifiers and mixed with primary sludge, the study considered mixed untreated sludge. The range of heating value was assumed to be 20000 to 23210 KJ/dry kg with average of 21610 KJ/dry kg. The steam electric heat rate was assumed to be 10550 kJ/kWh with a conversion factor of 3.6 MJ/KWh (Stillwell et al., 2010).

Table S2: Emissions to Air and Water from the Treatment of One Dry Kg of Solids in Multiple Hearths Incinerator. Data are for Incineration Process Only. All Data has Lognormal Distribution.

Emission Type	Unit	Typical	Data Source	Uncertainty	Remarks*
Emissions to Air					
Sulfur dioxide	Kg/D. kg	6.05E-04	USEPA,2011	1.11	(1,1,1,1,1,1,4)
Carbon dioxide, biogenic	Kg/D. kg	7.26E-02	Doka, 2006	1.91	Uncertainty calculated by Doka, 2006
Nitrogen oxides	Kg/D. kg	1.85E-03	USEPA,2011	1.79	(1,1,1,1,1,5,4)
Ammonia	Kg/D. kg	1.68E-06	Doka, 2006	10.44	Uncertainty calculated by Doka, 2006
Dinitrogen monoxide	Kg/D. kg	9.79E-06	Doka, 2006	9.83	
Cyanide	Kg/D. kg	1.91E-06	Doka, 2006	10.44	
Arsenic	Kg/D. kg	5.45E-07	USEPA, 1995	19.00	Uncertaintycovers the range reported by EPA, 1995
Cadmium	Kg/D. kg	2.73E-06	USEPA, 1995	5.38	(1,5,4,2,4,5,3)
Chromium	Kg/D. kg	9.27E-07	USEPA, 1995	8.83	Uncertainty covers the range reported by EPA, 1995
Copper	Kg/D. kg	1.82E-06	USEPA, 1995	5.39	(1,5,4,2,4,5,4)
Mercury	Kg/D. kg	4.55E-09	USEPA, 1995	5.38	(1,5,4,2,4,5,3)
Manganese	Kg/D. kg	7.73E-07	USEPA, 1995	1.90	(1,5,4,2,4,5,4)
Nickel	Kg/D. kg	8.18E-07	USEPA, 1995	5.39	(1,5,4,2,4,5,4)
Lead	Kg/D. kg	3.44E-09	USEPA,2011	5.27	(1,1,1,1,1,5,4)
Tin	Kg/D. kg	7.27E-06	USEPA, 1995	1.90	(1,5,4,2,4,5,4)
Zinc	Kg/D. kg	2.18E-05	USEPA, 1995	5.39	(1,5,4,2,4,5,4)
Silicon	Kg/D. kg	4.00E-05	USEPA, 1995	1.90	(1,5,4,2,4,5,4)
Calcium	Kg/D. kg	2.36E-04	USEPA, 1995	1.90	(1,5,4,2,4,5,4)
Aluminum	Kg/D. kg	3.45E-05	USEPA, 1995	1.90	(1,5,4,2,4,5,4)
Magnesium	Kg/D. kg	3.82E-06	USEPA, 1995	1.90	(1,5,4,2,4,5,4)
Heat, waste	MJ/D. Kg	7.52E+00	Calculated based on Stillwell et al., 2010 equation		
Particulates	Kg/D. kg	1.09E-03	USEPA,2011	3.33	(1,5,4,2,4,5,3)
Hydrogen chloride	Kg/D. kg	9.09E-06	USEPA, 1995 and MDNR, 2012	1.89	(1,5,4,2,4,5,3)

Barium	Kg/D. kg	2.91E-06	USEPA, 1995	5.39	(1,5,4,2,4,5,4)
Potassium	Kg/D. kg	6.36E-06	USEPA, 1995	1.90	(1,5,4,2,4,5,4)
Selenium	Kg/D. kg	5.46E-08	USEPA, 1995	1.90	(1,5,4,2,4,5,4)
Titanium	Kg/D. kg	2.83E-06	USEPA, 1995	5.39	(1,5,4,2,4,5,4)
Carbon monoxide	Kg/D. kg	1.11E-02	USEPA,2011	5.27	(1,1,1,1,1,5,4)
VOC, volatile organic compounds	Kg/D. kg	1.71E-03	USEPA,2011	2.24	(1,1,1,1,1,5,4)
Furan	Kg/D. kg	1.18E-12	USEPA, 1995	1.90	(1,5,4,2,4,5,4)
Dioxin, 2,3,7,8 Tetrachlorodibenzo-p-	Kg/D. kg	3.36E-12	USEPA, 1995	1.90	(1,5,4,2,4,5,4)
Emissions to water					
Ammonium, ion	Kg/D. kg	2.76E-04	Doka, 2006	1.58	Uncertainty calculated by Doka, 2006
Nitrogen	Kg/D. kg	1.89E-05	Doka, 2006	1.67	
BOD5, Biological oxygen demand	Kg/D. kg	6.96E-05	Doka, 2006	1.18	
COD, Chemical oxygen demand	Kg/D. kg	2.34E-04	Doka, 2006	1.12	
TOC, Total organic carbon	Kg/D. kg	5.47E-05	Doka, 2006	1.14	
DOC, Dissolved organic carbon	Kg/D. kg	5.47E-05	Doka, 2006	1.17	
Sulfate	Kg/D. kg	5.07E-04	Doka, 2006	2.25	
Nitrate	Kg/D. kg	1.28E-03	Doka, 2006	1.57	
Phosphate	Kg/D. kg	1.44E-05	Doka, 2006	1.58	
Chloride	Kg/D. kg	5.70E-05	Doka, 2006	1.58	
Emissions to Groundwater					
BOD5, Biological oxygen demand	Kg/D. kg	1.61E-04	Doka, 2006	1.78	Uncertainty calculated by Doka, 2006
COD, Chemical oxygen demand	Kg/D. kg	4.92E-04	Doka, 2006	1.78	
TOC, Total organic carbon	Kg/D. kg	1.95E-04	Doka, 2006	1.78	
DOC, Dissolved organic carbon	Kg/D. kg	1.95E-04	Doka, 2006	1.78	
Sulfate	Kg/D. kg	2.33E-03	Doka, 2006	2.67	
Nitrate	Kg/D. kg	7.62E-05	Doka, 2006	3.31	
Phosphate	Kg/D. kg	1.18E-04	Doka, 2006	74.31	
Arsenic, ion	Kg/D. kg	5.02E-08	Doka, 2006	13.12	
Cadmium, ion	Kg/D. kg	6.52E-10	Doka, 2006	230.36	
Cobalt	Kg/D. kg	3.28E-07	Doka, 2006	10.82	
Chromium VI	Kg/D. kg	3.00E-07	Doka, 2006	10.86	
Copper, ion	Kg/D. kg	1.05E-05	Doka, 2006	7.22	
Mercury	Kg/D. kg	3.38E-09	Doka, 2006	41.16	
Manganese	Kg/D. kg	1.06E-05	Doka, 2006	8.16	
Molybdenum	Kg/D. kg	1.83E-07	Doka, 2006	11.98	
Nickel, ion	Kg/D. kg	1.14E-06	Doka, 2006	9.50	
Lead	Kg/D. kg	2.57E-07	Doka, 2006	215.69	
Tin, ion	Kg/D. kg	4.67E-07	Doka, 2006	13.49	

Zinc, ion	Kg/D. kg	5.51E-07	Doka, 2006	107.71	
Silicon	Kg/D. kg	1.20E-04	Doka, 2006	95.48	
Iron, ion	Kg/D. kg	2.92E-03	Doka, 2006	7.59	
Calcium, ion	Kg/D. kg	2.04E-03	Doka, 2006	3.11	
Aluminum	Kg/D. kg	5.13E-04	Doka, 2006	3.81	
Magnesium	Kg/D. kg	2.43E-04	Doka, 2006	4.67	

*All data assumed to have lognormal distribution. The uncertainty represents the square geometric standard deviation that covers 95% of the possible data. The 7 numbers in parentheses refers to the ranking (from 1 to 5) of seven data quality indicators used to estimate uncertainty of the data that are not enough to run a goodness of fit test as described by Frischknecht and Jungbluth, (2007). Emissions to water and groundwater with their uncertainties were taken from Doka (2006).

Table S3: Inventory Data for a Fluid Bed Incineration Scenario.

Parameter	Units	Typical	Distribution	Uncertainty[a]	Data Source[b]
Inputs*					
Polymer to BFP	Kg/dry ton	1.51	Lognormal	3.31	Same as MHI
Electricity (entire solids handling unit)	kWh/dry kg	0.344	Lognormal	2.48	Calculated (criteria from USEPA, 1979)
Land Occupied by BFP	m^2	1394	Normal	269	Same as MHI
Steel materials for BFP	Kg	125872	Normal	10206	Same as MHI
Concrete for stands	Kg	82871	Normal	8287	Same as MHI
Steel for stands	Kg	2858	Normal	285	Same as MHI
Steel for scum concentrator	Kg	11197	Normal	215	Same as MHI
Steel for piping	Kg	9385	normal	905	Same as MHI
Auxiliary fuel for FB Incineration	MJ/dry kg	3.28	lognormal	1.71	USEPA, 1979[c](4,4,5,2,4,5,4)
Land Occupied by FB Incinerators	m^2	883	Normal	46	Same as MHI
Refractory Brick for Incinerator	Kg	26522	Normal	6949	Estimated based on the design
Steel for FB Incinerator and heat boiler	Kg	56067	Normal	3389	Estimated based on the design
Brick for stock for FB Incinerator	Kg	506113	Normal	27311	Same as MHI
Aluminum for FB incinerator (venting)	Kg	11499	Normal	2300	Same as MHI
Concrete for FB Incinerator for the flat base	Kg	355162	Normal	21503	Estimated based on the design
Concrete for ash slurry holding tank	Kg	108862	Normal	4536	Same as MHI
Steel for ash slurry holding tank	Kg	3628	Normal	227	Same as MHI
Polyurethane used for slurry ash piping to holding pond	Kg	16556	Normal	675	Same as MHI
Land Occupied by ash slurry pond	M^3	20100	Normal	980	Same as MHI
Stones used for constructing the pond	Kg	10061150	Normal	453592	Same as MHI
Concrete used for walk way	Kg	479864	Normal	22680	Same as MHI
Bricks for pond's floor	Kg	5755905	Normal	131542	Same as MHI
Steel used for walk way	Kg	16547	Normal	453	Same as MHI
Steel used for walk way hand rail	Kg	680	Normal	69	Same as MHI
Steel for piping	Kg	9384	Normal	725	Same as MHI
Steel for pumps	Kg	4890	Normal	685	Same as MHI
Transportation of ash to landfill	Kg.km/dry kg	0.23 kg of as per dry kg of solids * 9.65 km the distance to landfill			USEPA (1979)[d]
Outputs					
Washwater from BFP	L/dry kg	18	Normal	1.59	Same as MHI
WW from treatment of fly ash	L/dry kg	113	lognormal	1.31	Estimated based on the design
Heat from FB Incinerator	MJ/dry kg	7.52	lognormal		Calculated based on Stillwell et al.,

					2010
Dry ash produced	Kg/dry kg	0.23	lognormal	1.46	USEPA (1979)

*For construction materials and equipment, service life for all mechanical equipment was assumed to have an average of 40 years, and the service life for building materials was 70 years as recommended by plant's engineers.

aIn a 95% confidence interval, the materials that have normal distributions, the uncertainties reported are the double arithmetic standard deviations, while for the materials that have lognormal distributions, the uncertainties reported are the square geometric standard deviations. The method used for uncertainty calculation was described by (Frischknecht and Jungbluth, 2007). The calculation of uncertainties for this case study can be found in (Alyaseri, 2014).

b Some construction materials were assumed to be the same as the Multiple Hearths Incineration scenario (MHI).

cThe supplemental fuel for the fluid bed incinerator was calculated based on a feed rate of 1806 dry Ib/hour as described by USEPA, 1979.

dAsh from incineration was calculated based on the criteria provided by USEPA (1979) to be 0.23 kg of bottom ash/kg of solids incinerated. This value was consistent with a range of 20 to 30% of solids in slurry ash from incineration reported by Metcalf and Eddy (2003). The unit kg.km is the weight of ash in kg multiplied by the distance to the landfill in km. This unit is required by SimaPro to calculate the environmental burdens associated to the transportation

Table S4: Emissions to Air and Water from the Treatment of One Dry Kg of Solids in Fluid Bed Incinerator. Data are for Incineration Process Only. All Data has Lognormal Distribution

Emission Type	Unit	Typical	Source	Uncertainty	Remarks*
Emissions to Air					
Sulfuric acid	Kg/D. kg	5.45E-05	USEPA, 1995	1.89	(1,5,4,2,4,5,3)
Carbon dioxide, biogenic	Kg/D. kg	1.50E+00	Akwo, 2008 from Hospido et al., 2005	1.71	(4,5,2,5,4,5,4)
Nitrogen oxides	Kg/D. kg	1.45E-06	Lederer and Rechberger, 2010.	2.88	Uncertainty covers the range reported by Lederer and Rechberger, 2010
Ammonia	Kg/D. kg	1.68E-06	Doka, 2006	10.44	Uncertainty calculated by Doka, 2006
Dinitrogen monoxide	Kg/D. kg	9.79E-06	Doka, 2006	9.83	
Cyanide	Kg/D. kg	1.91E-06	Doka, 2006	10.44	
Arsenic	Kg/D. kg	1.36E-08	USEPA, 1995	5.33	(1,5,4,2,3,5,3)
Cadmium	Kg/D. kg	5.26E-08	USEPA, 1995 and White et al., 1999	9.50	Uncertainty covers the range between USEPA, 1995 and White et al., 1999
Chromium	Kg/D. kg	1.32E-08	USEPA, 1995 and White et al., 1999	16.39	
Copper	Kg/D. kg	2.73E-07	USEPA, 1995	5.39	(1,5,4,2,4,5,4)
Mercury	Kg/D. kg	7.35E-08	USEPA, 1995 and White et al., 1999	5.37	(1,5,3,2,4,5,3)
Manganese	Kg/D. kg	2.73E-07	USEPA, 1995	1.90	(1,5,4,2,4,5,4)
Nickel	Kg/D. kg	1.84E-07	USEPA, 1995 and White et al., 1999	7.99	Uncertainty covers the range between USEPA, 1995 and White et al., 1999
Lead	Kg/D. kg	2.56E-07	USEPA, 1995 and White et al., 1999	270.6	Uncertainty covers the range reported by USEPA, 1995

Tin	Kg/D. kg	3.18E-07	USEPA, 1995	1.90	(1,5,4,2,4,5,4)
Zinc	Kg/D. kg	9.09E-07	USEPA, 1995	5.39	(1,5,4,2,4,5,4)
Silicon	Kg/D. kg	2.91E-06	USEPA, 1995	1.90	(1,5,4,2,4,5,4)
Calcium	Kg/D. kg	4.55E-06	USEPA, 1995	1.90	(1,5,4,2,4,5,4)
Aluminum	Kg/D. kg	1.73E-06	USEPA, 1995	1.90	(1,5,4,2,4,5,4)
Magnesium	Kg/D. kg	5.45E-07	USEPA, 1995	1.90	(1,5,4,2,4,5,4)
Heat, waste	MJ/D.kg	1.33E+00	Calculated based on Stillwell et al., 2010 equation		
Particulates	Kg/D. kg	2.38E-04	Averaged from USEPA, 1972; USEPA, 1995; White et al., 1999; and Neuman et al., 2012	8.69	Uncertainty calculated to cover 95% of the data collected
Hydrogen chloride	Kg/D. kg	4.55E-05	USEPA, 1995	1.89	(1,5,4,2,4,5,3)
Barium	Kg/D. kg	2.18E-07	USEPA, 1995	5.39	(1,5,4,2,4,5,4)
Potassium	Kg/D. kg	5.45E-07	USEPA, 1995	1.90	(1,5,4,2,4,5,4)
Selenium	Kg/D. kg	1.82E-07	USEPA, 1995	1.90	(1,5,4,2,4,5,4)
Titanium	Kg/D. kg	3.64E-07	USEPA, 1995	5.39	(1,5,4,2,4,5,4)
Emissions to water					
Ammonium, ion	Kg/D. kg	2.76E-04	Doka, 2006	1.58	Uncertainty calculated by Doka, 2006
Nitrogen	Kg/D. kg	1.89E-05	Doka, 2006	1.67	
BOD5, Biological oxygen demand	Kg/D. kg	6.96E-05	Doka, 2006	1.18	
COD, Chemical oxygen demand	Kg/D. kg	2.34E-04	Doka, 2006	1.12	
TOC, Total organic carbon	Kg/D. kg	5.47E-05	Doka, 2006	1.14	
DOC, Dissolved organic carbon	Kg/D. kg	5.47E-05	Doka, 2006	1.17	
Sulfate	Kg/D. kg	5.07E-04	Doka, 2006	2.25	
Nitrate	Kg/D. kg	1.28E-03	Doka, 2006	1.57	
Phosphate	Kg/D. kg	1.44E-05	Doka, 2006	1.58	
Chloride	Kg/D. kg	5.70E-05	Doka, 2006	1.58	
Emissions to Groundwater					
BOD5, Biological oxygen demand	Kg/D. kg	1.61E-04	Doka, 2006	1.78	Uncertainty calculated by
COD, Chemical oxygen demand	Kg/D. kg	4.92E-04	Doka, 2006	1.78	

TOC, Total organic carbon	Kg/D. kg	1.95E-04	Doka, 2006	1.78	Doka, 2006
DOC, Dissolved organic carbon	Kg/D. kg	1.95E-04	Doka, 2006	1.78	
Sulfate	Kg/D. kg	2.33E-03	Doka, 2006	2.67	
Nitrate	Kg/D. kg	7.62E-05	Doka, 2006	3.31	
Phosphate	Kg/D. kg	1.18E-04	Doka, 2006	74.31	
Arsenic	Kg/D. kg	5.02E-08	Doka, 2006	13.12	
Cadmium	Kg/D. kg	6.52E-10	Doka, 2006	230.4	
Cobalt	Kg/D. kg	3.28E-07	Doka, 2006	10.82	
Chromium VI	Kg/D. kg	3.00E-07	Doka, 2006	10.86	
Copper, ion	Kg/D. kg	1.05E-05	Doka, 2006	7.22	
Mercury	Kg/D. kg	3.38E-09	Doka, 2006	41.16	
Manganese	Kg/D. kg	1.06E-05	Doka, 2006	8.16	
Molybdenum	Kg/D. kg	1.83E-07	Doka, 2006	11.98	
Nickel, ion	Kg/D. kg	1.14E-06	Doka, 2006	9.49	
Lead	Kg/D. kg	2.57E-07	Doka, 2006	215.7	
Tin, ion	Kg/D. kg	4.67E-07	Doka, 2006	13.48	
Zinc, ion	Kg/D. kg	5.51E-07	Doka, 2006	107.71	
Silicon	Kg/D. kg	1.20E-04	Doka, 2006	95.48	
Iron, ion	Kg/D. kg	2.92E-03	Doka, 2006	7.59	
Calcium, ion	Kg/D. kg	2.04E-03	Doka, 2006	3.11	
Aluminum	Kg/D. kg	5.13E-04	Doka, 2006	3.81	
Magnesium	Kg/D. kg	2.43E-04	Doka, 2006	4.67	

* All data assumed to have lognormal distribution. The uncertainty represents the square geometric standard deviation that covers 95% of the possible data. The 7 numbers in parentheses refers to the ranking (from 1 to 5) of seven data quality indicators used to estimate uncertainty of the data that are not enough to run a goodness of fit test as described by Frischknecht and Jungbluth, (2007). Emissions to water and groundwater with their uncertainties were taken from Doka (2006).

Table S5: Inventory Data for the Anaerobic Digestion Scenario.

Parameter	Units	Typical	Distribution	Uncertainty[a]	Source[b]
Inputs*					
Electricity (for thickening)	kWh/dry kg	8.89 x10^{-4}	lognormal	1.53	EPA, 1979; Goldstein and Smith, 2002; Stillwell et al., 2010; Smith, 1977; and Burton, 1993[c]
Electricity (for digestion)	kWh/dry kg	0.16	lognormal	1.53	Stillwell et al., 2010; Menendez, 2012; and Butron, 1993[d]
Electricity (for pumping)	kWh/dry kg	5.5 x10^{-3}	lognormal	1.53	Averaged from Goldstein and Smith, 2002 and Burton, 1993
Electricity (for lighting and building)	kWh/dry kg	16.55 x10^{-3}	lognormal	1.71	Smith, 1977
Land Occupied by anaerobic digesters	m^2	9420	Normal	465	Estimated based on the design
Reinforcement steel for digesters	Kg	361792	Normal	36103	
Concrete for digesters	Kg	10491963	Normal	1046995	
Construction materials for gravity thickeners and scum concentrators	Reinforcement Steel (Kg)	22125	Normal	2177	
	Steel for skimmers and bridges (Kg)	8066	Normal	807	
	Concrete (Kg)	641621	Normal	64410	
	Steel for scum concentrator (Kg)	11197	Normal	215	Same as MHI
	Steel for piping (Kg)	9385	normal	905	Same as MHI
Fuel to heat digester	MJ/dry kg	0.17	lognormal	1.71	Akwo, 2008
Land Occupied by thickeners	m^2	502	Normal	50	Estimated based on the design
Concrete for ash slurry holding tank	Kg	108862	Normal	4536	Same as MHI
Steel for ash slurry holding tank	Kg	3629	Normal	227	Same as MHI
Polyurethane used for slurry ash piping to holding pond	Kg	16556	Normal	675	Same as MHI
Land Occupied by ash slurry pond	m^3	20100	Normal	980	Same as MHI
Stones used for constructing the pond	Kg	10061150	Normal	453592	Same as MHI
Bricks for pond's floor	Kg	5755905	Normal	131542	Same as MHI
Concrete used for walk way	Kg	479864	Normal	22680	Same as MHI
Steel used for walk way	Kg	16547	Normal	453	Same as MHI
Steel used for walk way	Kg	680	Normal	69	Same as MHI

hand rail					
Steel for piping	Kg	9385	Normal	725	Same as MHI
Steel for pumps	Kg	4890	Normal	685	Same as MHI
Transportation of ash to landfill	Kg.km/dry kg	0.68 kg of ash per dry kg of solids * 9.65 km the distance to landfill=6.54			USEPA, 1985; Tarantini et al., 2007; Akwo, 2008; and Murray et al., 2008[e]
Outputs					
Energy from biogas produced	KWh/dry kg	1.94	lognormal	2.51	Stillwell et al., 2010; USDOE, 1981; Burton, 1993; Poulsen and Hansen, 2003; ERG and RDC, 2011; EPA, 1978; Murray et al., 2008; and Johnson, 2006[f]
Solids to landfill or land application	kg/kg	0.68	lognormal	1.30	USEPA, 1985; Tarantini et al., 2007; Akwo, 2008; and Murray et al., 2008
Heat loss from digesters	KWh/dry kg	0.13	lognormal	1.65	Average from ERG and RDG, 2011 and Ghazy et al., 2011

*For construction materials and equipment, service life for all mechanical equipment was assumed to have an average of 40 years, and the service life for building materials was 70 years as recommended by plant's engineers.

a In a 95% confidence interval, the materials that have normal distributions, the uncertainties reported are the double arithmetic standard deviations.While for the materials that have lognormal distributions, the uncertainties reported are the square geometric standard deviations. The method used for uncertainty calculation was described by (Frischknecht and Jungbluth, 2007). The calculation of uncertainties for this case study can be found in (Alyaseri, 2014).

b Some construction materials were assumed to be the same as the Multiple Hearths Incineration scenario (MHI).

C Based on the designed surface area and the EPA (1979) study, the estimated power needed for thickening was 0.19 KWh/dry ton. Goldstein and Smith (2002) reported a power need of 3.4 KWh/dry ton for a 10 MGD plant. Stillwell et al. (2010) reported a power need of 1.90, 2.07, 2.55 and 3.44 KWh/dry ton for a 100, 50, 20 and 10 MGD plant respectively. Smith (1977) reported the amount of this power needed as 13.90, 2.79 and 0.56 KWh/dry ton for a plants have an average flow rates of 1, 10 and 100 MGD, respectively. Burton (1993) reported a 4.13, 3.44, 2.55, 2.07 and 1.86 KWh/dry ton for a plant of 5, 10, 20, 50 and 100 MGD, respectively. A correlation analysis between the power needed and plant size was performed and for the flow rate in the plant, the power needed for thickening was estimated 8.89×10^{-4} KWh/dry kg as shown in Figure S-1 below.

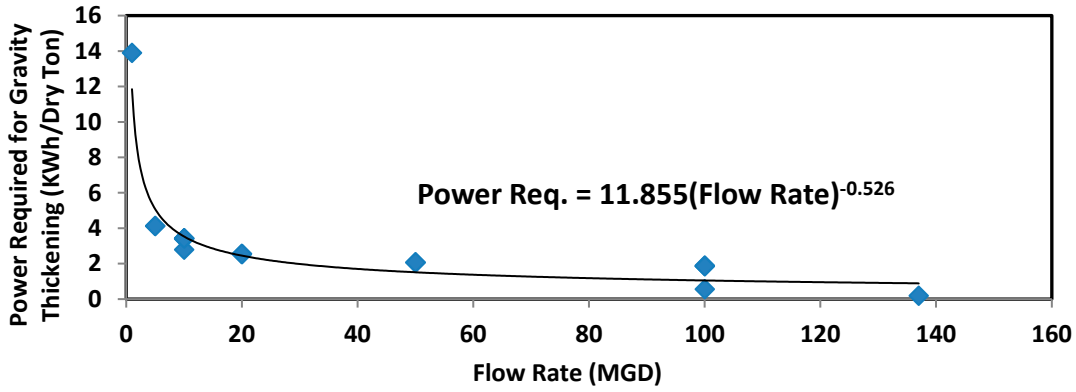


Figure S1: The Correlation between the Power Required for A Gravity Thickening Process and the Plant's Flow Rate.

d Stillwell et al. (2010) estimated the energy requirement as 11,000 KWh/day for a plant of 100 MGD which is equal to 0.152 KWh/dry kg. Menendez (2012) estimated the power needed to be 11% of the entire plant consumption of power. This percentage was applied to the specific data from BPWWTP, and the result was 0.177 KWh/dry kg. Butron (1993) reported that the power needed for AD in a 100 MGD plant using trickling filter was 0.152 KWh/ dry kg. The average of the previous data is 0.16 KWh/dry kg with a lognormal distribution and uncertainty of 1.53.

eThe influent volatile solids is 70% while the volatile solids destroyed through the digestion process is 40% to 60% (EPA, 1985) or 46% (Tarantini et al., 2007). If 46% is assumed to be destroyed, then the solids destroyed 0.7 * 0.46= 32%, and the solids to landfill is 0.68 kg/dry kg digested. This value is close to values reported by Akwo (2008) (0.78 kg/dry kg) and Murray et al. (2008) (0.71 Kg/dry kg). The unit kg.km is the weight of ash in kg multiplied by the distance to the landfill in km. This unit is required by SimaPro to calculate the environmental burdens associated to the transportation.

f Based on Stillwell et al. (2010) equation, a 0.626 KWh will be recovered from each dry kg of total solids went into anaerobic digesters. USDOE (1981) showed that unit methane production from anaerobic digester is not related to the treatment method. The study also shows that the actual production of biogas is not likely expected by calculations and has no effect of region and flow rate on the biogas production. From USDOE (1981) study, the data from 13 plants using trickling filter ranged from 1.54 to 4.96 Kwh/dry kg (CH_4 is 65% of biogas and the density of CH_4 was 0.06242796 1b/ft^3 and the amount of dry tons of sludge per million gallons was 0.73 DT/MG; the net KWh for methane was 14.10 KWh/dry kg; 1 Kg of CH_4 is equal to 55.58 MJ or 15.439 KWh and net heating value for CH_4 is 910 BTU/ft^3 (BBBP, 2009)). Energy recovered can be estimated from Burton (1993) to be 0.386 KWh/dry kg. Poulsen and Hansen (2003) reported a production of 734.16 m^3 for each 1 dry ton of sludge digested, and this value can be changed to 3.76 KWh/dry kg. ERG and RDC (2011) reported a biogas production of 10,000 ft^3/MGD. This value can be changed to 2.599 KWh/dry kg. The study reported that electricity can be produced as equal to 0.842 KWh/dry kg. EPA (1978) reported that 390 m^3 can be generated from each dry ton sludge which can be changed to 2.612 KWh/dry kg. Murray et al. (2008) reported that a production of CH_4 was 227.5 kg/dry ton and the value can be changed to 3.207 KWh/dry kg. Johnson (2006) conducted a survey on several plants and estimated the amount of energy recovered is ranging from 1.526 to 4.880 KWh/dry kg. The data from all previous studies ranged from as low as 0.386 KWh/dry kg (Burton, 1993) to as high as 4.96 KWh/dry kg (USDOE, 1981). A geometric mean of 1.94 KWh/dry kg was taken as the best guess value with an uncertainty of 2.51 to cover this range.

Table S6: Emissions to Air and Water from the Treatment of One Dry Kg of Solids in Anaerobic Digestion. All Data have Lognormal Distribution

Emission Type	Unit	Typical	Source	Uncertainty	Remarks[a]
Emissions to Air					
Heat, waste	kWh/D. kg	6.56E-03	Ghazy et al., 2011	1.66	(4,4,2,5,3,5,4)
Methane	Kg/D. kg	5.50E-03	Akwo, 2008	1.56	(2,4,2,5,3,5,4)
Carbon dioxide, biogenic	Kg/D. kg	1.29E+00	Hospido et al., 2005	1.56	(2,4,2,5,3,5,4)
Carbon monoxide	Kg/D. kg	8.40E-04	Hospido et al., 2005	1.56	(2,4,2,5,3,5,4)
Nitrogen dioxide	Kg/D. kg	8.50E-04	Hospido et al., 2005	1.75	(2,4,2,5,3,5,4)
Nitric oxide	Kg/D. kg	2.00E-05	Hospido et al., 2005	1.75	(2,4,2,5,3,5,4)
Particulates	Kg/D. kg	8.00E-05	Hospido et al., 2005	3.27	
NMVOC, non-methane volatile organic compounds	Kg/D. kg	1.38E-05	Hospido et al., 2010	2.28	(3,4,2,5,3,5,4)
Ammonia	Kg/D. kg	3.38E-03	Hospido et al., 2010	1.83	(3,4,2,5,3,5,4)
Emissions to Water					
Potassium	Kg/D. kg	1.50E-03	Hospido et al., 2005	1.83	(3,4,2,5,3,5,4)
Aluminum	Kg/D. kg	1.00E-03	Hospido et al., 2005	1.83	(3,4,2,5,3,5,4)
Magnesium	Kg/D. kg	3.00E-03	Hospido et al., 2005	1.83	(3,4,2,5,3,5,4)
Phosphate	Kg/D. kg	8.28E-04	Hospido et al., 2010	1.83	(3,4,2,5,3,5,4)
Copper	Kg/D. kg	1.54E-04	USEPA, 1978	1.83	(3,4,2,5,3,5,4)
Nickel	Kg/D. kg	3.68E-04	USEPA, 1978	1.83	(3,4,2,5,3,5,4)
Chromium	Kg/D. kg	8.82E-04	USEPA, 1978	1.83	(3,4,2,5,3,5,4)
Iron	Kg/D. kg	1.31E-02	Hospido et al., 2005	1.83	(3,4,2,5,3,5,4)
Zinc	Kg/D. kg	7.07E-03	USEPA, 1978	1.83	(3,4,2,5,3,5,4)
Lead	Kg/D. kg	1.50E-03	USEPA, 1978	1.83	(3,4,2,5,3,5,4)
Cadmium	Kg/D. kg	1.37E-04	USEPA, 1978	1.83	(3,4,2,5,3,5,4)
Mercury	Kg/D. kg	5.00E-07	USEPA, 1978	1.83	(3,4,2,5,3,5,4)
Emissions to Groundwater					
Sulfate	Kg/D. kg	2.33E-03	Doka, 2006	2.66	Uncertainty calculated by Doka, 2006
Nitrate	Kg/D. kg	7.62E-05	Doka, 2006	3.31	
Phosphate	Kg/D. kg	1.18E-04	Doka, 2006	74.31	
Arsenic	Kg/D. kg	5.02E-08	Doka, 2006	13.12	
Cadmium	Kg/D. kg	6.52E-10	Doka, 2006	230.36	
Cobalt	Kg/D. kg	3.28E-07	Doka, 2006	10.82	
Chromium VI	Kg/D. kg	3.00E-07	Doka, 2006	10.86	
Copper, ion	Kg/D. kg	1.05E-05	Doka, 2006	7.22	
Manganese	Kg/D. kg	1.06E-05	Doka, 2006	8.16	
Molybdenum	Kg/D. kg	2.33E-03	Doka, 2006	11.98	

Tin, ion	Kg/D. kg	7.62E-05	Doka, 2006	13.49	
Silicon	Kg/D. kg	1.20E-04	Doka, 2006	95.48	
Iron, ion	Kg/D. kg	2.92E-03	Doka, 2006	7.59	
Calcium, ion	Kg/D. kg	2.04E-03	Doka, 2006	3.11	

[a]In a 95% confidence interval, the materials that have normal distributions, the uncertainties reported are the double arithmetic standard deviations.While for the materials that have lognormal distributions, the uncertainties reported are the square geometric standard deviations. The method used for uncertainty calculation was described by (Frischknecht and Jungbluth, 2007). The calculation of uncertainties for this case study can be found in (Alyaseri, 2014).

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