DOKUZ EYLÜL UNIVERSITY
GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

THE INVESTIGATION OF CARBON ACCOUNTING AND MANAGEMENT TOOLS FOR DIFFERENT SLUDGE TREATMENT AND DISPOSAL METHODS

by
Ege YALÇINKAYA

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İZMİR

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ABSTRACT

The term carbon footprint, as a result of the increasing awareness of global warming, has become very popular recently. Most of the greenhouse gases that cause global warming and naturally exist are the result of industrial processes increased with industrialization, human activities cause significant of these gases into the atmosphere. Wastewater treatment plants are recognized as one of great contributors of GHG emissions. The scope of this thesis is examining the effect of wastewater treatment plants, in particular sludge treatment and disposal methods on the carbon footprint. The aim of this thesis is to investigate the carbon footprint of different sludge treatment and disposal methods.

Existing protocols, guidance documents, and calculation tools that are applicable to GHG emissions reporting were examined and given in detail in chapter 1. For this purpose, general literature items were used. Chapter 2 includes information about wastewater treatment facilities and relating GHG emissions from these facilities. Different sludge treatment and disposal processes and their GHG emissions were defined in detail. The literature review is formed the basis for this chapter. Emissions from each sludge management process were investigated separately and were discussed for each unit sludge management process. The existing GHG calculation methods and techniques for sludge management processes were examined and they were also given this chapter. In chapter 3, different flow charts were created for different sludge treatment and disposal options according to the aim of the thesis and emission calculations were made according to the selected technique. Chapter 4 includes comparison and discussion the GHG emissions coming from different sludge management processes.

In the fifth and last chapter of this thesis, the related drawbacks of the topic have reviewed and recommendations are made for future researches on this topic.

Keywords: Carbon footprint, greenhouse gas emissions, sludge management

FARKLI ÇAMUR İŞLEME VE BERTARAF YÖNTEMLERİ İÇİN KARBON BÜTÇELERİ VE YÖNETİMİNİN İNCELENMESİ

ÖZ

Karbon ayakizi terimi, artan küresel ısınma bilincinin bir sonucu olarak, son zamanlarda oldukça popüler bir terim haline gelmiştir. Küresel ısınmaya neden olan sera gazlarının çoğu doğada doğal olarak bulunmasına rağmen, sanayileşme ile birlikte artan endüstriyel prosesler ve insan faaliyetleri sonucu bu gazların atmosfere yayılmasına önemli ölçüde neden olmaktadır. Atıksu arıtma tesisleri operasyonları atmosferdeki sera gazı emisyonlarına önemli ölçüde katkıda bulunan faaliyetler olarak kabul edilmektedir. Bu tezin kapsamını, atıksu arıtma tesislerinin ve özellikle bu tesislerin arıtma çamuru işleme ve bertaraf proseslerinin karbon ayakizi üzerindeki etkisinin incelenmesi oluşturmaktadır. Tezin amacı, farklı çamur arıtma ve bertaraf yöntemlerinin karbon ayakizi üzerindeki etkisini proses bazında karşılaştırmalı olarak araştırmaktır.

Tezin amacına uygun olarak çalışmaya konuyla ilgili mevcut protokollerin literatür taramasıyla başlanmıştır. Sera gazı emisyonlarının hesaplanması ve raporlanmasıyla ilgili mevcut protokoller birinci bölümde detaylı bir şekilde sunulmuştur. Tezin ikinci bölümüne atıksu arıtma tesisleri ve bu tesislerin sera gazı emisyonları ile ilgili genel bilgiler verilerek başlanmıştır. İkinci bölümde arıtma çamurlarının işleme ve bertaraf yöntemleri hakkında proses bazında genel bilgiler ve bu proseslerden kaynaklanan emisyonlar hakkında detaylı bilgi verilmiştir. Bu bölümde ayrıca sera gazı emisyonlarının hesaplanmasıyla ilgili mevcut teknikler ve teknolojiler incelenmiş ve detaylı olarak sunulmuştur. Tezin üçüncü kısmında farklı çamur yönetim proseslerinden kaynaklanan emisyonların karşılaştırılması amacıyla farklı akım şemaları oluşturulmuş ve seçilen hesaplama tekniğine göre emisyonlar hesaplanmıştır. Dördüncü bölümde, oluşturulan akım şemalarına göre proses bazında elde edilen emisyon sonuçları karşılaştırılmış ve senaryo bazında tartışılmıştır.

Tezin beşinci ve son bölümünde, çalışma genel hatlarıyla ele alınmış ve konu ile ilgili görülen mevcut eksiklikler değerlendirilmiş ve ileride yapılabilecek olan çalışmalar ile ilgili değerlendirmeler yapılmıştır.

Keywords: Karbon ayakizi, sera gazı emisyonları, çamur işleme ve bertaraf yöntemleri

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CHAPTER ONE
INTRODUCTION

1.1 Description of Greenhouse Gases

Gases which make heat increased in the atmosphere are called greenhouse gases (GHG). Greenhouse gases affect the temperature of the Earth. These gases can absorb and emit infrared radiation in the atmosphere. This process is often called on the greenhouse effect. In other words, the greenhouse effect is concerned with the infrared radiation given off by the earth. The Kyoto Protocol, which originated at the 3rd Conference of the Parties to the United Nations Convention on Climate Change in 1997, has identified six greenhouse gases: carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), sulphur hexafluoride (SF_6), perfluorocarbons (PFCs), hydrofluorocarbons (HFCs). Many greenhouse gases such as water vapor, carbon dioxide, methane, ozone, and nitrous oxide, occur in the atmosphere naturally. Other greenhouse gases result from human industrial processes, for example hydrofluorocarbons, perfluorocarbons, sulfur hexofluoride. These gases are synthetic and powerful. Despite they are emitted in smaller quantities, they are sometimes referred as high global warming potential gases.

Human activities contribute to the level of the GHG emissions, although CO_2, CH_4, N_2O already exist naturally in the atmosphere. The most important greenhouse gas produced by human activities is carbon dioxide. CO_2 is released into the atmosphere by the burning of solid waste, fossil fuels (oil, coal and natural gas), and also as a result of certain chemical reactions. CH_4 is emitted by the production of oil and coal, by the degradation of organic waste in municipal solid waste landfills. N_2O is emitted during industrial and agricultural activities, combustion of fossil fuels and solid waste.

Concentration is the amount of a particular gas in the atmosphere. Greenhouse gas concentrations are measured in parts per million (ppm), parts per billion (ppb), and even parts per trillion (ppt). GHG emissions can remain in the atmosphere from a few to thousands of years. All of these gases can become well-mixed, meaning that the amount measured in the atmosphere is roughly the same all over the world, regardless of the source of the emissions.

Since the beginning of the Industrial Revolution, concentrations of CO_2, CH_4, and N_2O have all risen dramatically because of human activities. Fossil fuel combustion, land-use change, increasingly intensive agriculture, and an expanding global human population are the primary causes for these increases. Land-use change such as deforestation interferes with the carbon cycle, moving carbon from its solid form to the gaseous state, made atmospheric concentrations of carbon dioxide increased. While concentrations of carbon dioxide were about 280 ppm in the eighteenth century, it is approximately 390 ppm presently. This increase of concentration of CO_2 can associate with the industrial revolution. Emissions from the combustion of fossil fuels account for about 65% of the carbon dioxide added to the atmosphere. The remaining 35 % is derived from deforestation and the conversion of woodland, and forestry ecosystems primarily into less productive agricultural systems (Reay & Hogan, 2010).

Methane is the second important gas in the atmosphere. Methane is emitted from both natural and anthropogenic sources. Natural sources of CH_4 include fires, geological processes, and bacteria that produce notably wetlands. Major anthropogenic sources of CH_4 are fossil fuel combustion and agriculture. Some sources can be related to both natural and anthropogenic processes, for example forest and grassland fires (CH_4 and N_2O from natural sources). CH_4 is emitted by rice cultivation, ruminant livestock sector, oil and gas extraction, coal mining, landfill out gassing. Especially rice cultivation accounts for about 20 % of worldwide methane emissions. Rice is the main source of methane, in especially developing Asian countries, because of the production of paddy cultivation and landfills. Another important source of methane emissions is grazing animals. They release methane to the atmosphere as a result of herbaceous digestion.

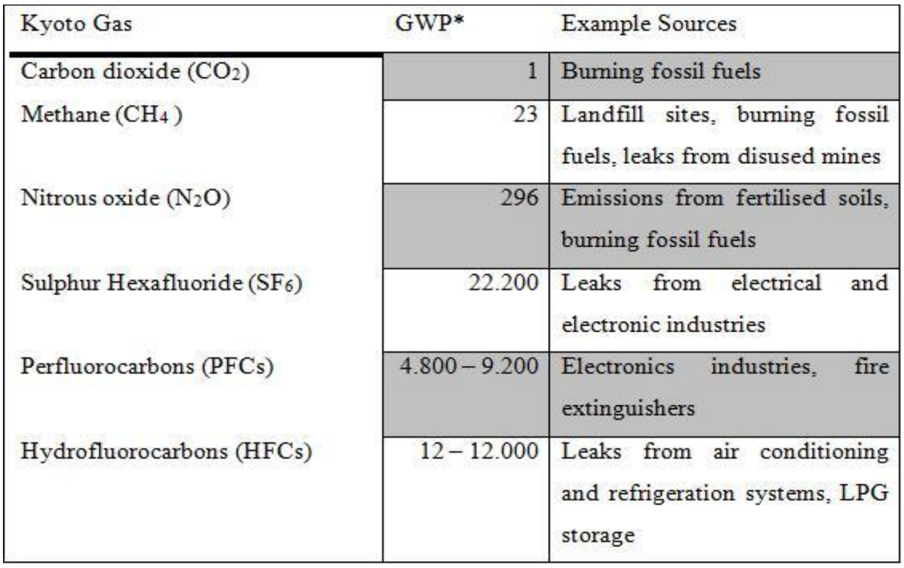
Contribution of nitrous oxide to the greenhouse effect is about 6 %. Agricultural activities, such as fertilizer use, are the primary source of N_2O emissions. N_2O is also emitted from both natural and anthropogenic sources, like CH_4. Sources of nitrous oxide in the atmosphere are fossil fuel combustion, biomass burning, soil fertilization, and chemical industrial processes.

Fluorinated gases (F-gases) which are man-made gases that included chlorofluorocarbons (CFCs), hydrofluorocarbons (HFCs) and sulphur hexafluoride (SF_6). They are highly persistent in the atmosphere and used as refrigerants, propellants and in electronics production. The Montreal Protocol is the international agreement that phases out ozone-depleting substances. The use of F-gases is limited by the Montreal Protocol of 1987. While reductions in the use of F-gases have restricted in Western Nations for twenty years, these chemicals are still used in some developing countries. The Montreal Protocol requires the end of chlorodifluoromethane production by 2020 in developed countries and 2030 in developing countries. CFCs have been gradually phased out in most nations and replaced by HFCs which avoid ozone depletion problems, but are still very potent greenhouse gases. The Kyoto Protocol aims to reduce emissions of these HFCs by tighter controls and the use of new alternatives such as using butane or propane as the coolant in refrigerators rather than HFCs (Reay & Hogan, 2010).

According to the Intergovernmental Panel for Climate Change (IPCC), the excessive generation of GHGs notably CO_2, CH_4, and N_2O by human activities such as deforestation, production and consumption of fossil fuels, and industrial and agricultural activities has been partly responsible for global warming and climate change.

It was mentioned that GHGs absorb thermal radiation reflected from the surface of the Earth and reduce the amount of energy that escapes to the atmosphere, thus leading to an increase in temperature. The contribution of a GHG to global warming is commonly expressed by its global warming potential (GWP). For each greenhouse gases, a GWP has been calculated to reflect how long it remains in the atmosphere, in average, and how strongly it absorbs energy. Gases with a higher GWP absorb more energy than gases with a lower GWP, and thus contribute more to the warming of the Earth. GWP is used the comparison of global warming impact of the gas by referencing typically CO_2. In simple terms, the GWP defines the potential of GHG is relatives to CO_2. The GWP of each GHG can be expressed in CO_2 equivalents as shown in the Table 1.1. The remaining GWP values vary significantly depending on the type of gas. For example methane's global warming potential value is 23 kg equivalent CO_2, but the global warming potential of nitrous oxide is 296 kg equivalent CO_2 (IPCC, 2001). For gases with a high global warming potential, a relatively small emission can have a considerable impact.

Table 1.1 GWP of each GHGs (Abbott , 2008)



Kyoto Gas	GWP*	Example Sources
Carbon dioxide (CO_2)	1	Burning fossil fuels
Methane (CH_4)	23	Landfill sites, burning fossil fuels, leaks from disused mines
Nitrous oxide (N_2O)	296	Emissions from fertilised soils, burning fossil fuels
Sulphur Hexafluoride (SF_6)	22.200	Leaks from electrical and electronic industries
Perfluorocarbons (PFCs)	4.800 – 9.200	Electronics industries, fire extinguishers
Hydrofluorocarbons (HFCs)	12 – 12.000	Leaks from air conditioning and refrigeration systems, LPG storage

*The global warming potential of a gas is its relative potential contribution to climate change over a 100 year period.

Wastewater treatment processes are significant sources of GHGs, specially CO_2, CH_4, and N_2O. These GHGs associated with wastewater conveyance and treatment. For example, CO_2 is a product of the aerobic degradation of organic matter. Methane is a product of the anaerobic decomposition of an organic matter. Nitrous oxide is created during the incomplete reduction of nitrate to nitrogen gas.

The U.S. Inventory of Greenhouse Gas Emissions and Sinks estimates wastewater treatment to be the seventh largest source of N_2O and the eighth largest source of CH_4 emissions, corresponding to approximately 4 % and 2 % of total annual emissions. From 1990 to 2007, wastewater treatment plants, N_2O emissions increased by 32 % and CH_4 emissions by 4 % (United States Environmental Protection Agency [USEPA], 2009).

1.2 Description of Carbon Footprint

Carbon footprint has become a very popular term recently; the increasing interest in carbon footprint comes as a result of awareness of global warming. Global warming is a type of climate change, and it refers to the increasing temperature of the surface of the Earth. Climate change is the rise in long term, global weather patterns due to human action and includes any change resulting from different factors, such as deforestation or an increase in GHGs. The increased concentration of GHGs in the atmosphere leads to rise of temperature and sea level, flooding, and causes for extreme weather conditions. Reduction of these emissions helps abate climate change and bring benefits to human health. People from all over the world appreciated the need to reduce GHG emissions to mitigate climate change. They begins to take responsibility about it.

A carbon footprint is defined as the total amount of greenhouse gases produced from directly and indirectly human activities, usually expressed in equivalent tons of carbon dioxide (CO_2). Carbon dioxide is also called greenhouse gas that causing global warming. Other greenhouse gases, for example methane (CH_4), ozone (O_3) etc., can be emitted as a result of people's activities such as driving a car, burning fuels. These greenhouse gases are normally also taken into account for the carbon footprint. A carbon footprint is an important tool to understand the impact of human behavior on global warming and it can be measured for an individual or an organization. In other words, the carbon footprint concept has emerged from the need of a tool to measure and quantify the climate change performance of an activity or a product. The global average of carbon footprint is about 4 tons of CO_2-eq per year.

Nearly everything we do produces GHG emissions either directly or indirectly. Direct GHG emissions sources are often easy to identify, for example burning fossil fuels for electricity generation, heating or transport. It sometimes less obvious that products and services also cause indirect GHG emissions throughout their life-cycles. Energy is required for production and transport of products, and GHGs emissions are also released when products are disposed at the end of their useful lives (Abbott, 2008).

The main reason for calculating a carbon footprint is to inform decision makers on how to reduce the climate change impact of companies, services or products. Calculating a carbon footprint can be a first step towards making quantifiable emissions reductions. It can also provide long term financial savings as well as reducing climate change impact (Stern, 2006). Carbon footprint methodologies range from simple online calculators to complex life-cycle analysis. Web-based calculators tend to only cover carbon dioxide emissions.

The Greenhouse Gas Protocol (GHG Protocol), a partnership between the World Resources Institute (WRI) and the World Business Council for Sustainable Development (WBCSD), is working with businesses, governments, and environmental groups around the world to build a new generation of credible and effective programs for tackling climate change. The GHG Protocol is the most widely used international accounting tool for government and business leaders to understand, quantify, and manage greenhouse gas emissions. The Corporate Standard provides guidance and standards for companies preparing a GHG inventory (Bakhshi, 2009). The Initiative also has an online calculation tools for calculating greenhouse gas emissions for a variety of business sector. The calculation tools can be used for all types of industry.

The GHG protocol divides emissions sources into three scopes. Scope 1 includes the direct greenhouse gas emissions and scope 1 emissions are defined as “direct GHG emissions occur from sources that are owned or controlled by the company” in The GHG Protocol Initiative (2004). Scope 2 includes beside the direct GHG emissions from scope 1 also the GHG emissions that occur from use of electricity. By the GHG Protocol Initiative (2004), the extra emissions are described as “GHG emissions from the generation of purchased electricity consumed by the company”. Scope 3 includes besides the GHG emissions of scope 1 and 2, also other indirect GHGs. This is applicable to emissions from sources not owned or controlled by the company (Snip et al., 2010).

There are different types of models available to estimate the GHG emissions. Empirical static models, that estimate the emissions as an average value for a given period, are such as Bridle Consulting (2007); National Greenhouse Gas Inventory Committee (2007); Monteith, Shaley, MacLaen & Bagley (2005).

There are lots of benefits of calculating and managing carbon footprint. At first, the calculation of the carbon footprint helps to reduce GHGs and mitigate climate change. Calculating of carbon footprint provides devising and implementing carbon reduction plans. Reducing costs such as energy consumption are also provided by managing of carbon footprint. And finally, calculation and management of footprint helps to understand the level of carbon risk exposure and it can be reduced efficiently (Suwanteep et al., n.d.).

1.3 Existing Protocols and Legislations

The Intergovernmental Panel on Climate Change (IPCC) is responsible for assessing the science related to climate change at a global level. The IPCC Guidelines (1996) were the first widely-used international standard for GHG emissions accounting. The IPCC Guidelines for National Greenhouse Gas Inventories (2006) were produced at the invitation of the United Nations Framework Convention on Climate Change (UNFCCC) to update the Revised 1996 Guidelines and associated good practice guidance which provide internationally agreed methodologies intended for use by countries to estimate greenhouse gas inventories to report to the UNFCCC (IPCC, 2006). Structure of the 2006 Guidelines consists of 5 volumes. From volume 2 to volume 5, GHG emissions are divided into main sectors, sources, and sinks: Energy, Industrial Processes and Product Use (IPPU), Agriculture, Forestry and Other Land Use (AFOLU), Waste. Furthermore, 2006 Guidelines also include one for general guidance (volume 1) applicable to all sectors: “General Guidance and Reporting”.

The IPCC Guidelines (1996) provide simple methodological approach for estimating GHG emissions. According to this approach, the amount of emissions can be estimated by multiplying emission factor and activity data. The 2006 IPCC guidelines generally provide advice on estimation methods at three levels of detail, from tier 1 to tier 3. A tier represents a level of methodological complexity and accuracy in GHG accounting. Tier 1 is the basic method, Tier 2 is intermediate, and Tier 3 is most demanding in terms of complexity and data requirements (IPCC, 2006).

IPCC methods use the following concepts: good practice, tiers, default data, key categories. According to IPCC, in order to promote the development of high quality national greenhouse gas inventories a collection of methodological principals, actions and procedures were defined in the previous guidelines and collectively referred to as good practice. Tiers have already explained above. Default data definition given by the IPCC as follows: “Tier 1 methods for all categories are designed to use readily available national or international statistics in combination with the provided default emission factors and additional parameters that are provided, and therefore should be feasible for all countries”. The concept of key category is used to identify the categories that have a significant influence on a country’s total inventory of greenhouse gases in terms of the absolute level of emissions and removals, the trend in emissions and removals, or uncertainty in emissions and removals. Key Categories should be the priority for countries during inventory resource allocation for data collection, compilation, quality assurance/quality control and reporting (IPCC, 2006).

The IPCC Guidelines also provides protocols and estimation methodologies for GHG emissions from wastewater treatment, composting, and other some practices relevant to biosolids management. Most of other protocols do not have specific methodologies for these activities yet.

The GHG Protocol Initiative is prepared by The World Resources Institute/World Business Council for Sustainable Development (WRI/WBCSD), is the first widely accepted protocols for development GHG inventories. This GHG Protocol is the basis for most subsequent protocols. The GHG Protocol is based on five principles: relevance, completeness, consistency, transparency, and accuracy. These principles are described in detail briefly in the next section.

The GHG Protocol: A Corporate Accounting and Reporting Standards (the Corporate Standards) was first published in 2011. The Corporate Standard is a part of the GHG protocol that provides the framework for developing a GHG inventory and contains methodologies for both private and public businesses and organizations to inventory and report their GHG emissions (Huxley, et al., 2009). The Corporate Standard does not have protocols specific to wastewater treatment or biosolids management. Spreadsheet calculators for a variety of business and activities have been developed (Sylvis, 2009). The contents of the Corporate Standards are as follows:

1. GHG Accounting and Reporting Principles
2. Business Goals and Inventory Design
3. Setting Organizational Boundaries
4. Setting Operational Boundaries
5. Tracking Emissions over Time (for base year assessment)
6. Identifying and Calculating GHG Emissions
7. Managing Inventory Quality
8. Accounting for GHG Reductions
9. Reporting GHG Emissions
10. Verification of GHG Emissions
11. Setting GHG Targets

The GHG Protocol website also contains Calculation Tools for calculating greenhouse gas emissions for cross sector tools and sector-specific toolsets. Cross sector tools include GHG emissions from stationary combustion, indirect CO_2 emissions from purchased electricity, heat or steam, CO_2 emissions from transport or mobile sources, emissions from employee commuting, measurement and estimation uncertainty for GHG emissions, CO_2 emissions from fuel use in facilities and business travel, allocation of emissions from a combined heat and power plant. Sector-specific toolsets for calculating greenhouse gas emissions include these sectors such as adipic acid, aluminum, ammonia, cement, iron and steel, lime, nitric acid, pulp and paper, refrigeration and air-conditioning equipment, semi-conductor, wood products. The Protocol also includes a Project Accounting Protocol and Guidelines for Calculating Reductions in GHG emissions from specific GHG reduction projects or climate change mitigation projects, such as Land Use, Land-Use Change and Forestry. The GHG Protocol and its Calculation Tools can be accessed at the website.

Other protocols and guidelines are developed by the California Climate Action Registry (CCAR), The Climate Registry (TCR), U.S. Environmental Protection Agency (USEPA) Climate Leaders, and International Organization for Standardization (ISO) 14064.

Climate Leaders is a USEPA industry-government partnership that works with companies to develop long-term comprehensive climate change strategies (USEPA, 2009). The Climate Leaders Design Principles guidance (USEPA, 2005) provides the general GHG accounting and reporting principles. These principles are similar to the GHG Protocol and assist in determining organizational and operational boundaries, identifying goals and objectives, managing inventory quality, and also setting reduction tools. The program also includes information on cross-sector guidance, such as quantifying GHG emissions from stationary combustion, mobile combustion, electricity usage, and fugitive emissions. Sector-specific guidance is provided for estimating process emissions from municipal solid waste landfills, but it not provided for water utilities (Huxley, et al., 2009). Emission factors for the quantification of direct emissions included in the guidance documents were developed from the USEPA Inventory of Greenhouse Gas Emissions and Sinks. The program's inventory guidance documents can be viewed at USEPA's website.

The California Climate Action Registry (CCAR) is a non-profit organization. The purpose of this organization is to help establishing GHG emissions baselines and reducing future GHG emissions in California. CCAR also developed the CCAR General Reporting Protocol in 2008. It contains quantifying emissions from various manufacturing processes and cross sector emissions. CCAR has also an online tool for reporting, known as the Climate Action Registry Reporting Online Tool (CARROT).

The International Council for Local Environmental Initiatives (ICLEI) is an international organization and it has a comprehensive protocol for accounting and reporting of GHG emissions inventories for domestic and foreign local governments. This protocol is similar to the WRI/WBCSD GHG Protocol. The ICLEI Protocol also provides guidance on quantifying direct emissions from stationary combustion, mobile combustion, fugitive and process-related sources and also offers options for estimating indirect emissions.

The ICLEI Protocol indicates that emissions from wastewater should be determined based on the First Order Decay model developed by the IPCC and described in the 2006 Guidelines for National Greenhouse Gas Inventories (Huxley, et al., 2009).

The Climate Registry (TCR) is a nonprofit organization and was developed to set standards for the measurement, verification, and public reporting of GHG emissions throughout North America in a single registry. TCR supports both voluntary and mandatory reporting programs for various states in North America and some Canadian provinces. TCR published its General Reporting Protocol (GRP), version 1.1 in 2008. GRP of TCR provides guidance and tools for calculating emissions from sectors, such as aluminum, cement, iron and steel, pulp and paper production. The

GRP also contains cross-sector guidelines for mobile combustion, stationary combustion, and fugitive emissions. TCR has adopted the IPCC's tier system, but it has renamed tiers and changed the order. Tier A is the preferred and most complex, accurate and demanding of data from local measurements. Tier B is intermediate level, and Tier C is the least complex and accurate.

TCR published the first version of its Local Government Operations protocol (LGO) in 2008. LGO protocol includes details on calculating emissions from wastewater treatment facilities, although it has only limited information regarding biosolids management. TCR recently teamed with CCAR and the International Council for Local Environmental Initiatives (ICLEI) to develop the Local Government Operations Protocol for the quantification and reporting of greenhouse gas emission inventories (Huxley, et al., 2009; ICLEI, 2008). The Climate Registry General Reporting Protocol can be found at its website.

The International Organization for Standardization (ISO) is a worldwide federation of national standards bodies. ISO develops international standards for government, business, society; and it published the ISO 14064 Standard for GHGs accounting protocol in 2006. International Standards is normally carried out through ISO technical committees, and ISO 14064 was prepared by Technical Committee. ISO 14064 is expected to benefit organizations and governments worldwide by providing clarity and consistency for quantifying, monitoring, reporting, and verifying GHG inventories or projects. The Standard contains three parts are as follows:

- ISO 14064 - 1: 2006, Greenhouse gases – Part 1: Specification with guidance at the organization level for the quantification and reporting of GHG emissions and removals.
- ISO 14064 - 2: 2006, Greenhouse gases – Part 2: Specification with guidance at the project level for the quantification, monitoring, and reporting of GHG emission reductions and removal enhancements.

- ISO 14064 – 3: 2006, Greenhouse gases – Part 3: Specification with guidance for the validation and verification of GHG assertions (ISO 2006).

ISO 14064 Part 1 contains guidance on inventory design and quality, reporting of GHG emissions, data management, and preparation for verification similar to the GHG Protocol. This part of the Standard also contains information on indirect emissions and GWPs; but there are no quantification tools. Part 2 of the Standard focuses on quantification of reduction of GHGs. Finally, the last part of the Standard provides guidelines for verification of inventories.

In order to estimate GHG emissions from WWTPs, the Life Cycle Assessment (LCA) analysis can be performed. LCA studies have shown that impacts associated with operating water or wastewater treatment plants are dominated by operational inputs and outputs. In order to make better use of calculation tools for estimating GHG emissions or constructing LCA models, good inventory data is required. LCA methodology is defined in ISO 14040/44 (Bringewski, 2011). LCA is a process of assessing the total environmental, social, and economic impacts of a product or action. ISO 14040:2006 describes the principles and framework for LCA including: definition of the goal and scope of the LCA, the life cycle inventory analysis (LCI) phase, the life cycle impact assessment (LCIA) phase, the life cycle interpretation phase, reporting and critical review of the LCA, limitations of the LCA, the relationship between the LCA phases, and conditions for use of value choices and optional elements. Estimating GHG emissions is generally a part of a LCA.

The United Kingdom Water Industry Research (UKWIR) Workbook for Quantifying Greenhouse Gas Emissions is published in 2005. The Workbook is focused specially on estimating GHG emissions of water utilities. The GHG accounting tools and guidelines are developed by a partnership of UKWIR, Water UK, and the Carbon Trust. These protocols ensure companies in the UK are able to measure and report GHG emissions. Protocols and guidelines include spreadsheet calculators available for a cost from UKWIR. Also in 2007, the Water Services Association of Australia (WSAA) published Fugitive Greenhouse Gas Emissions from Wastewater Systems (Foley & Lant, 2007). It includes a throughout literature review and identification of emissions factors for WWTP processes. The report also includes detailed sections and information on sludge management.

1.4 GHG Accounting and Inventory Principles

World Resources Institute/World Business Council on Sustainable Development's (WRI/WBCSD) Corporate Accounting and Reporting Guidance develop five principles of GHG accounting that ensures a high quality GHG emission inventory. These principles are relevance, completeness, consistency, transparency, and accuracy. These principles also ensure the reporting of accurate GHG inventory.

Relevance is defined by the Protocol as, "Ensure that the GHG inventory appropriately reflects the GHG emissions and serves the decision-making needs of users - both internal and external to the organization". An important aspect of relevance is the selection of an appropriate inventory boundary. When choosing the inventory boundaries, some factors must be considered, such as organizational structures, operational boundaries (on-site and off-site activities), and business context such as industry sectors, geographic locations, purposes of information etc.

Completeness is accounting and reporting all GHG emission sources and activities within the defined inventory boundary. All relevant emissions sources within the chosen inventory boundary need to be accounted. But in practice, a lack of gathering data may be a limiting factor. In such cases with a lack of data must be documented for transparency.

Consistency is essential to producing comparable GHG emissions data over time. The consistent application of accounting approaches, inventory boundary, and calculation methodologies is important to ensure comparable GHG information. The Protocol is clearly denoted that whether there are any changes in the inventory boundary, methods, and data is affecting emission estimates and these changes should be transparently documented.

Transparency relates to the degree to which information on the process, procedures, assumptions, and limitations of the GHG inventory are disclosed in a clear. A “transparent” report will provide a clear understanding of the issues in the context of the reporting company and a meaningful assessment of performance. An independent external verification is a good way of ensuring transparency and determining that an appropriate audit trail has been established and documentation provided (GHG Protocol, 2008).

Accuracy is defined by the Protocol as GHG emissions estimations should be closely as possible as the actual emission values. Uncertainties must be reduced as much as possible. GHG measurements, estimates, or calculations should be systemically. Accuracy helps promoting credibility and enhancing transparency.

Each processes, products, or services generate direct or indirect GHG emissions. As mentioned above that WRI/WBCSD Greenhouse Gas has categorized the GHG emissions according to emission sources: Scope 1 (direct), Scope 2 (indirect) and Scope 3 (optional indirect). Scope 1 is defined as “GHG emissions that occur within the territorial boundary of the city or local region”. Scope 1 emissions can also be broken down into the following subsets:

- *Stationary Combustion Sources:* These sources are fixed. These sources include combust to produce steam, heat, power, or electricity at facilities within the organizational boundaries. There is some stationary equipment, such as boilers, furnaces, burners, turbines, heaters, incinerators, engines, flares, etc.
- *Mobile Combustion Sources:* Sources include movable equipment or transportation vehicles that combust fuels to operate. Combustion of fuels in transportation devices such as cars, trucks, buses, trains, airplanes, boats, ships, barges, vessels, etc.
- *Process Emission Sources:* These sources include emissions from physical or chemical processes, such as CO_2 from the calcinations step in cement manufacturing, CO_2 from catalytic cracking in petrochemical processing, PFC emissions from aluminum smelting, etc. Methane production from anaerobic processes of wastewater

treatment plants would be considered a process emission source. Process emissions are generally only relevant to certain industry sectors like aluminum, cement, etc.

- *Fugitive Emission Sources:* intentional and unintentional releases such as equipment leaks from joints, seals, packing, gaskets, as well as fugitive emissions from coal piles, wastewater treatment, pits, cooling towers, gas processing facilities, etc. (GHG Protocol, 2008).

According to Protocol, Scope 2 include that the indirect emissions that occur outside of the city boundary as a result of activities that occur within the city. In Scope 2, these indirect emissions are limited to only electricity consumption; district heating, steam and cooling. The Protocol noted that all Scope 2 emissions are double-counted. The entity generating the electric power includes the associated emissions in its Scope 1 inventory, but the consumer of the power includes its fraction of the same emissions in its Scope 2 inventory (Huxley, et al., 2009).

Scope 3 is defined as, “Other indirect emissions and embodied emissions that occur outside of the city boundary, as a result of activities of the city” (Urban GHG Standard, 2010). Scope 3 include electrical transmission and distribution losses, solid waste disposal, waste incineration, wastewater handling, aviation, marine, embodied emissions upstream of power plants; embodied emissions in fuels, imported construction materials, imported water, imported food.

A Corporate Accounting and Reporting Standard provides accounting standards and guidance for preparing a GHG inventory for companies or other entities, such as universities. The Corporate Standard addresses such issues as determining the inventory’s boundaries, establishing and adjusting a base year, and deciding on the information to include in a public GHG report. Key steps in developing GHG inventory is shown in Figure 1.1.

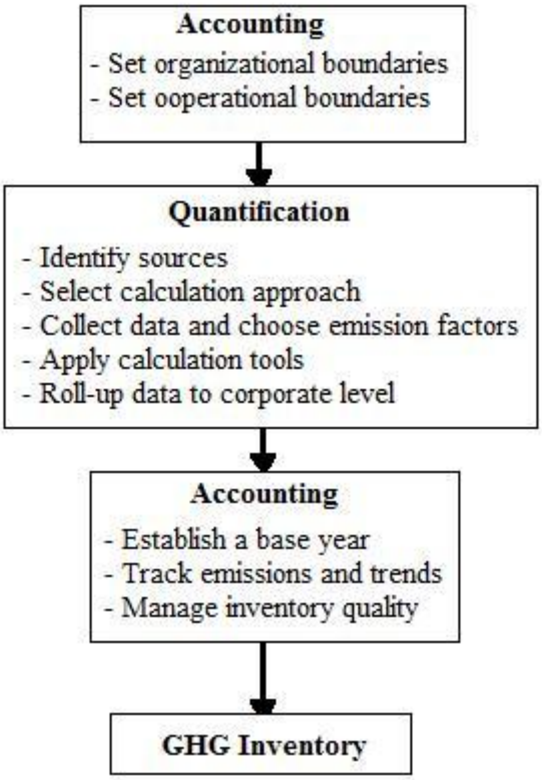


Figure 1.1 Steps in development inventory (GHG Protocol, 2008)

1.4.1 Defining Organizational and Operational Boundaries

The first step in completing a GHG emissions inventory is determining the content of the inventory. Setting organizational and operational boundaries determines the framework for the inventory. The organizational boundaries of GHG accounting specify which parts of an organization’s emissions are included in its inventory. The operational boundaries divide the entity’s sources into different types of direct and indirect emissions, or scopes (GHG Protocol, 2008).

1.4.1.1 Setting Organizational Boundaries

There are two approaches for definition of organizational boundaries in most of the protocols and guidance documents: Equity share and control approach. Which approach is recommended often depends on the structure of the industry and the objective of the GHG inventory. Companies operating GHG-intensive units and facilities often prefer control approaches (operational or financial), because with this approach, most of their relevant GHG emissions are included in the inventory. This approach also provides possibilities to companies for reducing their GHG emissions. Sectors with complex upstream and downstream supply chains that represent a significant portion of the GHG emissions and in which they often hold extensive equity investments and have significant influence - but not control of operations - may prefer the equity share approach. This allows them to think about their GHG emissions and ways of reducing emissions more broadly (GHG Protocol, 2008).

For the Equity Share approach, inclusion of an operation in the inventory is primarily determined by financial ownership (Huxley, et al., 2009). Under equity share approach, an entity would report all GHG emissions from sources wholly-owned and partially owned. A company accounts for GHG emissions from operations according to its share of equity in the operation. The equity share reflects economic interest, which is the extent of rights a company has to the risks and rewards flowing from an operation (GHG Protocol, 2008).

For the Control approach, an entity must determine whether control is based on operational or financial control of the asset. Under the Control approach, an entity would report 100 percent of the GHG emissions from operations over which it has control. It does not account for GHG emissions from operations in which it owns an inters but has no control. Control can be defined in either financial or operational terms. When using the control approach, an entity must choose between either the operational control and financial control approach as defined below:

- Financial Control: The decision to use financial control should be based upon the same procedures employed in an entity’s financial accounting process. An entity has financial control if it directs the financial policies of the asset.
- Operational Control: The decision to use operational control should be based upon the same procedures employed in an entity’s operating policy. An entity has operational control if it has full authority over the operational policies (operating

policies and health, safety, and environmental policies) of the asset or holds the operating license (Huxley, et al., 2009).

1.4.1.2 Setting Operational Boundaries

After determining of organizational boundaries, operational boundaries will be determined. This involves identifying emissions, categorizing them as direct and indirect emissions, and choosing the scope of accounting and reporting for indirect emissions. To set operational boundaries, the entity identifies all relevant sources within its organizational boundaries, classifies them as either direct or indirect emissions based on ownership, and allocates the indirect emissions to either scope2 or scope 3 (GHG Protocol, 2008). Definition of Scope 1, 2, and 3 emission sources are given above. A Corporate Accounting initiatives and most voluntary initiatives require that the GHG inventory include all scope 1 and scope 2 emissions. Generally, entities do not include scope 3 emissions unless there are sources for significant emissions.

After the emission sources are identified, then the gases will be reported. CO_2 emissions will be included for every source category. For scope 1 direct emissions, CH_4 and N_2O emissions are included for stationary and combustion sources. Emission concentration of CO_2, CH_4, N_2O can vary depending on processes. Fugitive emissions sources mainly emit HFCs, PFCs, and SF_6. Scope 2 indirect emissions are only based on purchased utilities: electricity, steam, and hot or chilled water. As a consequence, there will be emissions of CO_2, CH_4, and N_2O resulting from stationary combustion of fuels associated with production of these utilities (Huxley et al., 2009). Scope 3 optional indirect emissions sources vary depending on out-sourced activities. Summary of greenhouse gases by emission sources is shown in Table 1.2.

Table 1.2 GHGs by emission sources (Huxley, et al., 2009)

Emission Source Type	GHG Emission
Scope 1 – Direct Emissions	
Stationary Combustion	
- Fuel Combustion	CO_2, CH_4, N_2O
- Incineration of other materials	CO_2, CH_4, N_2O
Mobile Combustion	CO_2, CH_4, N_2O
Processes	CO_2, CH_4, N_2O, HFCs, PFCs, SF_6
Refrigeration/Cooling Agents	HFCs, PFCs
Water Treatment	CH_4, N_2O
Scope 2 – Indirect Emissions	
Indirect Emissions (electricity, steam purchase)	CO_2, CH_4, N_2O
Scope 3 – Other Indirect Emissions	
Indirect Emissions – upstream product usage, transport	CO_2, CH_4, N_2O (typical)
Indirect Emissions – downstream product usage, transport, etc.	CO_2, CH_4, N_2O (typical)

1.4.2 Identifying and Calculating GHG Emissions

A few steps are followed to calculate the GHG emissions, after the inventory boundary are established. According to the GHG Protocol, identifying and calculating GHG emissions include five steps: identifying sources, selecting calculating approach, collecting data and choosing emission factors, applying calculation tools, rolling up data to corporate level.

The first step of the identifying and calculating GHG emissions is identifying emissions sources. The GHG Protocol calculation tools are organized based on the four source categories listed above to identifying scope 1 emission. After determining the scope 1 emissions, scope 2 emissions must be calculated. Almost all services and processes generate indirect emissions addition to direct emissions due to use of electricity, heat or steam. The final step in the stage of determining emission sources is identification of other indirect emissions (scope 3). This is the optional step. Scope 3 emissions associated with outsource manufacturing and not include in scope 1 or scope 2. Identifying of scope 3 emissions allows expanding inventory boundary and determining all relevant GHG emissions. It also provides opportunities for significant GHG emission reductions.

The second step of identifying and calculating GHG emissions is selecting a calculation approach. Emission factors may be based on data collected, averaged, or aggregated differently depending on the intended use of the emission factor and the availability of the data. GHG Protocol calculation tools provide default emission factors from several sources, for example the IPCC, USEPA. The most common approach for calculating GHG emissions is through the application of documented emission factors.

In the step of collecting activity data and choosing emission factors, published emission factors are used to calculate GHG emission. Scope 3 GHG emissions will primarily be calculated from activity data. In most cases, if source or facility specific emission factors are available, they are preferable the general emission factors.

GHG Protocol Corporate Standards provide more accurate and consistent GHG calculation methods for companies than their own calculation methods. There are two main categories of calculation tools in applying calculation tools section: cross-sector tools and sector-specific tools. Cross-sector tools can applied to different sectors that include stationary combustion, mobile combustion. Sector-specific tools are designed to calculate emissions in specific sectors, such as aluminum, cement, oil and gas, pulp and paper, etc. Each of these tools consists of a guideline and worksheets. The guideline provides the possibility to choose activity data and emission factors, calculation methods, and quality control section. In some cases, both of these tools can be used to calculate all GHG emissions.

The last step of identifying and calculating GHG emissions according to the GHG Protocol is rolling-up GHG emissions data to corporate level. GHG programs or initiatives may have specific requirements regarding how data must be collected. The tools and processes chosen to report data will depend upon the information and communication infrastructure. Data collection and management tools could include:

- Secure databases available over the company intranet or internet, for direct data entry by facilities,
- Spreadsheet templates filled out and e-mailed to a corporate or division office, where data is processed further,
- Paper reporting forms faxed to a corporate or division office where data is re-entered in a corporate database. However, this method may increase the likelihood of errors if there are not sufficient checks in place to ensure the accurate transfer of the data (GHG Protocol, 2008).

According to the GHG Protocol, there are two basic approaches for gathering data on GHG emissions: centralized and decentralized. In centralized approach, individual facilities report activity data to the corporate level, where GHG emissions are calculated. Centralized approach may be suitable for office- based organization. In decentralized approach, individual facilities collect activity data, directly calculate their GHG emissions using approved methods, and report this data to the corporate level (GHG Protocol, 2008). Two approaches can be used to maximize accuracy.

1.4.3 Accounting GHG Emissions

To track emissions over time, choosing a base year and drawing up a base year emissions recalculation policy is required. If the GHG initiative or program does not require using a single year or an averaging approach for choosing a base year, year-to-year GHG emissions stability may help making a more informed decision (GHG Protocol, 2008). GHG programs must have general guidelines for calculating the base year. A fixed base year helps to compare GHG emissions data over a longer time. Most emissions trading and registry programs require a fixed base year policy to be implemented.

Most GHG programs have guidelines for recalculating the base year according to significant structural changes in the company. But helping companies understand how best to define a “significance threshold” based on the relevant structural changes most likely to affect the sector may be useful (GHG Protocol, 2008). “Significance threshold” is a qualitative or quantitative criterion used to define any significant change to the data, inventory boundary, methods, or any factors. According to the Protocol it is the responsibility of the company to determine the “significance threshold”.

Managing the quality of GHG emissions inventory help to identify the opportunities for improvement. According to the GHG Protocol, a quality management system is essential to ensuring the principles of the GHG Protocol Corporate Standard and anticipates the requirements of future GHG emissions programs. A quality management system provides a systematic process for preventing and correcting errors. However, the primary objective of quality management is ensuring the credibility of a company’s GHG inventory information.

Preparing a GHG inventory is both an accounting and a scientific practice. All of the protocols discuss the uncertainty regarding the accuracy of calculated estimates of GHG emissions (Sylvis, 2009). Uncertainties associated with GHG inventories can be categorized into scientific uncertainty and estimation uncertainty. For example, many direct and indirect factors associated with GWP values that are used to combine emission estimates for various GHGs involve significant scientific uncertainty (GHG Protocol, 2008). According to the Protocol, estimation uncertainty can be further classified into two types: model uncertainty and parameter uncertainty. Model uncertainty refers to the uncertainty associated with the mathematical equations. Parameter uncertainty refers to the uncertainty associated with quantifying the parameters that used in estimation models, such as activity data and emission factors. The GHG Protocol Corporate Standard has developed a supplementary guidance document on uncertainty assessments along with an uncertainty calculation tool, both of which are available on the GHG Protocol website.

In addition to the GHG Protocol's guidance document on uncertainty assessment, guidance and information on assessing uncertainty can also be found in EPA's Emissions Inventory Improvement Program, Volume VI: Quality Assurance/Quality Control (1999) and in chapter 6 of the IPCC's Good Practice Guidance (2000).

In general, GHG emissions are estimated by using activity data, emission factors and global warming potentials. The general equation for estimating GHG emissions is presented in Equation 1.1. Activity data is a measurement of the activities that generate GHG emissions; for example energy use. Emission factors are ratios of the GHGs emitted per unit of activity data; such as metric tons of CO_2 emitted per kilowatt hour of generated electricity (ICF International, 2011). The default emission factors are given GHG protocol and guidance documents, as well as, emission factors can be calculated by using data. GWP values are calculated and published primarily by IPCC, then GWP values has published relevant updates in the Second Assessment Report (SAR), Third Assessment Report (TAR), and Fourth Assessment Report (AR4). These GWP values are shown in Table 1.3.

$$\text{GHG Emission} = \text{Activity data} * \text{Emission factor} * \text{GWP} \tag{1.1}$$

Table 1.3 Global warming potential estimates

		GWP (100 year)		
Common Name	**Formula**	**SAR**	**TAR**	**AR4**
Carbon Dioxide	CO_2	1	1	1
Methane	CH_4	21	23	25
Nitrous Oxide	N_2O	310	296	298
Suphur Hexafluoride	SF_6	23,900	22,200	22,800

Source: Intergovernmental Panel on Climate Change, Second Assessment Report (1995), Third Assessment Report (2001), and AR4 (2007), Huxley et. al. (2009)

The carbon footprint calculation methodologies range from automated web-based calculators to complex life-cycle analysis. Automated web-based calculators, such as BP and BSkyB household calculators, tend to only cover carbon dioxide emissions (Abbott, 2008).

The GHG Protocol work with businesses, governments, and environmental groups around the world to build a new generation of credible and effective programs for tackling climate change. The GHG Protocol calculation tools are used all around the world to manage GHG emissions. In addition, GHG accounting tools are mostly developed for general use or are geared toward a specific industry. The GHG calculation tools generally are made up of a guidance document and Excel spreadsheets that allow industry and service sector users to easily quantify the GHG emissions from the various sources in their inventory, as defined by the Corporate Standard. The GHG calculation tools also provide more specific information not found in the Corporate Standard, such as which activity data and emission factors are required to quantify emissions from a specific source and how to roll up these data into one inventory (GHG Protocol, 2008). The Initiative also has an online calculation tools for calculating greenhouse gas emissions for a variety of business sector. The calculation tools can be used for all types of industry.

According to the IPCC Guidelines for National Greenhouse Gas Inventories, an important goal of IPCC inventory guidance is to support the development of GHG inventories that can be readily assessed in terms of quality. It is good practice to implement quality assurance/quality control (QA/QC) and verification procedures in the development of national greenhouse gas inventories to accomplish this goal. A QA/QC and verification system improves transparency, consistency, relevance, completeness, and accuracy of inventories. The terms of the quality control, the quality assurance and the verification are used in different ways. Quality control (QC) is a system of routine technical activities to assess and maintain the quality of the inventory. QC activities also include technical reviews of categories, activity data, emission factors, other estimation parameters, and methods (IPCC, 2006). Quality Assurance (QA) is a system of review procedures in the inventory compilation and development process. Verification refers to the collection of activities and procedures conducted during the planning and development. Verification helps to establish reliability of inventories. More detailed information of QA/QC and verification systems and their procedures can be found in the IPCC Guidelines for National Greenhouse Gas Inventories.

CHAPTER TWO

GREENHOUSE GAS EMISSIONS OF WASTEWATER TREATMENT PLANTS

The greenhouse gases that are emitted in a wastewater treatment plant (WWTP) are CO_2, CH_4, and N_2O. In other words, wastewater treatment plants are recognized as one of the major contributors of GHG emissions. WWTPs produce these emissions during the treatment processes, both directly and indirectly. Direct emissions occur during the treatment process such as CO_2, CH_4, and N_2O. Indirect emissions occur during the use of energy and ancillary activities. In 2011, USEPA have listed WWTPs as the 7th largest contributors to both CH_4 and N_2O emissions.

GHG emissions from WWTPs depend on source of wastewater. It is well known that domestic and industrial wastewaters have significantly different characteristics. The type and amount of GHG production in WWTPs highly depended on the degradable organic materials in wastewater (Ashrafi, 2012). It is also known that organic loading is especially the cause of GHG emissions in WWTPs. Most of the industrial wastewaters have generally very low organic loading which is the cause of GHG emissions (Zhang et al., 2012).

Greenhouse gas emissions produced by unit processes within a typical wastewater treatment plant include CO_2, CH_4, and N_2O. GHG emissions from wastewater treatment plants also depend on the type of treatment system and its configurations. For example primary treatment does not produce significant GHGs; but secondary treatment processes produce all three gases. Specifically, aerobic biological treatment plants emit a significant quantity of greenhouse gases because of using considerable amounts of power (Das, 2011; Shaw et al., 2008).

To estimate the carbon footprint for the wastewater industry entails complex processes that examines all relevant activities that consume energy such as chemical production, transportation, and treatment processes. Although there are many computer software programs that provide carbon footprint estimation for personal use and specific industries, none of them takes into account the total water system contributing elements and the associated geographical variants (Bakhshi, 2009).

The sewerage wastewater is normally treated by screening, primary settling, biological processing, and secondary settling. As mentioned earlier, the organic loading plays a major role of GHGs emission from wastewater treatment as it directly leads to the CH_4 and N_2O emission. Among all the processes bioreactor is the emission generator, while others contribute GHG emissions due to the energy or chemical consumption.

The GHG emissions of wastewater treatment plants are from two sources; one is considered as direct emissions due to the production of CO_2, CH_4, and N_2O during the processes, and the other is called indirect emissions caused by the utilization of electricity, fossil fuels, and materials, such as chemicals. The CO_2 emission from the biological treatment process due to organic matter conversion is not considered as GHG emission, because it will be finally sequenced to the system by photosynthesis and finally reenters the treatment. Therefore, GHG emissions produced in wastewater treatment plants result from CH_4 and N_2O discharges during treatment processes as well as CO_2 emission due to energy consumption.

The emissions of greenhouse gases from wastewater treatment plants can be calculated according to the IPCC Guidelines (1996) and IPCC Good Practice Guidelines (GPG, 2000). The emissions are to be calculated for domestic and industrial wastewater and the resulting two types of sludge; i.e. domestic and industrial sludge. The IPCC methodology is described in detail below.

The main GHGs produced in wastewater treatment plants mostly generated during biological processes. The type of biological treatment becomes a critical factor for GHG emissions. Aerobic, anaerobic, and anoxic are three basic categories of biological treatment, and generally, the three types of treatment operate together in a wastewater treatment plant (Zhang et al., 2012). CO_2 emissions from wastewater are not considered in the IPCC Guidelines because these are of biogenic origin and should not be included in national total emissions.

CH_4 is considered as the most important GHG emitted from the wastewater treatment plant as it contributes 5% of the total global methane emission (El Fadel & Massoud, 2001). Methane production is directly resulting from degradation of the organic matter under anaerobic conditions. When organic materials decay in the absence of oxygen, carbon compounds are converted to highly potent GHG methane. The methanogenesis or CH_4 production rate depends on the concentration of the degradable organic material in wastewater. Biochemical Oxygen Demand (BOD) and Chemical Oxygen Demand (COD) are common parameters used to measure the organic component of the wastewater. Under the same conditions, wastewater with higher COD or BOD concentrations usually yields more CH_4 than wastewater with lower COD or BOD concentration.

CH_4 emissions are emitted in anaerobic conditions. Most of the CH_4 emissions come from open anaerobic reactors, lagoons and the sludge handling processes. Limited amounts of CH_4 can also be emitted from aerobic processes when it is poorly managed (Lim, 2012). Environmental factors also affect the production of CH_4. These environmental factors include pH, temperature, retention time, presence of sulphate reducing bacteria and methanogens (Guisasola et al., 2008). Anaerobic conditions also exist in landfills. Landfills emit much more methane than wastewater treatment plants (USEPA, 2000).

N_2O is related with the degradation of nitrogen components in the wastewater, for example urea, nitrate and protein. Wastewater with a high nitrogen load has a high potential of N_2O emission. There are mainly three ways of nitrous oxide production: nitrification, denitrification, and chemical reaction (Wunderlin et al., 2012; Zhang et al., 2009). Nitrification is an aerobic process. Ammonia and other nitrogen compounds convert into nitrate (NO_3^-) in nitrification process. Denitrification is an anoxic process. Nitrate converts into dinitrogen gas (N_2) in denitrification process. Nitrous oxide can be an intermediate product of both processes but among them, denitrification is more often associated with nitrous oxide emission (IPCC, 2006). Aerobic treatment process produces relatively small emissions, whereas anaerobic processes emission can increase by 50 – 80 % (Park et al., 2000). Combustion of digester gas can also emit small amounts of N_2O gas. Biological nutrient removal (BNR) processes have the ability to transform the ammonia and organic nitrogen compounds into nitrogen gas, which can be released to the atmosphere (Listowski, et al., 2011).

Energy utilization of the treatment is another important contributor of the GHG emission. Electricity consumption in the operation and management of the wastewater treatment plants, pipelines and pumping stations causes the release of GHGs. The quantity of emission depends on the power generation sources, which mainly include coal, hydro, nuclear, heavy fuel oil etc. Chemical consumption, location of treatment plant and climate also affect GHG emissions from WWTPs.

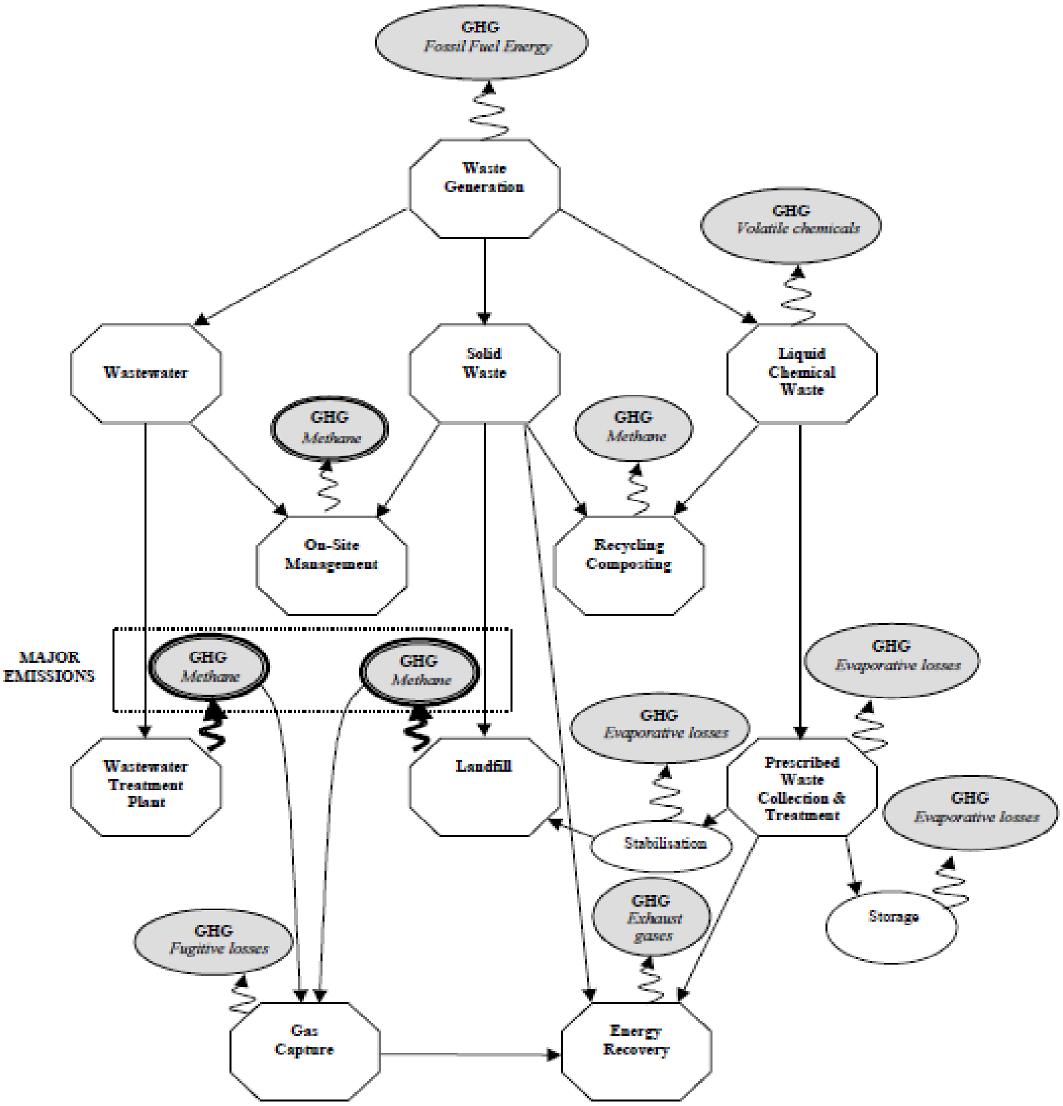


Figure 2.1GHG emissions from the waste and wastewater management sector (USEPA, 2000)

To sum up, WWTPs have been recognized as a source of GHG emissions, because they produce CO_2, CH_4 and N_2O during the treatment processes and CO_2 from the energy demand of the plant. The GHG emissions of wastewater treatment plants are from two sources; one is considered as direct emissions due to the production of CO_2, CH_4, and N_2O during the processes; and the other is called indirect emissions caused by the utilization of electricity, fossil fuels, and materials. Methane is considered as the most important GHG emitted from the WWTPs. Specifically, methane is produced when soluble organic matter of wastewater and sludge are handled by biological processes under anaerobic conditions.

Generally, the methane producing potential of wastewater can be determined in terms of biochemical oxygen demand (BOD) or chemical oxygen demand (COD). Nitrous oxide could also be emitted during wastewater treatment when produced wastewater has significant nitrogen (urea, ammonia, and proteins) loading, ultimately leading to nitrification and denitrification processes responsible for the emission (Zhang, et al., 2012).

2.1 Overview of Wastewater Treatment Plants

Wastewater is treated to remove soluble organic matter, suspended solids, pathogenic organisms, and chemical contaminants. Wastewater treatment facilities remove pollutants from wastewater using a variety of technology. Small wastewater treatment systems include generally septic tanks. Septic tanks are inexpensive and widely used in both developed and developing countries. More advanced treatment systems include activated sludge treatment, trickling filters, anaerobic digestion etc (Gregory & Sutamihardja, n.d). Wastewater treatment systems include a variety of processes depending on the required effluent standards. These systems can vary from primary treatment to secondary biological treatment and also they may include tertiary treatment for nutrient removal, disinfection, and more filtration processes.

Primary treatment, which is also known as pre-treatment, include screens, shredders/chippers, balancing ponds, sand traps, flotation tanks, sedimentation tanks, aerators, filters. Primary treatment is a first stage of most wastewater treatment processes. Oils, fats, grease, rags, grits and large solids are removed by physical processes. To prevent damage to pumps and clogging of pipes, wastewater passes through bar screens. Smaller inorganic materials are removed by a grit removal system. Smaller organic solids remain suspended in the water and flow into larger tanks, called primary clarifiers. The heavier organic solids settle by gravity in primary clarifiers. These settled solids, called primary sludge, are removed along with floating scum and grease and pumped to a sludge process for further treatment.

The wastewater that come from the primary treatment is transferred to biological or secondary treatment processes. Secondary treatment consists of a combination of biological processes that promote biodegradation by microorganisms. The wastewater is mixed with a controlled population of bacteria and an ample supply of oxygen. The microorganisms digest the fine suspended and soluble organic materials, thereby removing them from the wastewater. The effluent is then transferred to secondary clarifiers, where the biological solids or sludges are settled by gravity. There are a number of different processes in secondary treatment, such as activated sludge, trickling filtration, rotating biological contactors, lagoons and ponds.

Tertiary treatment is additional treatment that is needed to remove suspended and dissolved substances remaining after secondary treatment. These processes are used to further purify the wastewater of pathogens, contaminants, and remaining nutrients such as nitrogen and phosphorus compounds (IPCC, 2006). Tertiary treatment processes may be used to remove such things as color, metals, organic chemicals etc. Several processes can be used in tertiary treatment, such as advanced filtration, carbon adsorption, ion exchange, and disinfection.

Sludge is produced in all of the primary, secondary, and tertiary stages of treatment. Sludge produced in primary treatment consists of solids that are removed from the wastewater. Sludge produced in secondary and tertiary treatment results from biological growth in the biomass. This sludge must be treated further before it can be safely disposed of. Methods of sludge treatment include aerobic and anaerobic stabilization, conditioning, and centrifugation, composting, and drying.

2.2 Sludge Treatment and Disposal Processes

Sludge is the end product of water and wastewater treatment plant, whether physical, chemical or biological treatment. Wastewater treatment plants generate millions of tons of sludge every year. Sludge treatment is a major consideration in the designing of wastewater treatment plants. Sludge and its disposal problems are getting greater due to developing of wastewater treatment facilities. Sludge management can be the most complex and costly operation in wastewater treatment plants.

Sludge contains both compounds of agricultural value (including organic matter, nitrogen, phosphorus etc.), and pollutants which consist of organic pollutants, pathogens, heavy metals etc. The solids in the sludge contain nutrients of value to plants, but industrial sources, including wastes and urban runoff, introduce quantities of toxic materials into municipal sludge. Human waste also contains harmful organisms, disease-causing bacteria, viruses and parasites. Sewage sludge consists of the organic and inorganic solids that were present in the raw waste and were removed in the primary clarifier, in addition to organic solids generated in the biological treatment and removed in the secondary clarifier process (Garg, 2009).

The characteristics of sludge depend on the original pollution load of the treated water, and also technical characteristics of the wastewater and sludge treatments carried out. Figure 2.2 shows the flow chart of the sludge that produced by WWTPs. Depending on the treatment processes, sludge can be liquid or semi-solid liquid. All over the world, sludge production is increasing. Sludge treatment is needed to reduce the water and organic content of the sludge and render the solids suitable for reuse or final disposal. The type of treatment needed depends on the disposal method proposed. Sludge has to be treated and disposed, because to prevent environmental contamination and health risk.

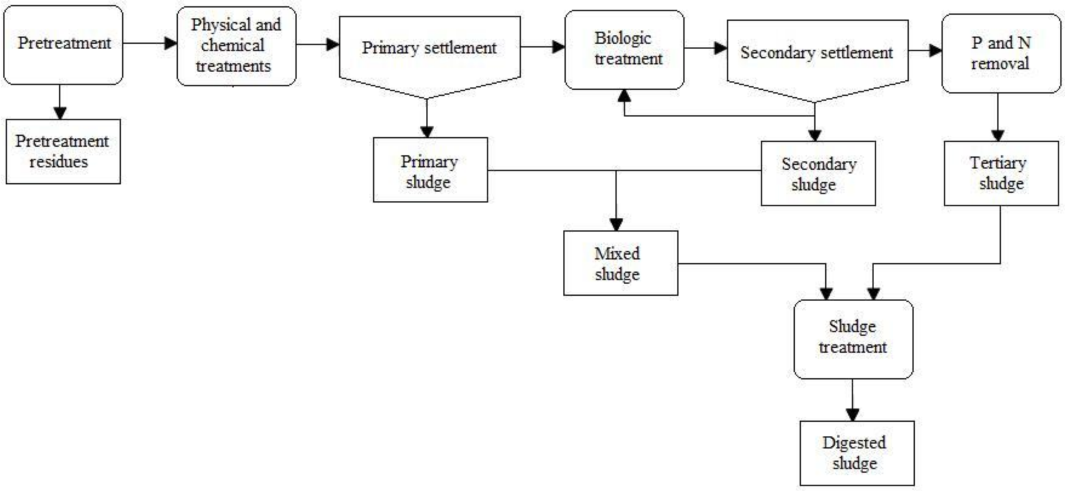


Figure 2.2 Wastewater treatment plants and sludge generation (Brown et al., 2010)

Sludge treatment is aimed at reducing the sludge volume and organic content. It is also aimed at eliminating toxins and pathogens in the sludge. Sludge is treated by various processes that can be used in various combinations. Pre-treatment consists of various physical and mechanical operations, such as screening, gritting, oil separation and fat extraction. Pre-treatment allows the removal of voluminous items, sands, oils and grease. The residues from pre-treatment processes are not considered as sludge, they can be disposed of in landfills.

Sludge is obtained from sedimentation tanks. Primary sludge is produced following primary treatment. As mentioned above that the primary settlement process is used to remove of suspended solids from water, such as solids, grease and scum. Sludge that obtained from sedimentation tanks is essentially the settleable solids in the raw sewage and is termed raw sludge. Raw sludge is usually gray, disagreeable in appearance, and it has a foul odor. Chemical treatments are generally chemical precipitation, coagulation and flocculation. Sludge from the chemical precipitation process is usually darker in color. Chemical treatment sludges decompose or digest, but more slowly than sludges from physical processes.

The sludge from the secondary settling tank following a trickling filter consists of partially decomposed organic matter. It is usually dark brown and flocculent, more homogenous in appearance, and has less odor than raw sludge. Activated sludge process is the most widely used biological treatment systems. In activated sludge process, bacteria are kept in suspension in the vessel in aerobic conditions. The excess sludge withdrawn from the activated sludge process is also partially decomposed, is golden brown and flocculent, and has a rather distinct earthy odor. Both sludges, with further decomposition can become septic and cause offensive odors. The primary and secondary sludge described above can be mixed together generating a type of sludge referred to as mixed sludge.

Tertiary sludge is generated when carrying out tertiary treatment. It is an additional process to secondary treatment processes and it is necessary when a high level of depollution is required. Tertiary treatment process is designed to remove remaining unwanted matters, such as nutrients. The removal of nutrients can be performed using chemical processes or biological treatments. The removal of nitrogen is a biological process. The removal of phosphorus increases the quantity of sludge produced by an activated sludge plant by about 30 % (Garg, 2009). Biological treatments employ specific microorganisms, which are able to store phosphorus.

The sludge characteristics are very important to determine the sludge treatment and disposal methods. Sludge treatment method is selected taking into account the sludge characteristics, land availability, capital and operating costs, suitability of sludge for disposal, the type and size of WWTP. The most common treatment processes are aerobic or anaerobic digestion, incineration, and composting. The disposal methods are land-filling after digestion and land application after composting. Some sludge treatment and disposal methods are shown in the Figure 2.3. The following section provides some information about common sludge treatment and disposal processes with a little detail.

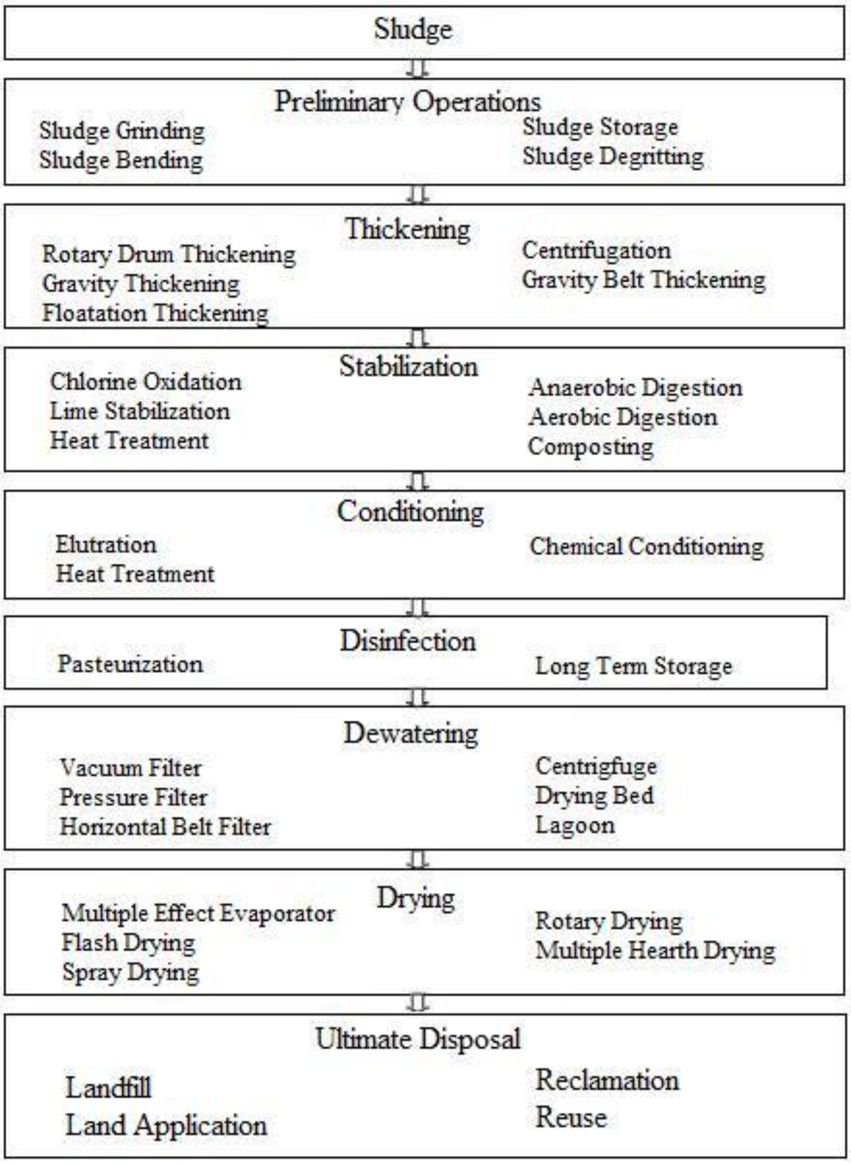


Figure 2.3 Some sludge treatment and disposal methods (Brown et al., 2010)

2.2.1 GHG Emissions during Sludge Treatment and Disposal Processes

Sludge treatment and disposal processes can constitute up to 40 % of total GHG emissions associated with wastewater treatment plants (Brown et al., 2010). Different sludge treatment and disposal processing technologies require varying energy and inputs, and GHG emissions are changed according to these variances. Emissions from each sludge process are classified as Scope 1 (direct emissions), Scope 2 (purchased electricity, heat or steam), or Scope 3 (indirect emissions from production of purchased materials and uses of end products). Direct GHG emissions were generated for storage, drying beds, anaerobic digestion, composting, land application, incineration, and landfilling. Indirect GHG emissions, expressed in CO_2-eq, are generated for each process using inputs such as electricity, gas, light and heavy fuel, lime, polymer, active carbon etc. (Pradel & Reverdy, 2012).

As mentioned earlier, CH_4 is produced under highly anaerobic conditions during the decomposition of organic matter. In sludge management, CH_4 emissions are most likely occur during thickening, digestion, composting, landfill disposal, storage. Small amounts of CH_4 can also be emitted by combustion of organic materials, including biosolids and digester biogas, for example an inefficient combustor may release up to 1 % unburned CH_4 (USEPA, 2007; Sylvis, 2009). N_2O is a by-product that can be formed during nitrification and denitrification processes. Both processes can produce N_2O, but denitrification process is the dominant source of N_2O production. N_2O can also be formed during combustion, particularly at combustion temperatures ranging from 500 – 920 º C (Guendehou et al., 2006; Sylvis, 2009).

2.2.1.1 Sludge Conditioning and Thickening

Sludge conditioning can be used to improve further sludge thickening and dewatering. Chemical and thermal conditioning processes are the most commonly used conditioning processes. Chemical conditioning is realized by using salts or lime, or polymers. Polymer manufacture requires energy and causes GHG emissions. The CO_2-eq emissions from polymer manufacturing are scope 3 emissions. Thermal conditioning is heating sludge for a while. Heat changes the physical structure of the sludge and reduces the property of water retention of sludge. Conditioning processes are unlikely to generate significant GHG emissions other than those attributable to electricity generation. Some programs may use fossil fuels to condition solids with heat to enhance dewatering (Metcalf & Eddy, 2003).

Thickening is the practice of increasing solids content of sludge by the removal of a portion of its liquid content. In other words, thickening is provided to reduce the volume of sludge. Water content of sludge is higher than its concentration of solids.

Combined primary and secondary sludge from an activated sludge treatment plant contains about 2 % solids and hence 98 % water (UNEP, n.d.). Thickening is carried out in a sedimentation tank or in a sedimentation pond. Plain settling tanks can produce solids contents in sludges of up to 8.0 percent for primary sludges and up to 2.2 % for activated sludges (Guyer, 2011). Thickening processes include gravity settling, floatation, centrifugation and gravity belts.

Gravity thickening is the simplest and least expensive process for consolidating sludge. Gravity thickeners are essentially settling tanks. Gravity thickeners are designed on the basis of hydraulic surface loading and solids loading. The design principles are to be the same as sedimentation tanks. Sludge with a solids content of ten percent or more can be produced by this method. Flotation thickening units are becoming increasingly popular at sewage treatment plants, especially for handling waste activated sludge which solids contents of 4 percent or higher are obtained (Guyer, 2011).

Gravity thickening may be a source of CH_4 and N_2O emissions, but field measurements are needed to confirm emission factors. Other forms of thickening processes, such as gravity belt thickeners or air flotation, are unlikely to produce CH_4 or N_2O emissions, because these processes are aerobic. They will, however, generate CO_2 emissions from electricity use. The GHG emissions from purchased electricity are in the scope 2 emissions. Electricity use is converted to CO_2 emissions based on estimates of emissions from electricity generation in each province. For CO_2 emissions from purchased electricity are calculated using the Equation 2.1.

$$\mathrm{CO_2(Mg/day) = Electricity\ use\ (kWh/day) * Eletricity\ EF\ for\ province\ (g/kWh)\ /\ 10^6(g/Mg)} \tag{2.1}$$

Where,

$$\mathrm{Electricity\ use\ (kWh/day) = Power\ needed\ (kWh/m^3\ sludge\ treated) * 24\ h/day * Sludge\ volume\ (m^3/day)} \tag{2.2}$$

According to the Sylvis (2009), default value for centrifuge is 101.4 kWh/dry Mg sludge treated, and default value for other options 4.9 kWh/ dry Mg sludge treated.

2.2.1.2 Sludge Dewatering

Sludge dewatering is generally the following step after thickening processes. Dewatering reduces the water content of the sludge so that it can more easily be disposed of by landfill, incineration, composting, and heat drying. The sludge can be handled like a solid after sludge dewatering process. There are a lot of sludge dewatering methods; such as belt press filtration, sludge drying beds, vacuum filtration, centrifugation etc. The selection of appropriate sludge dewatering technique depends upon the characteristics of the sludge, available land, moisture content requirements for ultimate disposal. When land is available and sludge quantity is small, natural dewatering systems such as sludge drying beds and drying lagoons are most attractive. Sludge drying beds processes rely on drainage and evaporation to effect moisture reduction. Drying beds are open; therefore they are highly influenced by climatic conditions such as precipitation, humidity, air temperature, sunshine etc. Efficiency of sludge drying beds can be improved significantly by covering the bed with glass or plastic and by providing artificial heat.

Dewatering process can be widely applied using several technologies, such as belt filter presses, centrifuges. Centrifuging is a mechanical process and it is possible to use for either as a thickening process or as a dewatering process. Centrifugation process uses centrifugal forces to separate the thickened sludge from the centrifugation. The energy needs of centrifuges are significant. It is also necessary to add a polymer to the sludge, such as lime, polymers. Belt filter presses is another technique for dewatering. In the belt filter process, dewatering is accomplished by applying a high pressure. Polymers are added in sludge in this process. As mentioned earlier, polymer manufacturing also causes GHG emissions and these are scope 3 (indirect) emissions. These GHG emissions are calculated using the following equation.

Electricity use is the only significant source of GHG emissions. Belt filter presses typically use from 0.0041 to 0.0111 kWh/m^3 of wet solids treated, while centrifuges use from 0.0413 to 0.1888 kWh/m^3 of wet solids treated (Hydromantis, 2006). GHG emissions from purchased electricity are calculated as scope 2 emissions. GHG emissions from purchased electricity are calculated by using Equation 2.1 in the previous section. Dewatering may be improved by chemical conditioning, such as addition of a polymer. Polymers widely used to enhance dewatering process. Producing polymers takes considerable energy and produces considerable indirect (scope 3) GHG emissions, an estimated 22.9 Mg CO_2-eq/Mg polymer (Sylvis, 2009). Roughly 5 kg of polymer are used to condition each Mg of dry solids in thickening and dewatering processes (Metcalf & Eddy, 2003).

$$\mathrm{CO_2(Mg/day) = Dry\ sludge\ mass\ (Mg/day) * Polymer\ use\ (kg/Mg\ solids\ treated) *} \\ \mathrm{CO_2eq\ for\ polymer\ manufacturing\ (Mg/Mg\ polymer)\ /10^3\ (kg/Mg)} \qquad \mathbf{2.3}$$

2.2.1.3 Sludge Stabilization

Sludge stabilization processes aim at reducing the fermentation of the putrescible matter contained in the sludge. Stabilization processes eliminate unwanted odours and pathogens. There are many methods that used for stabilization of sludge. Some of these methods are given in detail below.

2.2.1.3.1 Lime Stabilization. Stabilization processes are used to reduce pathogen content in sludge, eliminate offensive odors, and eliminate the potential for putrefaction. This process is associated with the impact on volatile or organic part of the sludge. Stabilization processes are provided by biological reduction of volatile portion, chemical oxidation of volatile matter, chemical addition in sludge, or heat treatment for the disinfection of sludge. The stabilization processes can be carried out under aerobic or anaerobic conditions. Technologies used for stabilization processes include lime stabilization, sludge digestion (aerobic digestion and anaerobic digestion), heat treatment and composting.

Lime stabilization is a very simple process. In the lime stabilization, lime is added to untreated sludge to raise the pH to 12 or higher. The high pH inhibits the survival of microorganisms, and inhibits the risk of putrefaction and odor. Similarly, pathogens are inactivated or destroyed by lime addition. Hydrated lime and quick lime (CaO) are most commonly in this process. Water in sludge is removed by the addition of hydrated lime.

Lime is added prior to dewatering or after dewatering. Three fundamental design parameters consider in the design of a lime stabilization process: pH, contact time, and lime dosage. The amount of lime required to stabilize sludge is determined by the type of sludge, its chemical composition, and the solids concentration. Its principal advantages are low cost and simplicity of operation. But there are problems in lime stabilization. It has two important impacts. First problem is lime addition does not make sludges chemically stable; if the pH drops below 11.0, biological decomposition will resume, producing noxious odors (USEPA, 1979). Another problem is large quantity of lime sludge produced. Thus, because of the increased volumes, the costs for transportation and ultimate disposal are often greater for lime-stabilized sludges than for sludge stabilized by other methods.

The production of lime or other alkaline products used to treat sludge results in significant GHG emissions. If the lime is mined and processes for stabilization, supply-chain carbon emissions associate with the mining, processing, and transportation. The emissions associated with the lime production are estimated to be 3.6 kg CO_2-eq/kg lime (Murray et al., 2008). Assuming lime stabilization requires adding 150 kg of lime to each Mg dry biosolids. GHG emissions from lime production are calculated using the following equation.

$$\mathrm{CO_2eq(Mg/day)} = \text{Sludge treated (dry Mg/day)} * \text{Alkaline product added} * \mathrm{CO_2eq} \text{ emissions from lime production (Mg/Mg lime produced)} \qquad \textbf{2.4}$$

2.2.1.3.2 Aerobic Sludge Digestion. Aerobic digestion sludge process is similar to the activated sludge process. Hydraulic residence time, process loading criteria, oxygen requirements, energy requirements for mixing are factors that must take into account in designing aerobic digesters. The function of aerobic digestion is to stabilize waste sludge solids by long term aeration, thereby reducing BOD and destroying volatile solids. It involves the direct oxidation of biodegradable matter and microbial cellular material in open tanks for an extended period of time.

Aerobic digesters can be either continuous or intermittent batch operations. With batch operation, waste sludge feed will be discontinued at specified time before digested sludge withdrawal. In continuous operation, supernatant is constantly withdrawn. Aerobic digestion tanks are open and generally require no special heat transfer equipment or insulation. In aerobic digestion process, the sludge is aerated for an extended time typically 12 to 20 days. Under aerobic conditions, bacteria can rapidly consume organic materials and produce carbon dioxide and water as final products. Aeration is provided by aerators or diffusers.

The GHG emissions can be estimated according to the energy utilization. In most cases, the only GHG emission attributable to mesophilic aerobic digestion is CO_2 associated with electricity use, and, possibly, fossil fuel use. CO_2 emissions from fossil fuel burned are considered as scope 1 emission. These emissions are calculated using the Equation 2.5. The default value of natural gas use is 4.62 m^3/day (Metcalf & Eddy, 2003).

$$\mathrm{CO_2(Mg/day) = Natural\ gas\ used\ (m^3/day) * CO_2 from\ natural\ gas\ combustion(kg/m^3)} \tag{2.5}$$

Where;

$$\mathrm{Natural\ gas\ used(m^3/day) =}$$
$$\mathrm{Natural\ gas\ use(m^3/m^3 wet\ sludge\ treated) * \ Sludge\ volume\ (m^3/day)} \tag{2.6}$$

Electricity is used to run mechanical mixers and aeration equipments; fossil fuels are used for the biologic activity in digesters by heating the solids in cold climates. The emissions of CH_4 and N_2O are likely to be negligible from mesophilic aerobic digesters. As there is no methane and nitrous oxide formation during the process, it is considered that the major GHG emissions is due to energy consumption in aerobic sludge digestion.

As mentioned earlier, GHG emissions from purchased electricity calculates scope 2 emissions. CO_2 emissions from purchased electricity are calculated using the following equation. According to the Metcalf and Eddy (2003), the default value for standard aerobic system is 0.03 kW/m^3 wet sludge treated.

$$\mathrm{CO_2(Mg/day) = Electricity\ use\ (kWh/day) * Electricity\ EF\ (g/kWh)\ /\ 10^6\ \ (g/Mg)} \tag{2.7}$$

Where;

$$\mathrm{Electricity\ use\ (kWh/day) = Power\ needed\ for\ aerators\ (kW/m^3\ wet\ sludge\ treated) * 24\ h/day * Sludge\ volume\ (m^3/day)} \tag{2.8}$$

2.2.1.3.3 Anaerobic Sludge Digestion. It is the oldest and the most applied technology for sludge stabilization before final disposal. Anaerobic sludge digestion is the destruction of biological solids using bacteria in the absence of oxygen. There are mainly four steps of the digestion: hydrolysis, acidogenesis, acetogenesis, and methanogenesis. At last, methane is produced under methanogenesis. CH_4 gas can be used as an energy source, because the calorific value of methane is the same as natural petroleum gas (Garg, 2009). It makes anaerobic digestion more economically than aerobic digestion. The methane produced could be of great benefit in cold regions as a supplemental source of heat. Therefore, the decision to use anaerobic digestion must carefully evaluate the operational capability of the installation (Guyer, 2011).

The objectives of anaerobic digestion are the stabilization of organic solids, sludge volume reduction, odor reduction, and destruction of pathogenic organisms, useful gas production, and the improvement of sludge dewaterability. The efficiency of the anaerobic digestion process is depend on solid content of sludge, retention time, temperature, pH value, and C:N ratio. While a high C:N ratio indicates a rapid consumption of nitrogen by methanogenic bacteria, results in lower gas production;

lower C:N ratio causes accumulation of ammonia and pH values exceeding 8.5 is toxic to methanogenic bacteria (Akwo, 2008).

Anaerobic digestion is performed by digester, where the content is mixed and the digester maintained at 35 º C by combusting the biogas produced. After digestion the sludge is passed to a sedimentation tank. The sludge is thickened in a sedimentation tank. Anaerobic digestion produces a significant quantity of biogas, which is up to 65 % CH_4 (Hydromantis, 2006). Biogas is collected from the digester. Biogas is a useable fuel similar to natural gas. Due to providing an alternative to fossil fuel for energy, anaerobic digestion has the benefit. When the CH_4 in biogas is burned for heat or electricity generation, CO_2 is emitted. Digester biogas is comprised of biogenic carbon and these emissions of CO_2 are not included in total net GHG emissions calculations. However, according to reporting protocols, such as GRP (TCR, 2008), require reporting of emissions from the combustion of biomass, including digester gas. The combustion of CH_4 is not 100 % efficient. According to USEPA, remaining CH_4 is 1 % and it is emitted (USEPA, 2007).

The GHG emissions during sludge treatment are mainly generated in the anaerobic digester. The carbon dioxide production belongs to the short carbon cycle which would not count for GHG emission. Anaerobic digesters produce abundant CH_4, if this is not captured or burned. For fugitive CH_4 emissions are calculated as Mg CO_2-eq per day using the Equation 2.9.

$$\text{Fugitive } \mathrm{CH_4}\text{emissions} = \left(\mathrm{CH_4}\text{ produced }(\mathrm{m^3/day}) * (1 - \%\text{ of }\mathrm{CH_4}\text{burned})\right) + \left(\mathrm{CH_4}\text{ produced}\left(\mathrm{m^3/day}\right) * \%\text{ of }\mathrm{CH_4}\text{burned} * \mathrm{CH_4}\text{ combustion inefficiency }(0.3\%))\right) * \mathrm{CH_4}\text{ density}(\mathrm{kg/m^3}) * \text{GWP of }\mathrm{CH_4}(21)/10^3(\mathrm{kg/Mg}) \tag{2.9}$$

Where;

$$\mathrm{CH_4}\text{produced }(\mathrm{m^3/day}) = \text{VS destroyed }(\mathrm{kg/day}) * \text{Biogas yield }(\mathrm{m^3/kg\ VS}) * (\%\ \mathrm{CH_4}\text{in biogas}) \tag{2.10}$$

According to WEF, default value for biogas yields 0.9 m^3/kg VS. It is known that the general fraction of methane in biogas generated from sludge anaerobic digestion is around 60 to 75 % (Sosnowski, 2003; Zhang et al., 2010). The default value for the general fraction of CH_4 in biogas is % 65 (Monteith et al., 2005).

The mixing of the solids in the digesters requires electricity, and it also causes GHG emissions from purchased electricity. These emissions calculate scope 2 emissions. For CO_2 emissions from purchased electricity is calculated the general formula which is given in Equation 2.1. But there, for the electricity use formula is different. Electricity use is calculated using Equation 2.11. The default value for power needed for mixing is 0.0065, according to the Metcalf and Eddy (2003).

$$\text{Electricity use (kWh/day)} = \text{Power needed for mixing (kW/m}^3\text{ wet sludge treated)} * 24\text{ h/day} * \text{Sludge volume (m}^3\text{/day)} \qquad \mathbf{2.11}$$

CO_2 emissions from fossil fuel burned are calculated by the formula given in the aerobic digestion section, the Equation 2.5. When the CH_4 in digester gas (biogas) is burned for heat, for electricity generation, CO_2 is emitted. As this CH_4 is comprised of biogenic carbon, these emissions of CO_2 are not included in total net anthropogenic GHG emissions (Sylvis, 2009). In anaerobic digestion, GHG emissions from biomass combustion are reported separately. CO_2 from biomass combustion is calculated using the Equation 2.12. According to the LGO, the default value for CO_2 emissions factor from burning CH_4 from biogas is 0.9267 kg CO_2/m^3.

$$\begin{aligned}&\text{CO}_2\text{(Mg/day)} = \\ &\text{VS destroyed (kg/day)/(10}^3\text{ kg/Mg)} * \\ &\text{Biogas yield from VS destroyed(m}^3\text{/kg VS destroyed)} * \text{CH}_4\text{in biogas} * \\ &\text{CO}_2\text{emissions factor from burning CH}_4\text{from biogas (kg CO}_2\text{/m}^3\text{)} \qquad \mathbf{2.12}\end{aligned}$$

2.2.1.3.4Composting. Sludge composting process is aimed at stabilization putrescible organics, destroying pathogenic organisms, and reducing the volume of sludge. Composting is a process to breakdown the organic materials into more stable substances through the aerobic or anaerobic process. There are several composting technologies used to co-compost sludges with other organic wastes, such as municipal solid wastes, wood wastes, food wastes, and pulp and paper residuals. Temperature can be up to 70 degrees during aerobic decomposition (Filibeli, 2009). The aerobic composting process is exothermic. Pathogenic organisms are destroyed at high temperatures. During composting organic material undergoes biological degradation, resulting in a 20 to 30 percent reduction of volatile solids.

In composting, aerobic microorganisms convert much of the organic matter into carbon dioxide leaving a relatively stable, odor free substance which has some value as a fertilizer. At the end of composting process, end product is stable and it contains nutrients and organic carbon. Sludge compost is a natural organic product with high humus content. The organic matter in compost makes it easier for plant roots to penetrate. It may be used as a soil conditioner in agricultural applications. The major advantage of this process is compost is a very good fertilizer.

GHG emissions associated with energy and fuel requirements for grinding, moving and aerating the compost feedstocks. Different compost systems have different energy requirements. The highest CH_4 emissions are observed early in the process, when oxygen is consumed and the compost settles, forming anaerobic micro sites. Windrow composting is a commonly used composting method. The sludge cake is mixed with a bulking agent and set out in piles in windrow composting. It is the production of compost by piling organic matter or biodegradable waste. The composting material is turned mechanically to introduce air and prevent excessive temperatures (European Commission, 2001). This system requires a large area. In a windrow composting, the highest CH_4 emissions are observed near the bottom of the windrow, and release occurring during turning (Hao et al., 2001). Control parameters of composting processes are the initial ratios of carbon and nitrogen, the pile size, moisture content in sludge, and turning frequency. Emissions of N_2O are possible early in the composting process, as well as during storage and end use. IPCC Guidelines (2006) indicated that composting process emit small quantities of GHGs.

Aerobic composting generates heat and carbon dioxide, while anaerobic one produces methane as well as heat. Compared to anaerobic composting, aerobic composting methods decompose material faster and more efficiently. The GHG emissions during composting are governed by the composting type. While energy consumption accounts for GHG emissions in aerobic composting, methane and nitrous oxide emissions contribute to GHG emission from anaerobic composting (Zhang et al., 2010). Additionally, transportation of the sludge from the wastewater treatment site to the composting site also generates GHG emission due to the fuel utilization. According to the research conducted by Zhang et al., the total GHG emissions of composting processes can be estimated according to Equation 2.13.

$$\begin{aligned}&\text{GHG emissions} = \text{GHG emission in thickening/dewatering process} + \text{GHG}(\text{CH}_4 + \\ &\text{N}_2\text{O})\text{production during composting} + \text{GHG emission from energy consumption} + \\ &\text{GHG emission from consumption of fuel to transportation} - \\ &\text{GHG credit taken from fertilizer production}\end{aligned} \tag{2.13}$$

Sylvis (2009) has dedicated that CO_2 emissions from fossil fuel burned can be calculated using the equation 2.5. Electricity is used for aeration, mixing, biofiltration, or air emission control in composting process. CO_2 emissions from purchased electricity are scope 2 emissions and they can be calculated using the equation 2.1. In these calculations, default values must be appropriate for composting process. Sylvis has emphasized that CH_4 emissions from composting operations are scope 1 emissions. If compost piles are covered or process air is treated in a biofilter, CH_4 emissions can be assumed as negligible. When composting air is released to the atmosphere and the compost contains less than 55 %, CH_4 emissions can be calculated using the Equation 2.14.

$$\begin{aligned}&\text{CH}_4\text{emissions (Mg/day)} = \text{Sludge treated (dry Mg/day)} * \text{\% organic C in sludge} * \\ &\text{CH}_4\text{emissions for uncovered pile} * \text{C to CH}_4\text{conversion factor}\end{aligned} \tag{2.14}$$

There is a potential for fugitive emissions in composting process. These emissions are CH_4 and N_2O gases, which are formed under oxygen-limiting conditions. A Clean Development Mechanism protocol provides default factors for these emissions. Some studies have shown minimal release of fugitive gases during storage of finished compost. Sylvis (2009) has noted that N_2O emissions may be also possible after compost is applied to soils.

2.2.1.4 Thermal Drying

Thermal drying process involves the application of heat to evaporate water to reduce the moisture content of sludge. By removing most of the water from sludge, thermal drying results in a significant reduction in both volume and mass. The advantages of this process are reduced transportation costs, further pathogen reduction, improved storage capability. Thermal energy can be provided by combustion of a variety of fuels such as natural gas, digester gas; by a reuse of waste heat; or by conversion of electrical power into thermal energy (Sieger et al., 2004). Thermal drying systems are referred to in two primary categories, direct and indirect. Dewatering dryers and electric dryers are also common thermal drying systems. In direct systems, hot air comes into direct contact with particles of wet solids. Examples of direct drying equipments are rotary drum dryers, flash dryers, and belt dryers. In indirect systems, solid metal walls separate the wet solids from the heat transfer medium such as steam, hot water, or oil (Sieger et al, 2004). The solids temperature is raised by contact with hot metal surface. Indirect thermal drying equipment includes vertical tray dryers, horizontal vessel dryers, and an indirect-type of fluidized bed dryer.

Thermal drying systems consume energy. The most common energy sources are natural gas, digester gas, and fuel oil. Electrical power is also required to operate equipment. The thermal energy consumption is based on the amount of water to be evaporated and the thermal efficiency of the drying system. Large consumers of power are fans, blowers, mixers, conveyors, elevators, and screens. Qualities of heat dried sludge are suitable for land application. Most of these sludges are used as soil conditioner, fertilizer, and agricultural purposes.

There is little published data regarding GHG emissions from thermal drying process. The most important factors for GHG emissions from this process are CO_2 emissions from purchased electricity and fossil fuel burned. CO_2 emissions from purchased electricity calculate scope 2 emissions, but CO_2 emissions from fossil fuel burned are scope 1 emissions. For CO_2 emissions from purchased electricity are calculated in Equation 2.1. Emissions from fossil fuel burned are calculated using the Equation 2.5. There is a little different in estimating natural gas used. The natural gas used is calculated using the following Equation 2.15.

$$\begin{aligned}&\text{Natural gas used } (\text{m}^3/\text{day}) = \\ &\text{Sludge entering dryer (wet Mg/day)} * \\ &(\text{\% solids leaving dryer} - \text{\% solids entering dryer}) * \text{Energy to evaporate water}/ \\ &\text{heat content of natural gas } (\text{GJ}/\text{m}^3 \text{of natural gas})\end{aligned} \qquad \mathbf{2.15}$$

2.2.1.5 Landfilling

Sludge landfilling is generally defined as burying of sludge. There are two possibilities in terms of landfilling process: mono-deposits, where only sludge is disposed of, and mixed-deposits, when the landfill is also used for municipal wastes. Suitability of landfilling process can vary due to sludge characterization. Not all wastewater treatment sludges are suitable for landfilling. Solids contents greater than or equal to 35 % are suitable for disposal in landfills. Waste deposit in landfill undergoes three steps. The first step is initial aerobic phase. The degradation occurs under aerobic conditions during aerobic microorganisms consume oxygen in the deposit. The second step is acetogenesis. When the level of oxygen decreases in deposit, acetogenic bacteria decompose degradable material of the sludge. The last step is methanogenesis. In this step, production of CH_4 is increased by methanogenic bacteria.

Landfilling process generates GHG emissions into the air. CO_2 emissions from landfill processes is minimal and likely negligible, can be ignored. CH_4 emissions from landfilling can be significant. N_2O emissions can release to the atmosphere in landfilling process. The amount of CH_4 and N_2O emissions vary with the volatile solids (VS) in sludge. These CH_4 and N_2O emissions are scope 1 emissions. The rate of CH_4 generation and total CH_4 generation potential can be estimated from the VS content of the biosolids being landfilled (Metcalf & Eddy, 2002). Fuels for vehicles, electricity are also sources of GHG emissions.

CH_4 emissions from sludge placed in landfilling are significant. Considerable research has been conducted on landfill CH_4 emissions in general. The BEAM method is generally used for calculating landfill CH_4 emissions. Additional minimal emissions are created when the CH_4 is burned for heat and power (Sylvis, 2009). In the BEAM methodology has also noted that N_2O emissions can occur in landfilling process. CH_4 emissions from sludge decomposition in the landfill during the first three years after placement are calculated according to the BEAM method by using the equation 2.16. The default value of % organic C in VS is 0.56 according to the Natural Resource, Agriculture, and Engineering Service (NRAES). The Clean Development Mechanism has noted that the default value of CH_4 in landfill gas is % 50.

$$\begin{aligned}&\mathrm{CH_4\ (Mg/day) = Sludge\ treated(dry\ Mg/day) * \%\ VS * \%\ organic\ C\ in\ VS *}\\&\mathrm{model\ uncertainity\ factor * C\ to\ CH_4 conversion * CH_4 in\ landfill\ gas * DOC_f *}\\&\mathrm{\%\ decomposed\ in\ first\ 3\ years * MCF_{landfill}}\end{aligned} \qquad \textbf{2.16}$$

DOC_f is the decomposable organic fraction of raw wastewater solids and default value is 80 % (Brown et al., 2009). UNFCCC has dedicated that the model uncertainty factor is 0.9. Percent of decomposed in first three years is calculated 69.9 according to the CDM for warm, wet conditions. $MCF_{landfill}$ is methane correction for anaerobic managed landfills and its default value is 1 according to the UNFCCC (2008).

CH_4 emissions from sludge decomposition in the landfill more than three years after placement are calculated the Equation 2.17, according to the BEAM method. Percent of landfill gas capture rate is defined as 75 according to the USEPA. The methodology has specified that the percent of CH_4 oxidation in cover soil depends on quality of soil over closed landfill.

$$\mathrm{CH_4(Mg/day)} = \text{Sludge treated} * \%\,\text{VS} * \%\,\text{organic C in VS} * \text{model uncertainity factor} * (1 - \%\,\text{decomposed in 3 years}) * (1 - \%\,\text{landfill gas capture rate}) * (1 - \%\,\mathrm{CH_4}\text{ oxidation in cover soil}) * \text{C to }\mathrm{CH_4}\text{conversion} * \mathrm{CH_4}\text{ in landfill gas} * \mathrm{DOC_f} * \mathrm{MCF_{landfill}} \qquad \textbf{2.17}$$

According to the BEAM methodology, N_2O emissions from landfilled sludge are calculated using the Equation 2.18. There is an important point is that the C:N ratio is less than 30 %. If C:N ratio is more than 30 %, N_2O emissions are assumed to be zero. The default value of percent of initial N in solids is 1.5 (Brown et al., 2009). The BEAM methodology has noted that the percent of N depends on whether sludge has been digested or not. If it is digested sludge, its default value is assumed to be 5 %.

$$\mathrm{N_2O}\text{ emissions(Mg/day)} = \text{Dry sludge mass(Mg/day)} * \%\,\text{N} * \mathrm{N_2O}\text{ emissions for low C: N} * \text{N to }\mathrm{N_2O}\text{ conversion} \qquad \textbf{2.18}$$

CH_4 emissions are significant. The quantity of emissions will depend on how the landfill is managed. More stable, digested sludge emit lower quantities of CH_4 emissions. If the landfill does not have an operating gas collection system, CH_4 and N_2O emissions will be released to the atmosphere from the rapid decomposition of the sludge. The BEAM method assumes gas capture will begin three years after sludge is placed in the landfill. There is an existing CDM protocol to calculate avoided CH_4 emissions for landfill diversion (UNFCCC, 2008). The potential CH_4 release is based on default factors of % solids, total carbon, the fraction of carbon that can degrade under anaerobic condition, and a decay rate constant. The BEAM method relies on this equation (Sylvis, 2009). Researches indicate that temperature is a critical factor. Higher CH_4 emissions have been widely reported during cooler landfill surface temperature. Optimum temperatures for methanotrophic activity were found to be 25 – 35° C (Park et al., 2008; SYLVIS, 2009). The CDM methodology does not provide factors for N_2O emissions. The BEAM estimates 1.5 % of total nitrogen in landfilled sludge are released as N_2O, which is similar to the factor for compost.

A study that conducted by the North East Biosolids and Residuals Association (NEBRA) at Merrimack, New Hampshire, USA estimated the energy use and GHG emissions associated with two sludge management options: continued composting and landfill disposal. The scope of this study included only the sludge management occurring after dewatering. Current GHG accounting principles developed by the IPCC, and others were used in the assessment. The study indicated that despite the greater use of energy to perform composting, composting accounts for less GHG emissions than landfill disposal. Calculations indicate that current composting processes account for an estimated total of 1,529 Mg CO_2 equivalent emissions. In contrast, landfill disposal were account for an estimated total of 3,754 Mg CO_2 equivalent emissions (Beecher, 2008). The study has emphasized that this difference in total GHG emissions driven by the fact that landfill disposal release to the atmosphere significantly more CH_4 emissions than composting.

2.2.1.6 Incineration

Incineration is a combustion reaction. Sludge processed by incineration is usually dewatered, untreated sludges. It is generally unnecessary to stabilize sludge before incineration. Incineration process can be performed in incinerators or in municipal solid waste incinerators under the particular constraints for each type, where the process results in combustion of the organic matter of the sludge. There are different types of incineration process. Sludge can incinerate in dedicated incineration plants, or incinerate with other wastes, mainly household wastes. Sludge can co-incinerate when sludge is used as a fuel in plants whose purpose is the generation of energy or production of material products such as coal power plants or cement plants. If the calorific value of the sludge is similar to the municipal wastes, sludge can be added to the municipal waste.

Sludge and waste inputs are necessary to operate an incineration plant. The water content and organic matter content of sludge is important. Incineration plants generate emissions to the atmosphere, soil and water, mainly located at the incineration site or at the landfill where ashes are disposed of. Emissions are depended on the sludge type and also the incineration process. CO_2, acid gases (SO_2, HCl, and HF), nitrogen oxides (NO_x), and organic compounds emit to the air and pollutants are dispersed in the atmosphere. Their concentration depends on several factors, such as local conditions, distance from the incineration plant, properties of the compounds etc. These pollutants, especially CO_2, have impacts on climate change.

Incinerators require considerable fossil fuels to burn sludge. CO_2 emissions that come from fossil fuel burned are scope 1 GHG emissions. This calculation takes into account the energy potential of the solids, which based on whether or not the solids are digested before incineration. Incineration of sludge may require supplemental energy if the water content of the material is more than 40 % (Sylvis, 2009). CH_4 emissions from combustion are minimal. The IPCC provides a default value of $4.85x10^{-5}$ kg CH_4 emitted/dry kg wastewater solids burned. This amount is small in comparison to other GHG emissions associated with incineration and it is considered negligible. N_2O emissions are the largest concern with incineration of sludge. They are caused mostly by thermal conversion of nitrogen. These CH_4 and N_2O emissions are considered as scope 1 emission. The greatest use of electricity for incineration of sludge is a reason of CO_2 emissions. CO_2 emissions from purchased electricity are scope 2 emissions.

2.2.1.7 Land Application

Land application is a common sludge disposal process. Sludge is commonly applied to agricultural lands, forest lands and reclamation sites. Land application process is defined as the spreading of sludge on or just below the soil surface. Application methods vary with types of sites. Sludge may be applied to agricultural land, forest land, disturbed land, or land disposal sites. In all cases, the process is designed with the objective of providing further sludge treatment. Finding a suitable site is a critical step in land application process, such as application to agricultural lands, forest lands, etc. Site characteristics of importance are topography, soil characteristics, soil depth to groundwater, and accessibility and proximity to critical areas (Metcalf & Eddy, 2003). The USEPA published some regulations for sludge to land application process. The regulations provide limits for trace metals management practice guidance, and requirements for monitoring, record keeping and reporting.

Land application process has proven a cost-effective method because of recycling organic matter and nutrient and improving soil quality. When sludge is land applied in accordance with the current regulations, sludge is generally applied in small, dispersed amounts to soils. Thus, land application process is not likely a significant source of CH_4 emission. However, if sludge is stored in piles, anaerobic conditions can occur and CH_4 emission can emit to the atmosphere. A study noted that release of CH_4 from stored raw and digested manure with higher releases during summer months and from raw materials (Clemens et al., 2006). Stored sludge with low moisture content, compost, and alkaline sludge are not likely to emit significant quantities of GHGs until they are land applied (CCME, 2009).

Sludge is generally applied to agricultural land as fertilizer. The agronomic rate is the amount of sludge required to provide the amount of nutrients. Generally, nitrogen is the plant nutrient, and the phosphorus is the limiting factor. There are some regulations and guidelines for sludge land application specify use of agronomic rates. The IPCC provides default emission factors for N_2O emissions for fertilizer use.

Direct N_2O emissions from application of fertilizer, compost, or sludge are estimated to generate N_2O from 1 % of the total N added (CCME, 2009).

CO_2 emissions from fossil fuel burned are the scope 1 emissions in land application process. It was mentioned above that CH_4 emissions are possible when sludge stored after stabilization and prior to land application. N_2O emissions are possible when nitrogen fertilizers, including sludge, are applied to soils. CCME (2009) is noted that emissions are likely greater when sludge are applied to fine-textured soils and when solids are wetter, namely sludge with less than 55 % solid content. N_2O emissions are also possible during storage.

2.3 Estimation of GHG Emissions from Wastewater Treatment Plants

Most of the current protocols originate from the GHG Protocol Initiative and it is internationally recognized as the most widely-used accounting tool for GHG emissions inventories. However, the GHG Protocol Initiative does not have a protocol for estimating GHG emissions from WWTP processes. Some of protocols, such as CCAR, and the USEPA, originate from the GHG Initiative and have a protocol for estimating GHG emissions from WWTPs. The Local Government Operations Protocol (LGO) was developed in partnership by the California Air Resources Board (ARB), CCAR, and ICLEI – Local Governments for Sustainability (ICLEI). The LGO Protocol provides the approach and methodology for estimating GHG emissions of WWTPs.

The IPCC has developed a methodology for estimating emissions from WWTPs. EIIP has a modified version of the IPCC methodology. The USEPA has conducted national and state level estimates of GHG emissions from WWTPs that using the IPCC and EIIP as a basis with some modifications. The USEPA Climate Leaders Program is also in the process of developing a WWTP protocol, which will also be based on the IPCC methodology.

A Life Cycle Assessment (LCA) is often conducted to properly account for all GHG emissions over the entire lifetime of a WWTP (Lim, 2012). LCA methodology is defined in ISO Standards. LCA is a tool that is used to estimate the potential environmental impacts of a product, a process or a service. In the section of this thesis, more detailed description of the IPCC, LCA, USEPA, LGO methodologies is researched and given below.

It is mentioned that domestic and industrial wastewaters have significantly different characteristics, because most of the industrial wastewaters have very low organic loading which is the cause of GHG emissions. The estimation of methane emission from industrial wastewater is more complicated than domestic wastewater. In this study, only domestic wastewater treatment plants and their GHG emissions are examined and taken into account. Different models to estimate the GHGs of WWTP exists. According to a study that conducted in the UNESCO-IHE Institute for Water Education, the Netherlands, the most common treatment processes that causes GHGs are activated sludge systems, anaerobic reactors and land disposal systems.

Activated sludge processes consist of two stages: a biological stage (anaerobic, anoxic, and aerobic tanks) and clarifier. Segregation of the bioreactor into anaerobic, anoxic, aerobic zones distinguishes biological nutrient removal (BNR) systems from other activated sludge systems. CO_2, CH_4, N_2O gases are emitted from activated sludge systems. In the aerobic oxidation tanks, organic molecules are metabolized to CO_2 and H_2O, and these gases directly go to the atmosphere. The ammonia in the wastewater undergoes transformations. The ammonia is oxidized to nitrite and the nitrite oxidized to nitrate in the nitrification process. And then the nitrate is reduced to nitrogen gas in denitrification process. In both of these processes, N_2O is produced. Also in activated sludge processes, energy consumption is very high due to the aeration equipments. This is the cause of emitting indirectly CO_2 via the burning of fossil fuels. Aeration is an essential process in the majority of WWTPs and accounts for 45 to 75 % of their energy consumption (Henze et al., 2008).

The sewerage wastewater is normally treated via screening, primary settling, biological processing, and secondary settling. As mentioned earlier, the organic loading plays a major role of GHGs emission from wastewater treatment as it directly leads to the methane and nitrous oxide emission. Among all the processes, bioreactor is the emission generator, while others contribute GHG emissions due to the energy or chemical consumption (Zhang et al., 2012). Therefore, the total emission can be described with the following the equation:

$$\text{GHG emissions} = \text{GHG emission from biological treatment } + \text{CO}_2 \text{ from material consumption} \qquad \textbf{2.19}$$

The case study conducted by Zhang aimed to estimate GHG emissions from biological wastewater treatment process. In this study, type of biological treatment appears to be a critical factor for greenhouse gas emissions. GHG emissions from biological wastewater treatment will be predominantly from methane and nitrous oxide, which are generated under anaerobic conditions. Aerobic, anaerobic, and anoxic are three basic categories of biological treatment, and generally, the three types of treatment are operated together in a wastewater treatment plant (Chan et al. 2009; Kassab et al. 2010). A typical wastewater treatment which includes biological treatment process is shown in Figure 2.4.

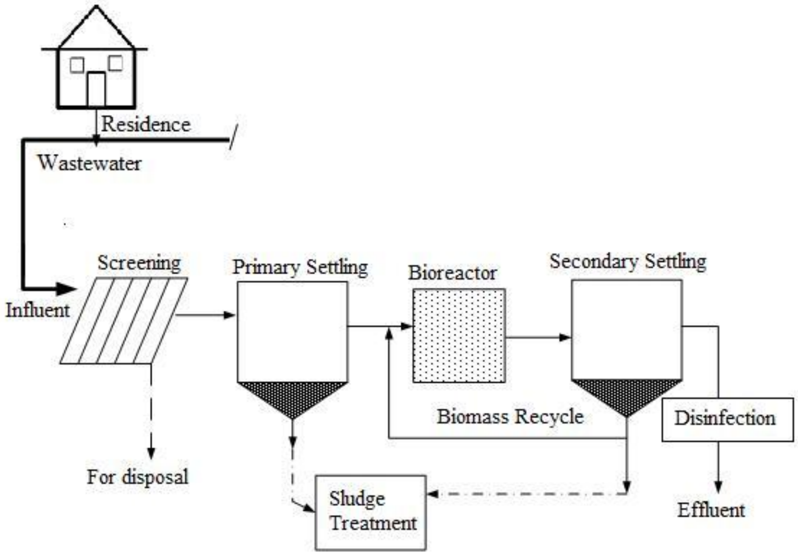


Figure 2.4 A typical wastewater treatment process (Zhang et al., 2009)

Aerobic biological treatment involves contacting wastewater with microorganisms, which act as catalysts to biodegrade organics and other contaminants such as ammonia, in the presence of oxygen. Carbon dioxide, water, and sludge are the final products of the aerobic treatment; thus it can be considered that no GHG emissions occur in the process. Anaerobic and anoxic treatments complete the biodegradation of organics and other contaminants using the microorganisms that have the ability to use the combined oxygen (e.g., SO_4^{2-}, NO_2^-, NO_3^-, CO_2) or organic compounds (e.g., via the fermentation processes) for oxidation. The resulting products are methane, denitrogen gas, nitrous oxide, and sludge. The methane emission in the anaerobic process is due to methanogenesis. Hence, it is clear that GHG emissions from wastewater treatment are due to the employment of anaerobic and anoxic treatments; however there is biomass decay in the aerobic system which would contribute to ammonia generation, see the Equation 2.20. This should be counted as it can be converted into nitrous oxide in the denitrification process.

$$\mathrm{C_5H_2O_2N} + 5\mathrm{O_2} \rightarrow 5\mathrm{CO_2} + 2\mathrm{H_2O} + \mathrm{NH_3} \qquad \textbf{2.20}$$

Where $C_5H_2O_2N$ = the element composition of biomass (Bridle Consulting 2007; Snip 2010; Zhang et al., 2012).

The study indicated that the methane emission can be estimated in the anaerobic process, if the organic material composition is known, and the general reaction can be expressed as Equation 2.21. In Equation 2.21, $C_nH_aO_b$ represents the organic material composition. However, the composition is unknown as wastewater is a complex mixture. The authors noted that, instead of using the Equation 2.21 to obtain methane production, COD loading can be used for the estimation. It is reported that for each kg COD, 0.23 kg methane is generated (Angelidaki & Sanders, 2004; Zhang et al., 2012); therefore, the methane emission can be calculated by multiplying the influent COD with 0.23. It has been reported that there are mainly three ways of nitrous oxide production, i.e., nitrification, denitrification, and chemical reaction. Among them, denitrification is the main emission source. It is noted that nitrous oxide emission from the anaerobic condition can be estimated with Equation 2.22.

$$\mathrm{C_nH_aO_b} + (\mathrm{n} - \mathrm{a}/4 - \mathrm{b}/2)\,\mathrm{H_2O} \rightarrow (\mathrm{n}/2 - \mathrm{a}/8 + \mathrm{b}/4)\,\mathrm{CO_2} + (\mathrm{n}/2 + \mathrm{a}/8 - \mathrm{b}/4)\,\mathrm{CH_4} \qquad \textbf{2.21}$$

$$\mathrm{N_2O\ emission} = \mathrm{Q} * \mathrm{C_{TN}} * \mathrm{R_{N_2O}} \qquad \textbf{2.22}$$

Where, Q = influent of anaerobic reactor (m^3/d); C_{TN} = total nitrogen concentration in the influent of the anaerobic reactor (kg N/m^3); R_{N_2O} = the conversion factor of N in the feed to N_2O (kg N_2O/kg N feed), and the factor has to be measured for each anaerobic process of wastewater treatment.

The study also indicated that besides the direct emission (emission from the generation of GHGs during the treatment), there are emissions from the utilization of materials. During the treatment, chemicals such as lime, polymers, and chlorine, are employed to aid the particle removal or disinfect the effluent of secondary treatment in case the additional requirement for the effluent needs to be satisfied. It is noted that the GHG emission from the usage of chemicals can be determined based on the amount consumed (Equation 2.23). As mentioned in the study, apart from chemicals, energy utilization of the treatment is another important contributor of the GHG emission. The emission depends on the power generation sources, which mainly include coal, hydro, nuclear, heavy fuel oil, and natural gas as the source decides the conversion factor of the emission (Zhang et al., 2012). It is specified in the study that equation 2.24 can be used to calculate the emission from the utilization of power in the treatment plant.

$$\mathrm{CO_2\ emission\ (kg/d)} = \mathrm{Q} * \mathrm{D} * \mathrm{r_{che}} \qquad \textbf{2.23}$$

Where, Q = influent of the chemical addition reactor (m^3/d); D = chemical addition ratio (kg chemical/m^3); r_{che} = CO_2 emission ratio of the chemical production (kg CO_2/kg chemical production).

$$\mathrm{CO_2\ emission\ (kg/d)} = \mathrm{P} * \mathrm{f} \qquad \textbf{2.24}$$

Where, P = the total power used in the treatment plant (kW/d); f = conversion factor of power generation (kg CO_2/kW).

According to study, based on the above discussion, the GHG emissions from wastewater treatment can be estimated according to the treatment processes (aerobic, anaerobic, or anoxic) (see Equation 2.25).

$$\begin{aligned}&\mathrm{GHG\ emissions\ (kg\ CO_2/d)} = \\ &21 * \mathrm{CH_4\ production\ (kg/d)} + 310 * \mathrm{N_2O\ production\ (kg/d)} + \\ &\mathrm{CO_2\ emission\ of\ chemical\ utilization\ (kg/d)} + \\ &\mathrm{CO_2\ emission\ of\ power\ consumption\ (kg/d)} \qquad \textbf{2.25}\end{aligned}$$

Where, 21 and 310 are global warming potential (GWP) of methane and nitrous oxide, respectively. The section on the estimation of GHG emission during wastewater treatment gives us an insight into the sources of GHG emission during the process.

According to CCAR and IPCC, the larger source of CH_4 emissions occurs from open anaerobic wastewater treatment processes, when the CH_4 produced is released directly to the atmosphere uncollected, uncontrolled, and without treatment, such as anaerobic lagoons, anaerobic reactor (e.g., digesters), or septic tanks. Anaerobic digestion is the fermentation process in which organic material is degraded and biogas (compose of CH_4 and CO_2) is produced. The anaerobic process includes four stages: hydrolysis, acidogenesis, acetogenesis, and methanogenesis. In anaerobic processes, CO_2, CH_4, N_2O are emitted directly into the atmosphere. CH_4 emissions also result from fugitive releases from solids handling processes, such as sludge digestion. Land application systems are also known to be sources of GHG (CH_4, CO_2 and N_2O) emissions in the atmosphere (Picek et al., 2007). These emissions are given as detailed in the following sections.

2.3.1 IPCC Methodology

The IPCC has developed a methodology for estimating emissions from wastewater treatment. The Revised 1996 IPCC Guidelines (IPCC Guidelines, 1997) included separate equations to estimate emissions from wastewater and from sludge removed from the wastewater. The distinction has removed because the CH_4 generation capacities for sludge and wastewater with dissolved organics are generally the same, and separated equations are not necessary (IPCC, 2006). The 2006 Guidelines also include a new section to calculate CH_4 emissions from uncollected wastewater. A new section is also located to estimate N_2O emissions from advanced treatment plants.

CO_2 emissions from wastewater are not considered in the IPCC Guidelines, because these are of biogenic origin and should not be included in total emissions. CH_4 are emitted from wastewater as well as its sludge components when it degrades anaerobically. The extent of CH_4 gas production depends on the quantity of degradable organic material in the wastewater. The temperature and the type of treatment system also affect to the CH_4 gas production. According to IPCC Guidelines, the principal factor in determining the CH_4 generation potential of wastewater is the amount of degradable organic material. Common parameters used to measure the organic component of the wastewater are BOD and COD. Under the same conditions, wastewater with high BOD or COD concentrations yield more CH_4 than wastewater with lower BOD or COD one.

Emissions from wastewater treatment are a function of the amount of organic waste present and an emission factor characterizes the extent to which this waste generated GHGs (Moumouni, 2009). According to IPCC, a simplified general algorithm for estimating GHG is as shown below, see Equation 2.26.

$$\text{Gas emission (kg/yr)} = \text{AD} * \text{Fr} * \text{DP} * \text{EF} * \text{CONVF} \tag{2.26}$$

In this equation, AD is activity data (population served by the system, volume of water and wastewater treated, organic loading, nitrogen content etc.). Fr is the fraction of treated wastewater in the treatment plants. DP is design parameter (treatment efficiencies). EF is the specific emission factor of each gas, such as CO_2, CH_4, and N_2O. CONVF is the conversion factor to standardize the calculation units for the GHG emission (Prendez et al., 2008; Moumouni, 2009).

2.3.1.1 *Methane Emissions from Wastewater*

Emissions are a function of the amount of organic waste generated and an emission factor that characterizes the extent to which this waste generates CH_4. There are three tier methods for estimating CH_4 emissions from wastewater.

The Tier 1 method applies default values for the emission factor and activity parameters. This method is considered *good practice* for countries with limited data. Tier 2 method follows the same method as Tier 1. But Tier 2 method allows country specific emission factor and activity data. For example, a specific emission factor for a prominent treatment system based on field measurements could be incorporated under this method. The amount of sludge removed for incineration, landfills, and agricultural land should be taken into consideration (IPCC Guidelines, 2006). Tier 3 method applies for a country with good data and advanced methodologies. For domestic wastewater treatment plants, which method be selected from these three methods is given in the Figure 2.5.

As described earlier, the wastewater characterization will determine the fraction of wastewater treated or disposed of by a particular system. To determine the use of each type of treatment or discharge system, it is good practice to refer to national statistics. If these data are not available, wastewater associations or international organizations may have data on the system usage (IPCC, 2006).

It is good practice to treat the three categories: rural population, urban high income population, and urban low income population separately (IPCC, 2006). The steps for good practice (Tier 1) in inventory preparation for CH_4 from domestic wastewater include three steps: step 1, step 2, and step 3. These steps are given in detail below.

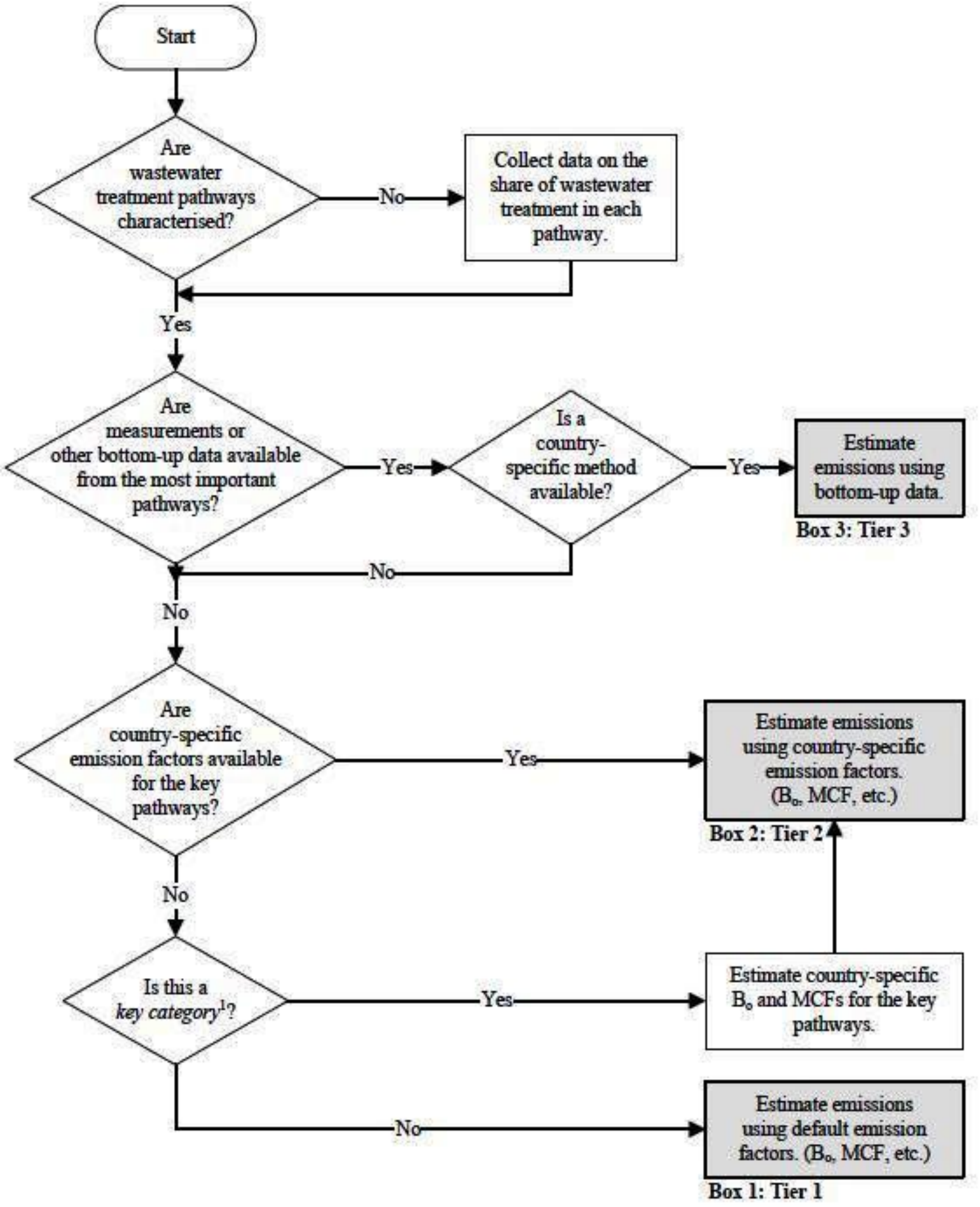


Figure 2.5 Choice of method for CH_4 emissions from domestic wastewater plants (IPCC, 2006)

Step 1 is estimating total organically degradable carbon in wastewater (TOW). Equation 2.27 is used to estimate TOW.

$$\mathrm{TOW} = \mathrm{P} * \mathrm{BOD} * 0.001 * \mathrm{I} * 365 \qquad \mathbf{2.27}$$

Where,

P = Country population in the inventory year

BOD = Country-specific per capita BOD in the inventory year, g/person/day

0.001 = Conversion from grams BOD to kg BOD

I = Correction factor for additional industrial BOD discharged into sewers

The factor I may not be available in some countries. The default suggested by the IPCC for collected wastewater is 1.25, and for uncollected is 1.00 (Narium and Towprayoon, 2012). IPCC Guideline 2006 also includes BOD default values for some regions and countries. When country-specific data are not available, BOD default value is selected in IPCC Guideline. For Turkey, estimated BOD_5 value in IPCC is 38 g/person/day, and the range of BOD_5 value for Turkey is given 27 – 50 g/person/day in the guideline.

Step 2 is selecting the pathway and systems according to country activity data. Equation 2.28 is used to obtain the emission factor for each domestic wastewater treatment/discharge pathway or system. Emission factors for domestic wastewater are calculated for each wastewater and sludge type. A weighted average of CH_4 conversion factor was calculated using estimates of wastewater managed by each wastewater handling method (Narium & Towprayoon, 2012).

$$\mathrm{EF_j} = \mathrm{B_o} * \mathrm{MCF_j} \qquad \mathbf{2.28}$$

The maximum methane producing capacity (B_o) is expressed in terms of kg CH_4/kg BOD or kg CH_4/kg COD. According to IPCC 2006 Guideline, a default value of 0.6 kg CH_4/kg BOD. Methane conversion factor (MCF_j) is an estimate of the fraction of BOD or COD that will ultimately degrade in an anaerobic process. In general, the MCF depends on the technology used (Narium and Towprayoon, 2012). The IPCC guideline suggested MCF values; these values are given in Table 2.1.

Table 2.1 MCF values (IPCC, 2006)

Type of treatment and discharge pathway	**Comments**	**MCF**	**Range**
Centralized, aerobic treatment plant	Must be well management. Some CH_4 can be emitted from settling basins and other pockets.	0	0 – 0.1
Centralized, aerobic treatment plant	Not well managed. Overloaded.	0.3	0.2 – 0.4
Anaerobic digester for sludge	CH_4 recovery is not considered here.	0.8	0.8 – 1.0
Anaerobic reactor	CH_4 recovery is not considered here.	0.8	0.8 – 1.0
Anaerobic shallow lagoon	Depth less than 2 meters.	0.2	0 – 0.3
Anaerobic deep lagoon	Depth more than 2 meters.	0.8	0.8 – 1.0
Septic system	Half of BOD settles in anaerobic tank	0.5	0.5

Step 3 is estimating emissions, adjust for possible sludge removal and/or CH_4 recovery and sum the results for each pathway/system. The general equation to estimate total CH_4 emissions from domestic wastewater is shown in Equation 2.29.

$$\mathrm{CH_4\ Emissions} = \left[\sum_{i,j}\left(U_i * T_{i,j} * EF_j\right)\right](TOW - S) - R \qquad \textbf{2.29}$$

Where,

CH_4 Emissions = CH_4 emissions in inventory year, kg CH_4/yr

TOW = total organics in wastewater in the inventory year, kg BOD/yr

S = organic component removed as sludge in inventory year, kg BOD/yr

U_i = fraction of population in income group *i* in inventory year

$T_{i,j}$ = degree of utilisation of treatment/discharge pathway or system, *j*, for each income group fraction *i* in inventory year

i = income group: rural, urban high income and urban low income
j = each treatment system
EF_j = emission factor, kg CH_4 / kg BOD
R = amount of CH_4 recovered in inventory year, kg CH_4/yr

Default values of U_i and $T_{i,j}$ for selected countries is given in IPCC guideline in the form of tables. There are no suggested values for urbanization (U_i) for Turkey in guideline. The IPCC has stated that the degree of urbanization for a country can be retrieved from various sources, (e.g., Global Environment Outlook, United Nations Environment Programme and World Development Indicators, World Health Organization). The urban high-income and urban low income fractions can be determined by expert judgment when statistical or other comparable information is not available.

The IPCC has noted that the same method and data sets should be used for estimating CH_4 emissions from wastewater for each year. If the share of wastewater treated in different treatment systems changes over the time period, the reasons for these changes should be documented. Sludge removal and CH_4 recovery should be estimated consistently across years in the time series.

2.3.1.2 Nitrous Oxide Emissions from Wastewater

N_2O emissions can occur as direct emissions from wastewater treatment plants or from indirect emissions from wastewater after disposal of effluent into waterways, lakes or the sea (IPCC Guidelines, 2006). As mentioned above that direct N_2O emissions are emitted from nitrification and denitrification processes in WWTPs.

According to IPCC methodology, no higher tiers and no decision tree are given for estimating N_2O emissions. Direct emissions need to be estimated only for countries that have predominantly advanced centralized WWTPs with nitrification and denitrification. The simplified general equation for estimating N_2O emissions is given below in the Equation 2.30.

$$\mathrm{N_2O\ emissions} = \mathrm{N_{EFFLUENT}} * \mathrm{EF_{EFFLUENT}} * 44/28 \qquad \textbf{2.30}$$

Where,

N_2O emissions : N_2O emissions in inventory year, kg N_2O/yr

$N_{EFFLUENT}$: nitrogen in the effluent discharged to aquatic environments, kg N/yr

$EF_{EFFLUENT}$: emission factor for N_2O emissions from discharged to wastewater, kg N_2O-N/kg N

The factor 44/28 is the conversion of kg N_2O-N into kg N_2O.

The default IPCC emission factor for N_2O emissions from domestic wastewater nitrogen effluent is 0.005 (0.0005 – 0.25) kg N_2O-N/kg N (CH2MHILL, 2007). The activity data that are needed for estimating N_2O emissions are nitrogen content in the wastewater effluent, country population and average annual per capita protein generation (kg/person/yr). The total nitrogen in the effluent is estimated as following Equation 2.31:

$$\mathrm{N_{EFFLUENT}} = (\mathrm{P} * \mathrm{Protein} * \mathrm{F_{NPR}} * \mathrm{F_{NON-CON}} * \mathrm{F_{IND-COM}}) - \mathrm{N_{SLUDGE}} \qquad \textbf{2.31}$$

Where,

$N_{EFFLUENT}$ = total annual amount of nitrogen in the wastewater effluent, kg N/yr

P = human population

Protein = annual per capita protein consumption, kg/person/yr

F_{NPR} = fraction of nitrogen in protein, default = 0.16 kg N/kg protein

$F_{NON\text{-}CON}$ = factor for non-consumed protein added to the wastewater

$F_{IND\text{-}COM}$ = factor for industrial and commercial co-discharged protein into the sewer-system

N_{SLUDGE} = nitrogen removed with sludge (default is zero), kg N/yr

According to data in Metcalf and Eddy (2003) default value of the factor of industrial and commercial co-discharged protein ($F_{IND\text{-}COM}$) is 1.25. Table 2.2 shows N_2O methodology default data in IPCC Guideline (2006).

Table 2.2 N_2O methodology default data

	Definition	Default Value	Range
Emission Factor			
$EF_{EFFLUENT}$	Emission factor (kg N_2O-N/kg N)	0.005	0.0005 – 0.25
EF_{PLANTS}	Emission factor (g N_2O/person/year)	3.2	2 – 8
Activity Data			
P	Population	Country-specific	± 10 %
Protein	Annual per capita protein consumption	Country-specific	± 10 %
F_{NPR}	Fraction of nitrogen in protein (kg N/kg protein)	0.16	0.15 – 0.17
T_{PLANT}	Degree of utilization of large WWTPs	Country-specific	± 20 %
$F_{NON\text{-}CON}$	Factor to adjust for non-consumed protein	1.1 for countries with no garbage disposals. 1.4 for countries with garbage disposals	1.0 – 1.5
$F_{IND\text{-}COM}$	Factor of industrial and commercial co-discharged protein	1.25	1.0 – 1.5

2.3.2 LCA Methodology

In order to estimate emissions of GHG from WWTPs, the Life Cycle Assessment analysis can be performed. LCA is used to evaluate possible environmental impacts of the products, or service from design to disposal. LCA involves the collection and evaluation of quantitative data on inputs and outputs of energy, and waste flows associated with a product over its entire life cycle so that the environmental impacts can be determined (Colliver, 2000). The use of a LCA approach to better quantify total environmental burden of treatment plants where, in addition to climate change, a larger number of other upstream and downstream impacts are also taken into account.

LCA studies have shown that impacts associated with operating water or wastewater treatment plants are dominated by operational inputs and outputs. In order to make better use of calculation tools for estimating GHG emissions or constructing LCA models, good inventory data is required (Haas, et al., 2009). The procedures of LCA are part of the ISO 14000 Environmental Management Standards which are in ISO 14040: 2006 and ISO: 14044: 2006. There are four stages in conducting the LCA: 1) Goal and Scope, 2) Life Cycle Inventory, 3) Life Cycle Impact Assessment, 4) Interpretation.

Goal and scope is the most important stage to identify the purpose of LCA method. The scope of study generally implies defining the system. It includes definition of system boundaries, data requirements, assumptions and limitations (Sundqvist, 1999). A Life Cycle Inventory (LCI) includes information on all of the environmental inputs and outputs associated with a product or service such as material and energy requirements, as well as emissions and wastes (Ibrahim & Salim, 2012). Life Cycle Impact Assessment is used to assess the impacts of the inputs and outputs identified in the inventory analysis. The impact assessment of an environmental LCA should consider the categories: resource depletion, impacts on human health, ecological impacts. Interpretation is a technique to evaluate the results of the inventory analysis.

2.3.3 LGO Protocol Methodology

LGO Protocol has a methodology for estimation of GHG emissions from wastewater treatment facilities. Protocol includes activities like wastewater collection, managing septic systems, primary and secondary treatment, solids handling and effluent discharge. This Protocol is also based on the Greenhouse Gas Protocol: A Corporate and Reporting Standard (WRI/WBCSD) and it use the same five principles. LGO Protocol occurs from four parts and appendices. Parts of protocols are introduction, identifying emissions, quantifying emissions, and reporting emissions. Appendices includes reporting requirements of CARB, CCAR, ICLEI, TCR; and global warming potentials, standard conversion factors, default emission factors and references.

The Protocol has stated that wastewater treatment processes encompass many different sources of GHG emissions. Defining the organizational boundaries of wastewater treatment activities is required to determine what emissions from WWTP from calculating and reporting under the Protocol. According to the LGO Protocol, WWTP processes can create a unique set of process and fugitive GHG emissions. Production of CH_4 and N_2O emissions is the section of the LGO Protocol as the same as other protocol and initiatives. After determining boundaries and scopes emissions, next step is quantifying GHG emissions. The Protocol provides emissions quantification guidelines on how to quantify GHG emissions from your various sources of emissions. In order to quantify GHG emissions, the Protocol contains a variety of calculation methodologies, such as calculation-based and measurement-based methodologies.

Calculation-based methodologies are used to quantify the most of GHG emissions. It is mentioned above that the calculation-based methodologies involve the calculation of emissions based on activity data and emission factors. Activity data is the relevant measurement of energy use or other GHG generating processes. Emission factors are used to convert activity data into the associated GHG emissions. Conjunction between an activity data and emission factor determine GHG emissions. The LGO Protocol provides default emission factors for most calculation methodologies. Measurement-based methodologies determine GHG emissions by means of continuous measurement of the exhaust stream and the concentration of the relevant GHG emissions in the flue gas. This methodology is relevant with facilities that using existing continuous emission monitoring systems, such as power plants or industrial facilities with large stationary combustion units.

As mentioned above that this protocol is a tool for accounting and reporting GHG emissions. The protocol provides guidance on estimating the process and fugitive GHG emissions from wastewater treatment. Table 2.3 summarizes the sources of fugitive and process CH_4 and N_2O emissions discussed. For most sources, two methodologies are provided - a source-specific method that requires source-specific data and a general method that requires only population served by the facility. For each applicable source, you will choose a method and associated equation based on data available (LGO Protocol, 2008).

Table 2.3 Process and fugitive emissions (LGO Protocol, 2008)

GHG Type	GHG Source	Data Available	Equation
Stationary CH_4 emissions	Incomplete combustion of digester gas at a centralized WWTP with anaerobic digestion of biosolids	Digester gas (ft^3/day) Fraction of CH_4 in biogas	Eq. 2.32
		Population served	Eq. 2.33
Process CH_4 emissions	Anaerobic and Facultative treatment lagoons	BOD_5 load (kg BOD_5/day) Fraction of overall BOD_5 removal performance	Eq. 2.34
		Population served	Eq. 2.35
Fugitive CH_4 emissions	Septic systems	BOD_5 load (kg BOD_5/person/day)	Eq. 2.36
		Population served	Eq. 2.37
Process N_2O emissions	Centralized WWTP with nitrification/denitrification	Population served	Eq. 2.38
Process N_2O emissions	Centralized WWTP without nitrification/denitrification	Population served	Eq. 2.39
Process N_2O emissions	Effluent discharge to receiving aquatic environments	N load (kg N/day)	Eq. 2.40
		Population served	Eq. 2.41

The LGO Protocol has indicated that CH_4 emissions are emitted from septic systems, aerobic systems that are not well managed, anaerobic treatment and facultative treatment lagoons, and anaerobic digesters when the captured biogas is not completely combusted. CH_4 emissions estimation methodologies in the LGO Protocol are adapted from the IPCC Guidelines and USEPA methodology. For each term in the equations, description ad appropriate default values are provided by the protocol. Stationary CH_4 emissions arise from incomplete combustion of digester gas. Many of WWTPs operate anaerobic digesters and anaerobic digestion process creates CH_4, when is then combusted. Equation 2.32 can be used to estimate these stationary CH_4 emissions from incomplete combustion of digester gas. But the protocol has noted that Equation 2.33 is more appropriate than the Equation 2.32 when significant industrial contributions of BOD_5 are discharged to WWTP.

$$\text{Annual } CH_4 \text{emissions (metric tons } CO_2\text{e)} = \left(\text{Digester Gas} * F_{CH_4} * \rho(CH_4) * (1 - D) * 0.0283 * 365.25 * 10^{-6}\right) * \text{GWP} \qquad \textbf{2.32}$$

$$\text{Annual } CH_4 \text{emissions (metric tons } CO_2\text{e)} = \left(P * \text{Digester Gas} * F_{CH_4} * \rho(CH_4) * (1 - D) * 0.0283 * 365.25 * 10^{-6}\right) * \text{GWP} \qquad \textbf{2.33}$$

Where,

F_{CH_4} : measured fraction of CH_4 in biogas
p (CH_4) : density of CH_4 at standard conditions (g/m^3)
D : CH_4 Destruction efficiency
0.0283 : conversion from ft^3 to m^3 (m^3/ft^3)
365.25 : conversion factor (day/year)
10^{-6} : conversion from g to metric ton (metric ton/g)
P : Population served by the WWTP with anaerobic digesters

According to the LGO Protocol, Equation 2.34 can be used to estimate the process CH_4 emissions from anaerobic or facultative treatment lagoons. The Protocol has also noted that amount of BOD_5 produced per day and fraction of BOD_5 removed in primary treatment are user inputs, but these site-specific data are not available, the Equation 2.35 can be used instead of the Equation 2.34. Equation 2.35 can be also adjusted to the population served and it can be used to account for the industrial contribution. This is done using a factor that accounts for industrial and commercial wastewater discharge ($F_{ind\text{-}com}$). The $F_{ind\text{-}com}$ is 1.25 (LGO Protocol, 2008). The

Protocol has also indicated that whether WWTP does not treat wastewater from industrial or commercial sources, Equation 2.35 can be ignored.

$$\text{Annual CH}_4\text{emissions (metric tons CO}_2\text{e)} = (\text{BOD}_5\text{load} * (1 - \text{F}_\text{P}) * \text{B}_\text{o} * \text{MCF}_\text{anaerobic} * 365.25 * 10^{-3}) * \text{GWP} \qquad \textbf{2.34}$$

$$\text{Annual CH}_4\text{emissions (metric tons CO}_2\text{e)} = \left((\text{P} * \text{F}_\text{ind-com}) * \text{BOD}_5\text{load} * (1 - \text{F}_\text{P}) * \text{B}_\text{o} * \text{MCF}_\text{anaerobic} * 365.25 * 10^{-3}\right) * \text{GWP} \qquad \textbf{2.35}$$

Where,

BOD_{5load} : amount of BOD_5 produced

F_P : fraction of BOD_5 removed in primary treatment, if present

B_o : maximum CH_4-producing capacity for domestic wastewater (kg CH_4/kg BOD_5 removed)

$MCF_{anaerobic}$: CH_4 correction factor for anaerobic systems

10^{-3} : conversion from kg to metric ton

P : Population served by lagoons adjusted for industrial discharge, if applicable

According to the Protocol, fugitive CH_4 emissions from septic systems are estimated by using the equation 2.36. If there is a site-specific data, the equation 2.37 can be used to estimate this source of CH_4 emissions.

$$\text{Annual CH}_4\text{emissions (metric tons CO}_2\text{e)} = (\text{BOD}_5\text{load} * \text{B}_\text{o} * \text{MCF}_\text{anaerobic} * 365.25 * 10^{-3}) * \text{GWP} \qquad \textbf{2.36}$$

$$\text{Annual CH}_4\text{emissions (metric tons CO}_2\text{e)} = (\text{P} * \text{BOD}_5\text{load} * \text{B}_\text{o} * \text{MCF}_\text{anaerobic} * 365.25 * 10^{-3}) * \text{GWP} \qquad \textbf{2.37}$$

Estimation of N_2O emissions from a centralized treatment plant with or without nitrification/denitrification processes. The protocol has emphasized that their methodology are adapted from the IPCC guidelines and USEPA methodology. The Find-com term in each equation define the factor for industrial and commercial discharges into a municipal wastewater facility. The default value of Find-com is

1.25. If there are not these types of wastewater inputs, Find-com term is ignored in these equations. Process N_2O emissions from treatment plant with nitrification and denitrification is estimated by using the Equation 2.38. Estimation of process N_2O emissions from WWTP without nitrification and denitrification is calculated by using the Equation 2.39.

$$\text{Annual } N_2O \text{ emissions (metric tons } CO_2e) = \left((P_{total} * F_{ind-com}) * \text{EF nit/denit} * 10^{-6}\right) * GWP) \qquad \textbf{2.38}$$

$$\text{Annual } N_2O \text{ emissions (metric tons } CO_2e) = \left((P_{total} * F_{ind-com}) * \text{EF w/o nit/denit} * 10^{-6}\right) * GWP) \qquad \textbf{2.39}$$

Where,
Ptotal : total population that is served by the WWTP
$F_{ind-com}$: factor for industrial and commercial co-discharge waste into the sewer system
EF : emissions factor for a WWTP with or without nitrification/denitrification

The Protocol has indicated that the Equation 2.40 should be used to collect measurement of the average total nitrogen discharged in accordance with all regulations or permits. If there is not site-specific data, the Equation 2.41 can be used to estimate process N_2O emissions from effluent discharge to rivers.

$$\text{Annual } N_2O \text{ emissions (metric tons } CO_2e) = (\text{N load} * \text{EF effluent} * 365.25 * 10^{-3} * 44/28) * GWP \qquad \textbf{2.40}$$

$$\text{Annual } N_2O \text{ emissions (metric tons } CO_2e) = \left((P_{total} * F_{ind-com}) * (\text{Total N load} - \text{N load} * BOD_5\text{load}) * \text{EF effluent} * 44/28 * (1 - \text{F plant nit/denit}) * 365.25 * 10^{-3}\right) * GWP \qquad \textbf{2.41}$$

Where,
Total N load : total nitrogen load

N uptake : nitrogen uptake for cell growth in aerobic an anaerobic system

44/28 : molecular weight ratio of N_2O to N_2

F plant nit/denit : fraction of nitrogen removed for the centralized WWTP w/o nit/denit

In the study, City of Atlanta Greenhouse Gas Emission Inventory (2009), LGO Protocol is used to calculate the GHG emissions from wastewater treatment. CH_4 emission released from incomplete combustion is calculated by using the Equation 2.32. The study indicated that nitrous oxide is another greenhouse gas than can be emitted from WWTP. Equation 2.39 was used to calculate the N_2O emissions. Annual N_2O emissions from effluent discharged into aquatic bodies is also calculated using Equation 2.41 in the study. After calculations using the data of the Atlanta city, the total wastewater greenhouse gas emissions are calculated as about 5400 metric tons CO_2-eq. The study indicates that GHG emissions of wastewater treatment plant are about 1 % of total GHG emissions from the city of Atlanta.

2.4 Calculation Methods for Sludge Management

In recent years, interest of the amount of GHG emissions from sludge management has increased. The estimation of GHG emissions from different sludge management options has recently started investigating. The existing researches shows that the sludge treatment and disposal processes constitute a significant amount of total GHG emissions from WWTPs.

2.4.1 IPCC Methodology

The 2006 IPCC Inventory has indicated that sludge is produced in all of the stages of treatment. Primary treatment sludge is not accounted for in the IPCC methodology. Again, it is likely that non-methane volatile organic compounds (NMVOCs) are dominating these emissions though it is possible some methane is generated within sludge layers held in primary tanks, which is transported in dissolved form into secondary treatment where it is released (Hopson, et al., n.d). It is mentioned that sludge of secondary and tertiary treatment processes must be treatment further before it can be safely disposed of. Sludge treatment processes are described as detailed in the previous section.

In some countries, sludge from domestic wastewater treatment plants is included in municipal solid waste (MSW) and sludge from industrial wastewater treatment plants is included in industrial waste. The IPCC Inventory has emphasized that if sludge separation is practiced and appropriate statistics are available, sludge category should be separated out as a subcategory of WWTPs. If default factors are being used, emissions from wastewater and sludge should be estimated together. It is important that CH_4 emissions from sludge sent to landfills, incinerated or used in agriculture are not included in the WWTP category. If sludge removal data are available, the data should be consisted across the sectors, and categories, amount disposed at solid waste disposal, applied to agricultural land, incinerated should be equal to the amount organic component removed as sludge (S).

According to the IPCC Inventory (2006), methods of sludge treatment include aerobic and anaerobic digestion, conditioning, and centrifugation, composting, and drying. Sludge from WWTPs is discussed as a separate section in the IPCC Guidelines 2006. The GHG emissions from sludge treatment and disposal processes at WWTPs are discussed in different chapters: Waste Generation, Composition and Disposal; Solid Waste Disposal; Biological Treatment and Disposal; Incineration and Open Burning of Waste. Application of wastewater and sludge on agricultural land is discussed in Volume 4 for AFOLU in IPCC. These chapters have their own methodologies, formulas, and data. If sludge is managed by these techniques, method of each section should be consulted.

According to the IPCC, composting and anaerobic digestion of organic wastes and sludge is common in all around the world. The IPCC Inventory has indicated that GHG emissions from wastewater and sludge treatment should be estimated together when default factors are used. When sludge is co-digested with other wastes, CH_4 and N_2O emissions should be reported under the Biological Treatment of Solid

Wastes category. Composting and anaerobic digestion of organic wastes produce both CH_4 and N_2O emissions. The emissions from composting and anaerobic digestion depend on some factors, such as type of waste composted, amount the type of supporting material used, temperature, moisture content and aeration during the process. The uncertainty is depended on the quality of data collection.

According to the IPCC's Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories, there are no routine measurements of methane emissions estimations. Three basic methods are proposed to estimate the CH_4 emissions in order of increasing complexity. All of these methodologies are based on the annual production of sludge for any country. Method 1 produces an imprecise estimation, but it is very simple to perform. The emission factor makes an estimate of the fraction of potential methane conversion and it can vary from one country to another. The IPCC Inventory has stated that the method 2 can be least satisfactory as it adds significant complexity and may not add too much accuracy. Method 3 is used to estimate CH_4 emissions from each treatment and disposal option in common use. Generally, the estimation of CH_4 emissions is calculated using the Equation 2.42, according to the IPCC Inventory. "i" is used as a term for each treatment and disposal combination. CH_4 emissions are separately summed for each step in a treatment and disposal option.

$$\text{Annual CH}_4\text{ emissions} = \sum_i \text{tonnes raw dry solids processed}_i * \text{CH}_4\text{ potential}_i * \text{Emission factor}_i \qquad \textbf{2.42}$$

2.4.2 CCME - Biosolids Emissions Assessment Model

Biosolids Emissions Assessment Model (BEAM) GHG calculator tool was developed for the Canadian Council of Ministers of the Environment (CCME) to allow municipalities for estimation of GHG emissions from biosolids management. The BEAM Project was undertaken in several stages. The first stage included a literature review for GHG emissions from possible unit biosolid processes. The literature review also include current GHG accounting and verification protocols.

After the literature review, next stage is developing a calculator that could be used to calculate biosolids management GHG emissions for WWTPs. The CCME identified ten biosolids management scenarios for GHG emissions calculations. Ten scenarios were identified and were provided relevant data request spreadsheets. This information was used to populate the corresponding unit process modules within the BEAM to quantify net GHG emissions from the specified biosolids management scenario provided by each scenario.

The BEAM has been made consistent with TCR General Reporting Protocol and its Local Government Operations Protocol (2008). These protocols are likely to become more widely used recently. The BEAM sums the GHG emission estimates from each unit process in a biosolids management scenario and provides total GHG emissions for that scenario. The BEAM also assists in evaluating potential GHG mitigation measures.

The BEAM methodology has three scopes that are consistent with the IPCC, TCR, and other existing protocols. Scope 1 emissions are direct emissions and the organization has direct control. As mentioned above that existing protocols require reporting of all Scope 1 emissions. These emissions include fugitive CH_4 from anaerobic digestion and emissions from burning natural gas to heat the digesters according to the BEAM method. Scope 2 emissions are indirect emissions associated with the consumption of purchased electricity, steam, heating or cooling. The electricity purchased for gravity belt thickening, blowers for aeration in aerobic digesters, centrifuges are examples for Scope 2 emissions.

Scope 3 emissions are all other indirect emissions not included in other scopes. These emissions include upstream and downstream emissions resulting from the extraction and production of purchased materials and fuels, transport related activities in vehicles not owned or controlled by the reporting entity and outsourced activities (CCME, 2009). Manufacturing and transporting of dewatering polymers or other conditions are example for Scope 3 emissions. These emissions are reported separately. The methodology has emphasized that all emissions is reported as in CO_2

equivalents. CH_4 and N_2O emissions are multiplied by 21 and 310 respectively to determine the CO_2 equivalent values.

CO_2 emissions as a result of aerobic decomposition of biosolids organics are considered biogenic in origin and not considered in the model (Brown et al., 2010). The method focused on the three primary GHGs: CO_2, CH_4, and N_2O. The focus of the BEAM methodology is wastewater sludge management, which comes from primary and secondary clarifiers or from the bottom of wastewater lagoons, and ends at sludge disposal or reuse processes. The BEAM User Guide has also noted that collection systems, such as sewers, are also potentially significant sources of CO_2, CH_4, and N_2O, but these are not included in the scope of the BEAM methodology. Additionally, significant sources of GHG emissions for each process are determined in the methodology, but some sources are considered negligible. These negligible GHG emission sources are specified in the guideline.

It is mentioned above that the focus of BEAM method is sludge management. Sludge treatment and disposal processes in the model include storage, conditioning and thickening, aerobic digestion, anaerobic digestion, dewatering, thermal drying, alkaline stabilization, composting, landfill disposal, combustion, land application, transportation. The BEAM method consists of an Excel spreadsheet consisting of thirteen worksheets that require user input and one worksheet that contains default values and assumptions (CCME, 2009). The user guide is provided how to use excel spreadsheets. The first worksheet requires the user to input general wastewater treatment and use information and it also provides some results. Other worksheets require inputs and they are generating results for specific unit processes according to these inputs. For each unit process, the user can input data from local, site-specific measurements, regional estimates, or more general default values provided in the spreadsheet tool. The final worksheet provides all of the default values and assumptions used for determining the results. The default emissions factors and conversions are current best estimates selected from the published literature.

Different colors are used in excel cells throughout the spreadsheet to make things easier for the user in the BEAM methodology. These colored cells alert the user to the type of information required or contained in each cell. There is also a key on each worksheet that defines the information contained in colored cells. For example, green cells have defined that require user input. The corresponding worksheet is selected for each unit process. Collecting specific data as possible for the green input cells is important to ensure the accuracy. The Inventory has stated that the data should represent an average over a relatively long period. The collected data is entered into the appropriate green cells for each applicable unit process worksheet. If the required data cannot be obtained, the calculator tool provides default values. Specific unit process results are provided on the relevant unit process worksheet and summarized on the first worksheet. The total emissions for a given unit process are provided in the summary table next to the cell entitled, CO_2 equivalents (Mg/year).

As mentioned above that the IPCC defines three tiers as representing a level of methodological complexity and accuracy in GHG accounting. TCR has adopted essentially the same tier system, but it has renamed them and reversed the order: Tier A is the most complex, Tier B is the intermediate level, and Tier C is the least complex and accurate. The BEAM tool does not track the tier system. The BEAM tool allows the use of user-defined data (Tier A), a combination of default and user-obtained data (Tier B) or the use of default values alone (Tier C) that were derived from the review of literature and existing protocols.

The BEAM methodology is accounted the GHG emissions as debits and credits. Debit emissions are positive numbers of metric tons (Mg) of CO_2 equivalents. Debit emissions are accounted, when a facility or operation releases GHG emissions to the atmosphere. Conversely, if facility or operation conducts an activity to offset GHG emissions, such as sequestering short-term-cycle carbon from biosolids, then credits are accounted. Credits emissions are negative numbers of metric tons of CO_2-eq. Credits are subtracted from debits to yield net GHG emissions from a given activity of the facility (CCME, 2009). GHG emissions flow chart is given with debits and credits emissions in the Figure 2.6.

The BEAM method focused on the three primary GHGs: CO2, CH4, and N2O. The focus of the methodology is wastewater sludge management, which comes from primary and secondary clarifiers, and ends at sludge disposal or reuse processes. The BEAM User Guide has also noted that collection systems, such as sewers, are also potentially sources of GHG emissions, but these are not included in the scope of the BEAM methodology. Significant sources of GHG emissions are determined in the method, but some sources are considered negligible. Table 2.4 provides the sources of negligible GHG sources in the BEAM method.

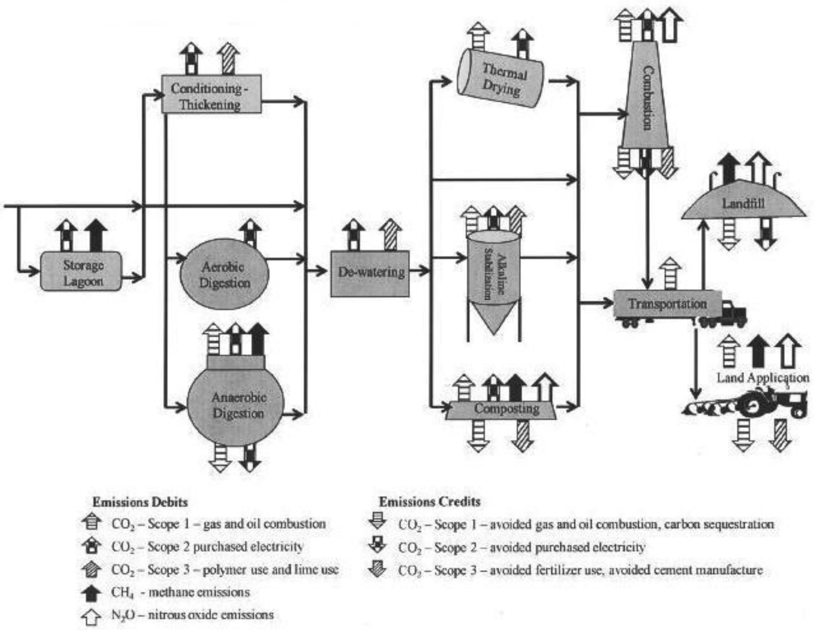


Figure 2.6 Emission debits and credits (Brown et al., 2009)

Some assumptions have been made in BEAM method. The scope of each emission is shown separate from the total in the method. Electricity that used for sludge pumping is negligible. The method does not perform LCA; for example, they do not include the GHG emissions associated with the construction of infrastructure, such as digesters, landfills, incinerators. The method assumes carbon embedded in infrastructure will be more or less equal from one sludge management process to another. It focuses on sludge treatment and disposal unit process only.

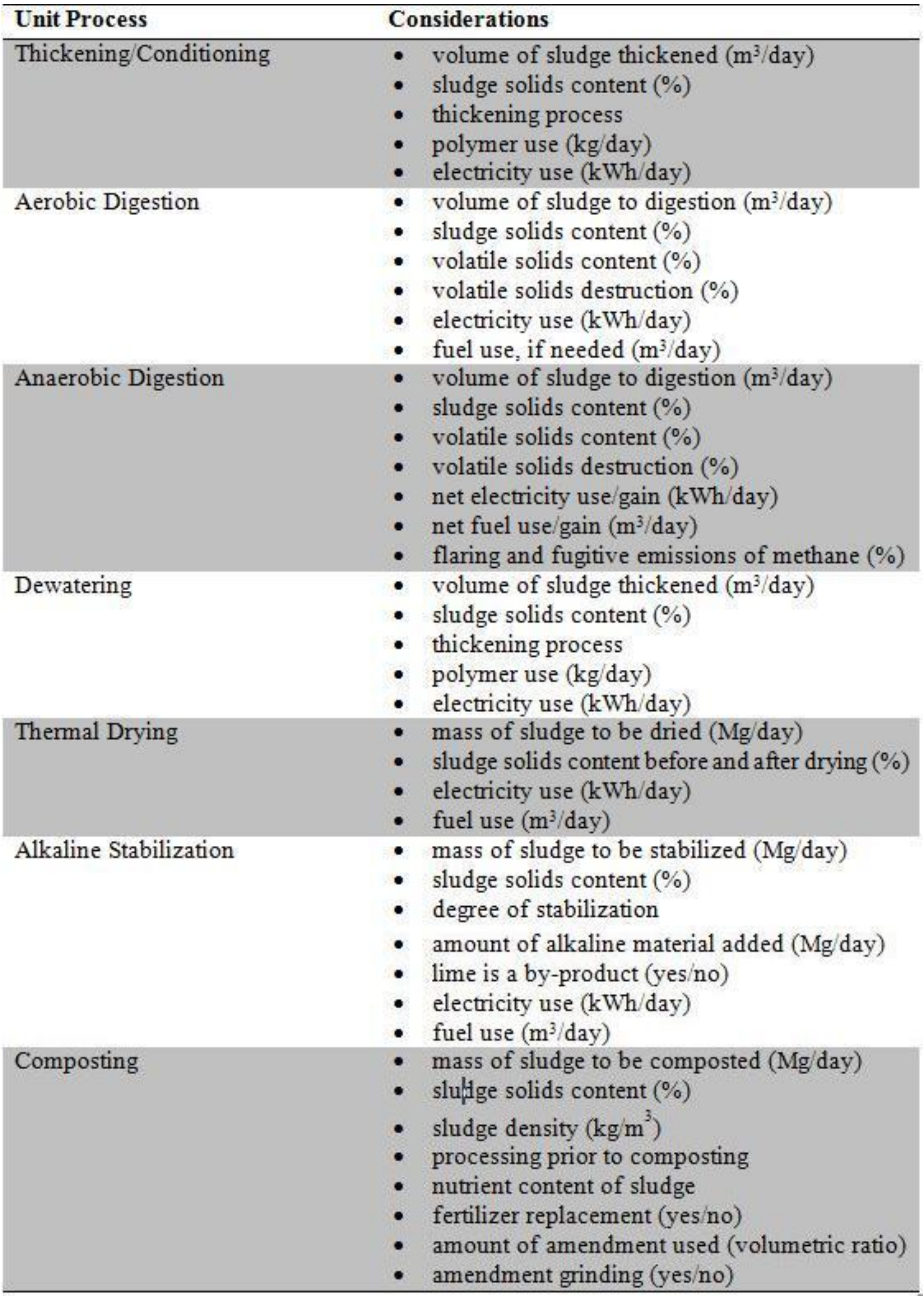
It is mentioned earlier that the BEAM method consists of excel spreadsheets to estimate GHG emissions. The first worksheet requires the user to input general wastewater treatment information. Other worksheets require some inputs and they generate results for specific unit processes according to these inputs. For each unit process, the user can input data from local, site-specific measurements, regional estimates, or more general default values provided in the spreadsheet tool (Sylvis, 2009). Different colors are used in excel cells to make things easier for the user in the methodology. For example, green cells have defined that require user input. The method provides default data, but collecting specific data for the green input cells is important to ensure the accuracy. Default values are shown in blue cells. Specific unit process results are provided on the relevant unit process worksheet. All emission results are shown in grey cells.

The boundaries for the BEAM methodology are from solids thickening through to sludge disposal. Summary of factors considered within the above scenarios for each unit process in the method are given in Table 2.5. It was mentioned above that the pumping and transporting to a WWTP are not within the boundaries of the method.

Table 2.4Negligible GHG sources (Sylvis, 2009)

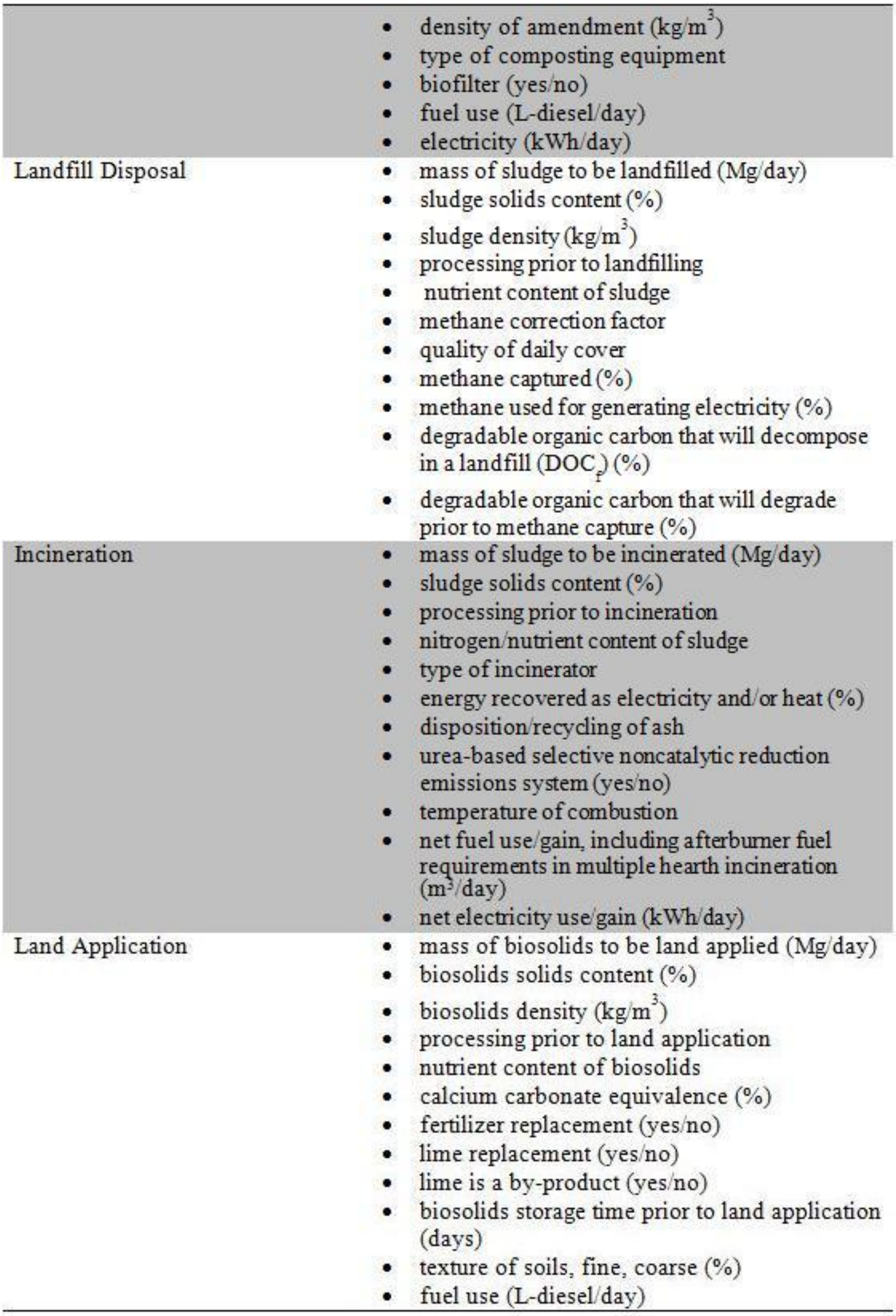
Unit Process	Negligible GHG	Rationale
Facultative Lagoon	CH_4	Aerobic surface layer effectively oxidizes CH_4
Aerated Lagoon	CH_4	Maintenance of an aerobic environment limits production
Mesophilic aerobic digestion	CH_4 and N_2O	Maintenance of an aerobic environment limits production
Physical addition of polymer in thickening	CO_2	Minimal energy requirement for process
Biogas recovery and combustion	N_2O	Anectodal evidence of small releases, but not supported by data
Composting	CH_4 and N_2O	Considered negligible if total solids content of windrow is > 55 % as this promotes an aerobic environment
Composting	CH_4	Considered negligible if process air treated in a biofilter
Composting	N_2O	Considered negligible if C:N > 30 %
Composting curing	CH_4 and N_2O	Compost is stable and microbial processes minimized, supporting data indicates minimal emissions
Gravity thickening	CH_4 and N_2O	Assumed that this process is kept aerobic
Passive dewatering	CO_2	Minimal energy use
Thermal drying	CH_4 and N_2O	Lack of supporting data

Table 2.5 Summary of considerations for unit process calculations (Sylvis, 2009)



Unit Process	Considerations
Thickening/Conditioning	• volume of sludge thickened (m^3/day) • sludge solids content (%) • thickening process • polymer use (kg/day) • electricity use (kWh/day)
Aerobic Digestion	• volume of sludge to digestion (m^3/day) • sludge solids content (%) • volatile solids content (%) • volatile solids destruction (%) • electricity use (kWh/day) • fuel use, if needed (m^3/day)
Anaerobic Digestion	• volume of sludge to digestion (m^3/day) • sludge solids content (%) • volatile solids content (%) • volatile solids destruction (%) • net electricity use/gain (kWh/day) • net fuel use/gain (m^3/day) • flaring and fugitive emissions of methane (%)
Dewatering	• volume of sludge thickened (m^3/day) • sludge solids content (%) • thickening process • polymer use (kg/day) • electricity use (kWh/day)
Thermal Drying	• mass of sludge to be dried (Mg/day) • sludge solids content before and after drying (%) • electricity use (kWh/day) • fuel use (m^3/day)
Alkaline Stabilization	• mass of sludge to be stabilized (Mg/day) • sludge solids content (%) • degree of stabilization • amount of alkaline material added (Mg/day) • lime is a by-product (yes/no) • electricity use (kWh/day) • fuel use (m^3/day)
Composting	• mass of sludge to be composted (Mg/day) • sludge solids content (%) • sludge density (kg/m^3) • processing prior to composting • nutrient content of sludge • fertilizer replacement (yes/no) • amount of amendment used (volumetric ratio) • amendment grinding (yes/no)

Table 2.5 Summary of considerations for unit process calculations (Sylvis, 2009), continue



	• density of amendment (kg/m^3) • type of composting equipment • biofilter (yes/no) • fuel use (L-diesel/day) • electricity (kWh/day)
Landfill Disposal	• mass of sludge to be landfilled (Mg/day) • sludge solids content (%) • sludge density (kg/m^3) • processing prior to landfilling • nutrient content of sludge • methane correction factor • quality of daily cover • methane captured (%) • methane used for generating electricity (%) • degradable organic carbon that will decompose in a landfill (DOC_f) (%) • degradable organic carbon that will degrade prior to methane capture (%)
Incineration	• mass of sludge to be incinerated (Mg/day) • sludge solids content (%) • processing prior to incineration • nitrogen/nutrient content of sludge • type of incinerator • energy recovered as electricity and/or heat (%) • disposition/recycling of ash • urea-based selective noncatalytic reduction emissions system (yes/no) • temperature of combustion • net fuel use/gain, including afterburner fuel requirements in multiple hearth incineration (m^3/day) • net electricity use/gain (kWh/day)
Land Application	• mass of biosolids to be land applied (Mg/day) • biosolids solids content (%) • biosolids density (kg/m^3) • processing prior to land application • nutrient content of biosolids • calcium carbonate equivalence (%) • fertilizer replacement (yes/no) • lime replacement (yes/no) • lime is a by-product (yes/no) • biosolids storage time prior to land application (days) • texture of soils, fine, coarse (%) • fuel use (L-diesel/day)

2.4.3 Bilan Carbone Method

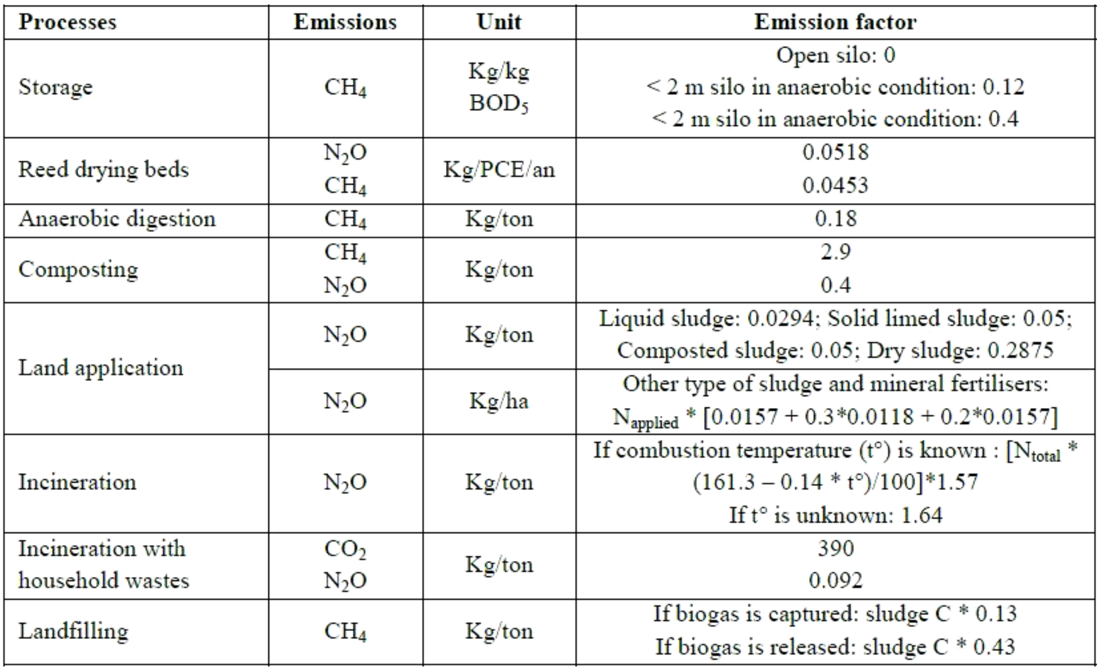
The French Environment and Energy Management Agency (ADEME) developed a carbon footprint framework called Bilan Carbone method, which allows quantifying and assessing the GHG emissions for human activities or organizations in France (ADEME, 2009). The Bilan Carbone method is a general method used to quantify GHG emissions generated from all processes. CO_2, CH_4, and N_2O gases are recorded in this method, similarly to other methods. Biogenic carbon is not taken into account. For each process involved in the sludge management processes, three types of emissions are considered: direct, indirect, and avoided emissions. Direct emissions are generated by each process. Indirect emissions are due to energy and chemical consumptions to operate each process. Avoided emissions are generated when products are not used and replaced by recyclable products, such as heat, electricity, fertilizer etc (Pradel & Reverdy, 2012).

This method is generally applied to assess the GHG emissions of industrial or tertiary activities in France. The method is not very concerning the way to account GHG emissions, and no information is given to the assessment of sludge treatment in WWTPs. Hence, Gestaboues tool is developed to help stakeholders to better understand the carbon footprint of sludge treatment and disposal options. Gestaboues calculate all direct and indirect emissions of CO_2, CH_4, and N_2O for all steps of sewage sludge treatment and sludge disposal processes.

Five types of sludge is defined that can be produced in WWTP depending on the type of treatment. Sludges from primary treatment are classified in the A class. Sludges from secondary treatment are classified in B1 or B2 classes. The difference between the B1 and B2 classes is the presence of a primary treatment. B1 class has not a primary treatment, but B2 class has it. The mixture of primary and secondary sludges is classified in the C class while a stabilization process provides sludges classified in the D class (Pradel & Reverdy, 2012).

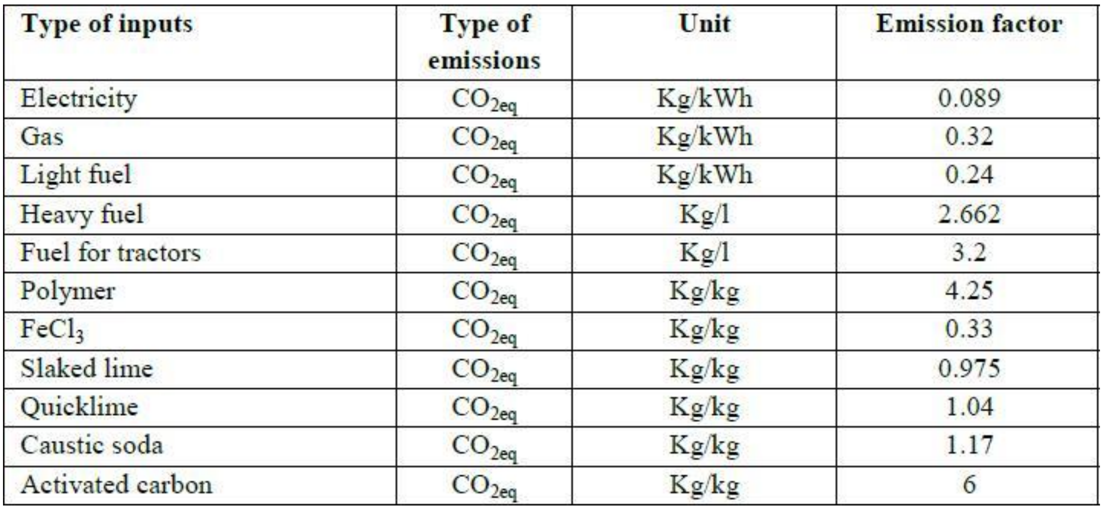
In this tool, GHG emissions are quantified for x tons of sludge produced by a wastewater treatment plant of x per-capita equivalent (PCE) during one year. Default values were defined for each process, including inputs, energy use, chemical consumption and GHG emissions. Data were collected from literature (Pradel & Reverdy, 2012). If the user has no specific data for WWTP, collected data will be used to assess the carbon footprint of the selected sludge treatment and disposal processes. The tool was developed with Visual Basic programming language. Direct emissions are generated for storage, reed drying beds, anaerobic digestion, composting, land application, incineration, and landfilling. Direct GHG emissions are summarized in Table 2.6. Indirect GHG emissions are expressed in CO_2-eq, and they are generated for each process using inputs such as electricity, gas, light and fuels, lime, soda, polymer etc. The GHG emissions generated by the production of these inputs are shown in the Table 2.7.

Table 2.6 Direct GHG emissions regarding the sludge treatment and disposal routes (Pradel & Reverdy, 2013)



Processes	**Emissions**	**Unit**	**Emission factor**
Storage	CH_4	Kg/kg BOD_5	Open silo: 0 < 2 m silo in anaerobic condition: 0.12 < 2 m silo in anaerobic condition: 0.4
Reed drying beds	N_2O CH_4	Kg/PCE/an	0.0518 0.0453
Anaerobic digestion	CH_4	Kg/ton	0.18
Composting	CH_4 N_2O	Kg/ton	2.9 0.4
Land application	N_2O	Kg/ton	Liquid sludge: 0.0294; Solid limed sludge: 0.05; Composted sludge: 0.05; Dry sludge: 0.2875
	N_2O	Kg/ha	Other type of sludge and mineral fertilisers: $N_{applied} * [0.0157 + 0.3*0.0118 + 0.2*0.0157]$
Incineration	N_2O	Kg/ton	If combustion temperature (t°) is known : $[N_{total} * (161.3 - 0.14 * t°)/100]*1.57$ If t° is unknown: 1.64
Incineration with household wastes	CO_2 N_2O	Kg/ton	390 0.092
Landfilling	CH_4	Kg/ton	If biogas is captured: sludge C * 0.13 If biogas is released: sludge C * 0.43

Table 2.7 Indirect GHG emissions regarding the inputs used for each process (Pradel & Reverdy, 2013)



Type of inputs	Type of emissions	Unit	Emission factor
Electricity	CO_{2eq}	Kg/kWh	0.089
Gas	CO_{2eq}	Kg/kWh	0.32
Light fuel	CO_{2eq}	Kg/kWh	0.24
Heavy fuel	CO_{2eq}	Kg/l	2.662
Fuel for tractors	CO_{2eq}	Kg/l	3.2
Polymer	CO_{2eq}	Kg/kg	4.25
$FeCl_3$	CO_{2eq}	Kg/kg	0.33
Slaked lime	CO_{2eq}	Kg/kg	0.975
Quicklime	CO_{2eq}	Kg/kg	1.04
Caustic soda	CO_{2eq}	Kg/kg	1.17
Activated carbon	CO_{2eq}	Kg/kg	6

Gestaboues tool is also used to compare different systems in order to analyze the best option either in sludge treatment or disposal processes. Pradel and Reverdy (2013) choose three different systems of a same WWTP to validate the Gestaboues tool. In this study, the WWTP has a capacity of 8500 per capita equivalents (PCE) and it produces around 71 tons of dry matter of sludge during one year (Pradel & Reverdy, 2013). In system 1 includes thickening, dewatering, liming and land application processes. System 1 generates about 71 tons CO_2-eq during one year and these GHG emissions are shared between CO_2, N_2O, and avoided emissions. CO_2 emissions are 61 tons CO_2-eq, N_2O emissions are 10 tons CO_2-eq, and the avoided GHG emissions is –51 tons CO_2-eq during one year. The study has stated that the land application emissions are 16.5 tons CO_2-eq and come from N_2O direct emissions and sludge transport between WWTP and fields. In this system, liming process is responsible to the most important GHG emissions. During liming process, more than 95 % of GHG are generated by lime production. Avoided GHG emissions are generated during land application.

In system 2 includes thickening, dewatering, composting, and land application. The second system generated about 21.9 tons CO_2-eq CO_2, 15.2 tons CO_2-eq CH_4, and 28.1 tons CO_2-eq N_2O emissions during one year. Total GHG emissions are 65.2 tons CO_2-eq and avoided GHG emissions are about - 47 tons CO_2-eq during one year in system 2. Land application emissions are 6.4 tons CO_2-eq during a year. Composting process is responsible for more than 70 % of GHG emissions. The study has indicated that the avoided GHG emissions are due to the non-use of mineral fertilizers and to carbon sequestration as for system 1 (Pradel & Reverdy, 2013).

The third system includes thickening, dewatering and incineration with household wastes processes. The study emphasized that the amount of CO_2 emissions are 198.6 tons CO_2-eq and the amount of N_2O emissions are 11.4 tons CO_2-eq during a year. Total GHG emissions are 210 tons of CO_2-eq and the avoided GHG emissions is about -147 tons of CO_2-eq during one year. Thickening and dewatering emissions are the same processes and similar with systems 1 and 2. Sludge incineration with household wastes is responsible 95 % of the GHG emissions. The study has shown that about 85 % of these GHG emissions generated during incineration are direct emissions. And the study emphasized that the avoided emissions in system 3 are due to the non-use of fuel replaced by the heat generated by incineration (Pradel & Reverdy, 2013).

The study that carried out by Pradel and Reverdy shows that GHG emissions of land application process vary between system 1 and 2 due to the nature of the sludge. It seems that the sludge composting before land application generate less GHG emissions than sludge liming. In comparison with systems, incineration with household wastes appears to be the worst option. The second system is the best option regarding the global warming impact. The study has stated that the results are order of magnitude to compare different systems and to identify the benefits the benefits. This tool only accounts GHG emissions and their impact on global warming potential. To complete analysis, LCA must be used with economic and social study (Pradel & Reverdy, 2013).

CHAPTER THREE
MATERIALS AND METHODS

The existing protocols, guidance documents, and calculation tools that are applicable to GHG emissions reporting were examined in previous sections. GHG emissions from wastewater treatment plant processes were investigated. Different sludge treatment and disposal processes and their GHG emissions were defined in detail. Potential GHG emissions were discussed for each unit sludge management process. The literature review is formed the basis for this study. This section of the thesis, different flow charts were created for different sludge management options. The aim of this section is to compare the GHG emissions that come from different sludge treatment and disposal processes.

Different sludge treatment and disposal options are considered. It is assumed six different sludge management scenarios:

- Scenario 1 includes thickening, aerobic sludge digestion, dewatering, composting, and finally land application.
- Scenario 2 includes thickening, anaerobic sludge digestion, dewatering, composting, and finally land application processes.
- Scenario 3 occurs sludge thickening, anaerobic sludge digestion, dewatering, alkaline stabilization, and land application processes.
- Scenario 4 occurs sludge thickening, anaerobic sludge digestion, dewatering, thermal drying, and finally landfill disposal processes.
- Scenario 5 includes sludge thickening, anaerobic sludge digestion, dewatering, thermal drying, and finally incineration processes.
- Scenario 6 occurs thickening, dewatering, incineration and final disposal. Flow charts of these scenarios are given in the Figure 3.1 – Figure 3.6.

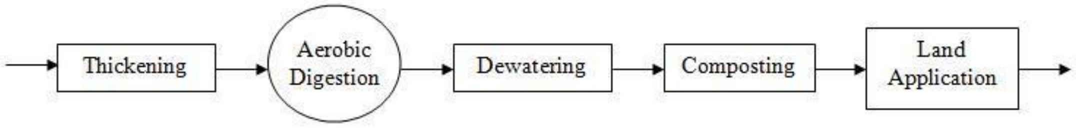


Figure 3.1 Scenario 1

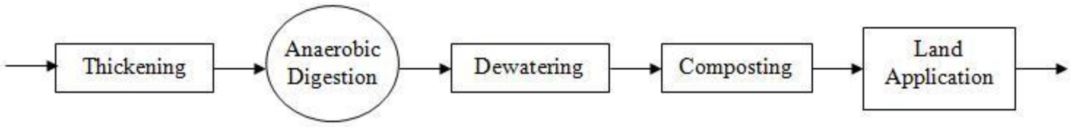


Figure 3.2 Scenario 2

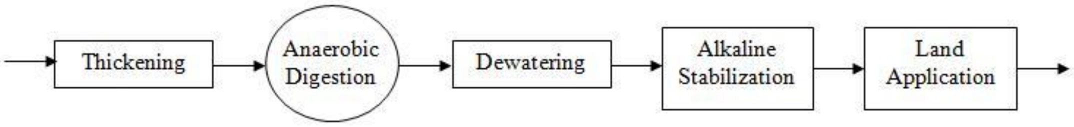


Figure 3.3 Scenario 3

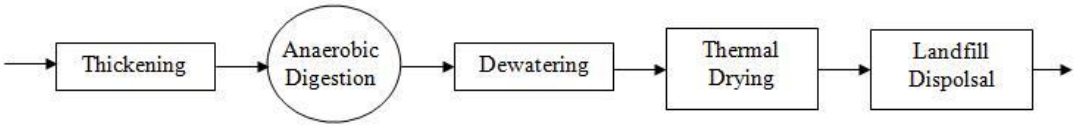


Figure 3.4 Scenario 4

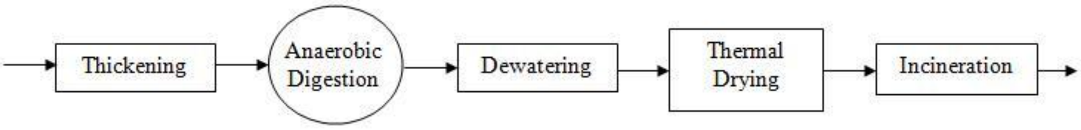


Figure 3.5 Scenario 5

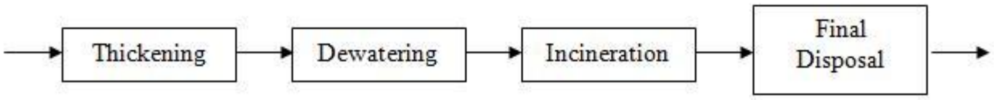


Figure 3.6 Scenario 6

The main objective of this thesis is the investigation of GHG emissions for different sludge treatment and disposal processes. When methodologies are examined, BEAM method is considered to be the most suitable for the purpose of the thesis. This method is divided into unit processes rather than focusing on complete management scenarios. This allows the users to combine unit processes for their particular management scenarios. The methodology sums the GHG emission estimates from each unit process in scenario and provides total GHG emissions for that scenario. The methodology has stated that it is easier to evaluate the accuracy of default values and the factors that have the greatest impacts on GHG emissions by separating unit processes. An important goal of BEAM method is to compare with the total GHG emissions from different sludge management scenarios.

GHG emissions are estimated for each unit process in each flow chart. As mentioned earlier that these GHG emissions are accounted by using BEAM methodology. It is mentioned in the previous section, there is a different worksheet for each unit treatment and disposal process in the method. The BEAM sums the GHG emission estimates from each unit process in a sludge management scenario and it provides total GHG emissions for that scenario. The BEAM has stated that it is easier by separating unit processes to evaluate the accuracy of default values and the factors that have the greatest impacts on GHG emissions. Total GHG emissions are reported in tones of CO_2 equivalent (Mg CO_2-eq) in the method.

The method has stated that the user can input their data from site-specific measurements, regional estimates, but these required data cannot be obtained, the method provides default values for users. As mentioned earlier that the BEAM calculator tool is used the tier system that has adopted from the IPCC. The user-defined data system is Tier A, a combination of default and user-obtained data system is Tier B, and finally Tier C system is the using of default values alone. The BEAM method integrates three tier levels into one model. Tier A estimation can be calculated when site-specific data is available. Tier A system is the most accurate estimate. Tier C system will be possible if default values are used for another scenario. Tier C system is least accurate than other tier levels.

It has mentioned that the focus of the methodology is sludge management, which comes from primary and secondary clarifiers. Before the calculation of GHG emissions, the amount of sludge should be calculated first. Hence, population has considered as 500.000 people, and the calculations were made according to this population. The calculations are simply made according to a typical wastewater treatment plant. The calculations are simply made according to a typical wastewater treatment plant. A flow chart of this wastewater treatment plant is given in Figure 3.7. There is a primary clarifier, aeration tank and secondary clarifier in WWTP. Primary settling sludge and secondary settling sludge are mixed, then the mixed sludge is treated other unit process for each scenarios.

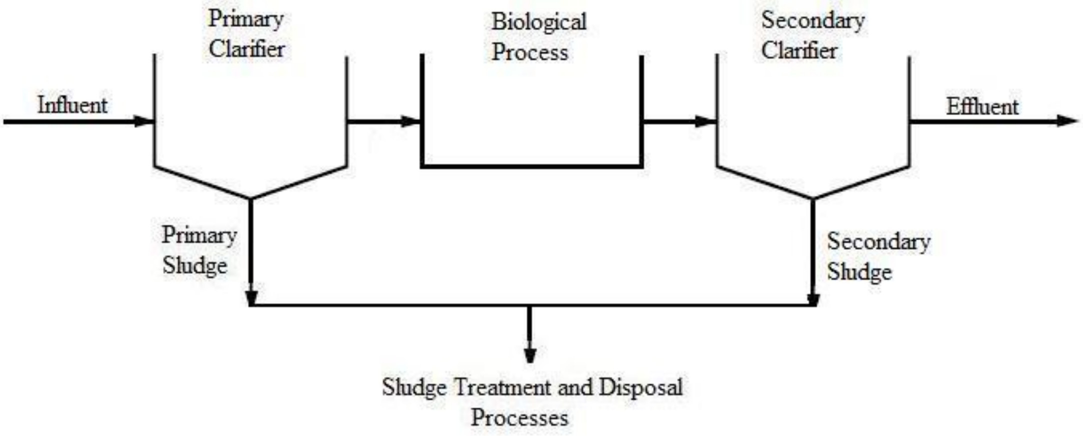


Figure 3.7 A typical WWTP flow chart

First, the flowrate (Q) was calculated according to the population. It is assumed that each person uses 200 liter of water per day. Q is calculated by multiplying the population (P) by the daily water consumption per capita (q), see equation 3.1.

$$Q = P * q \tag{3.1}$$

$$Q = 500.000 \text{ person} * 0.2 \text{ m}^3/\text{person}/\text{day}$$

$$Q = 100.000 \text{ m}^3/\text{day}$$

Influent characteristics are assumed. Influent BOD is 240 g/m^3 and influent total suspended solid (TSS) is 300 g/m^3. Daily influent mass values are calculated according to these assumptions. Influent mass calculations can be seen in the Equation 3.2 and Equation 3.3.

$$\text{Influent BOD mass} = 100000\ \text{m}^3/\text{day} * 240\ \text{g/m}^3 * 10^{-3}\ \text{g/kg} = 24000\ \text{kg/day} \qquad \textbf{3.2}$$

$$\text{Influent TSS mass} = 100000\ \text{m}^3/\text{day} * 300\ \text{g/m}^3 * 10^{-3}\ \text{g/kg} = 30000\ \text{kg/day} \qquad \textbf{3.3}$$

Some treatment efficiencies assumptions were made in primary settling tank. BOD removal is 30 %, TSS removal is 60 %. The solid content for primary sludge is 4 % (assumed). BOD removed in primary clarifier is 7200 kg/day. Then, effluent BOD is calculated as 16800 kg/day. TSS removed in primary settling tank is 18000 kg/day. Volatile suspended solids (VSS) are assumed as 65 percent of TSS. VSS removed is 11700 kg/day. At 4 % concentration, primary settling sludge flow ($\text{V}_{\text{S,TSS}}$) is calculated by using the Equation 3.4

$$\text{V}_{\text{S,TSS}} = \frac{\Delta \text{X}_{\text{TSS}}}{\rho_{\text{S}} * \gamma_{\text{S}}} \qquad \textbf{3.4}$$

$$\text{V}_{\text{S,TSS}} = \frac{18000\ \ \text{kg/day}}{0.04 * 1000\ \text{kg/m}^3} = 450\ \ \text{m}^3/\text{day}$$

The effluent TSS concentration is assumed as 20 g/m^3, and the effluent BOD concentration is assumed as 10 g/m^3, according to the Water Pollution Control Regulation (Resmi Gazete, 2004). The amount of TSS that came in secondary settling tank is; $300\ \text{g/m}^3 * (1 - 0.6) = 120\ \ \text{g/m}^3$. The amount of effluent TSS is 20 g/m^3, so 100 g/m^3 TSS was treated in biological treatment. The sludge mass that came from TSS (X_1) is calculated by using the Equation 3.5.

$$\text{X}_1 = \text{Q} * \text{C} \qquad \textbf{3.5}$$

$$\text{X}_1 = 100000\ \text{m}^3/\text{day} * 100\ \text{g/m}^3 * 10^{-3}\ \text{kg/g}$$

$$\text{X}_1 = 10000\ \text{kg/day}$$

The amount of BOD came in secondary settling tank is, $240 * (1 - 0.30) = 168\ \mathrm{g/m^3}$. The amount of effluent BOD is 10 g/m^3, so 158 g/m^3 BOD was treated in biological treatment. The sludge mass that come from BOD ($\mathrm{X_2}$) is calculated by using the Equation 3.6.

$$\mathrm{X_2 = Q * C * Y} \qquad \textbf{3.6}$$

$$\mathrm{X_2 = 100000\,m^3/day * 158\,g/m^3 * 10^{-3}\,kg/g * 0.5}$$

$$\mathrm{X_2 = 7900\,kg/day}$$

The total amount of waste activated sludge $\left(\mathrm{X_{S,WAS}}\right)$ is 17900 kg/day. The solid content is assumed as % 1 in waste activated sludge. At 1 % concentration, waste activated sludge flow is ($\mathrm{V_{S,WAS}}$) calculated using the Equation 3.7.

$$\mathrm{V_{S,WAS}} = \frac{\mathrm{X_{S,WAS}}}{\rho_{\mathrm{S}} * \gamma_{\mathrm{S}}} \qquad \textbf{3.7}$$

$$\mathrm{V_{S,WAS}} = \frac{17900\ \mathrm{kg/day}}{0.01 * 1000\,\mathrm{kg/m^3}} = 1790\ \mathrm{m^3/day}$$

The amount of mixed sludge ($\mathrm{X_{MS}}$) is calculated by addition $\mathrm{X_{S,WAS}}$ to $\mathrm{X_{S,TSS}}$. The mixed sludge flow is calculated by using the Equation 3.9. The solid content (SC) is calculated by using this equation in mixed sludge.

$$\mathrm{X_{MS} = X_{S,WAS} + X_{S,TSS}} \qquad \textbf{3.8}$$

$$\mathrm{X_{MS} = 17900\,kg/day + 18000\,kg/day}$$

$$\mathrm{X_{MS} = 35900\,kg/day}$$

$$\mathrm{V_{MS}} = \frac{\mathrm{X_{MS}}}{\rho_{\mathrm{MS}} * \gamma_{\mathrm{MS}}} \qquad \textbf{3.9}$$

$$\mathrm{V_{MS} = 450 + 1790 = 2240\ m^3/day}$$

$$2240\,\mathrm{m^3/day} = \frac{35900\,\mathrm{kg/day}}{1000\,\mathrm{m^3/day} * \%\,\mathrm{SC}}$$

% SC ≅ % 1.6 (it is appropriate)

3.1 Calculation of Scenarios

3.1.1 Scenario 1

Scenario 1 includes sludge thickening, aerobic digestion, dewatering, composting, and finally land application process. The flow chart is shown in the Figure 3.1. It was mentioned in the Table 2.5 in Section 2 that the first worksheet in the method has required the user to input general wastewater treatment and use information. A small "x" in each box corresponding to the sludge management unit processes is inserted in the summary table entitled "CO_{2}-eq Totals (Mg/year)". This table also provides outputs that updated using the individual unit process worksheets. For each unit process selected, refer to the corresponding worksheet for that unit process. The method has noted that if the required data can not be obtained, the tool provides default values in blue cells.

First, the general wastewater inputs are entered in the brown cells on the first worksheet. The inputs are entered into the appropriate brown cells in the method for conditioning/thickening worksheet. Sludge thickening process is assumed as gravity belt thickener process. The amount of the mixed sludge is calculated as 35900 kg/day. The mixed sludge flow is determined as 2240 m^3/day at a solids concentration of 1.6 %. The default values that provided in the blue cell are used for calculation in the solids content of sludge, type of thickener, and electricity use cells. Solids in thickened sludge are calculated by multiplying the sludge solids and the solids capture efficiency. The solids capture efficiency is assumed as 95 %. Therefore, thickened sludge flow is calculated as 897 m^3/day at 4 % concentration. Electricity use is assumed 110 kWh/day. CO_2 emissions from electricity used are found in 0.020 Mg/day. Scope 2 emissions are calculated as 7 Mg CO_{2}-eq/year.

In aerobic digester, VSS destruction in digester is assumed as 47 percent. It has also assumed that the digesters are heated by electricity. When natural gas is used for heating the digesters, scope 1 emissions also release to the atmosphere. Default SRT for aerobic digestion is assumed as 15 day. The method has dedicated that whether there is no supernatant recycle, flow to digester and from the digester is the same. Default values that provided by the method are entered the corresponding brown cells and estimation of aerobic digestion emissions are calculated. Flow to digester is calculated by addition the primary settling sludge flow to the thickened sludge flow. It is assumed that there is no supernatant recycle. TSS to digester is calculated by addition the solids in thickened sludge to the TSS removed in primary clarifier. VSS to digester is calculated by addition the VSS in thickened sludge to the VSS removed in primary clarifier. It was assumed that the VSS in thickened sludge was 70 % of TSS. When the inputs are entered in corresponding cells, the method is calculated the aerobic digestion emission as 641 Mg CO_2eq/year. These emissions of aerobic digestion are scope 2 emissions and come from the electricity used. The CO_2 emissions from electricity used is calculated as 1.76 Mg/day by the method.

In dewatering process, solids content of sludge is assumed as 4 %. TSS remaining after digestion was calculated as 16480 kg/day. The amount of sludge to be dewatered is calculated as 418 m^3/day. The default value of polymer use is 84 kg/day. Energy use default value is 189 kWh/day in the method. The default values and the amount of sludge to be dewatered are entered in the excel. Thus, dewatering emissions is calculated as 288 Mg CO_2-eq/year by the methodology. Dewatered cake solids are assumed as 25 % and it is also assumed that the specific gravity of sludge cake is 1170 kg/m^3. Thus, sludge cake flow to composting process is calculated as 56 m^3/day.

Type of composting operation is assumed as aerated static pile system. The percent of sludge content is assumed as 25 %. The method has asked that whether the sludge has been digested prior to composting. This scenario includes aerobic digestion unit. The percent of total nitrogen and total phosphorus are respectively assumed as 5 % and 1.9 % according to the default value of the method. The default value of total volatile solids is given as 51 %, and the percent of organic carbon is given as 29 % in the method. Compost use is replaced commercial fertilizer use according to the method. Volumetric ratio of amendment to sludge is 3 m^3 amendments per m^3 sludge. The default value of density of amendment is 250 kg/m^3

according to the worksheet. Solids content of composted sludge is assumed as 41 % according to the method. Total fuel use for composting equipment is calculated as 396 L diesel fuel per day by the method.

The CO_2 emissions from diesel used is calculated as 1.20 Mg CO_2-eq per day. The default value of electricity requirements of composting system is given as 2.520 kWh/day by the method, so CO_2 emissions from electricity used is calculated as 0.46 Mg CO_2-eq/day. CH_4 emitted from compost pile is calculated as to be zero by the method. N_2O emitted from compost pile is calculated as 0.017 Mg CO_2-eq per day and N_2O emitted from applying compost to soils is calculated as 0.0055 Mg CO_2 per day by the method. Total CO_2 emissions equivalents from released N_2O is calculated as 5.12 Mg CO_2-eq/day by the method.

Carbon sequestration from compost applied to soil is calculated as -3.50 Mg CO_2-eq/day by the worksheet. The fertilizer off-set credits from nitrogen applied to soil is given as -2.80 Mg CO_2-eq/day and from phosphorus applied to soil is given as -0.53 Mg CO_2-eq/day by the method. Scope 1 emissions are CO_2 emissions from diesel used, CH_4 emitted from compost pile, CO_2 emissions equivalents from released N_2O and CO_2 equivalents from compost applied to soil. Scope 2 emissions include CO_2 emissions from electricity used. Scope 3 emissions include fertilizer off-set credits from nitrogen and phosphorus applied to soil. The estimate of net emissions consists of debits and credits. Scope 1 emissions are calculated as 1.029 Mg CO_2-eq/year; Scope 2 emissions are calculated as 167 Mg CO_2-eq/year and Scope 3 emissions are calculated as -1.216 Mg CO_2-eq/year by the method. The estimate of total GHG emissions in composting process is calculated as -21 Mg CO_2-eq/year.

Sludge quantity going to land application is calculated as 12 m^3/day by the method in composting worksheet. Type of biosolids to be land applied is selected as digested. The default value of total nitrogen and total phosphorus are respectively 5 % and 1.9 %. Percent dry weight of TVS and organic carbon are assumed as 51 % and 28.6 % according to the default values of the method. Average number of days biosolids is stored prior to land application is assumed as 25 day according to the method. It is assumed that the sludge replace commercial fertilizer where it is applied. Soil texture at land application sites is assumed as fine 50 % of fine-textured soils and 50 % coarse-textured soils.

The fuel used is used applying biosolids to land and the default value of fuel use is 8 L diesel fuel per day according to the method. CO_2 emissions from diesel used are calculated as 0.02 Mg/day. CO_2 emissions equivalents from released CH_4 are calculated as 0.05 Mg/day by the method. N_2O emitted from land application in fine-textured soils and from land application in coarse-textured soils are respectively calculated as 0.0027 Mg/day and 0.0006 Mg/day by the method. N_2O emitted from storage of biosolids prior to land application is calculated as 0.0001 Mg/day by the method. The CO_2 emissions equivalents from released N_2O are calculated as 0.04 Mg CO_2-eq/day. Carbon sequestrations from biosolids applied to soil is calculated as -0.75 Mg CO_2 per day by the method. Fertilizer off-set credits from nitrogen applied to soil and from phosphorus applied to soil are respectively calculated as -0.60 Mg/day and -0.11 Mg/day by the method. Only the fertilizer off-set credits are scope 3 emissions, other emissions are scope 1 emissions. The total GHG emissions from land application process are calculated as -493 Mg CO_2-eq/year.

3.1.2 Scenario 2

Scenario 2 includes sludge thickening, anaerobic digestion, dewatering, composting, and finally land application process. The flow chart is shown in the Figure 3.2. A small “x” in each box corresponding to the sludge management unit processes is inserted in the summary table entitled “CO_2-eq Totals (Mg/year)”. The general wastewater inputs are entered in the brown cells on the first worksheet. Sludge thickening process is assumed as gravity thickening process, exactly the same as scenario 1. Thickening GHG emissions are the same as scenario 1. The amount of the mixed sludge is calculated as 35900 kg/day. The mixed sludge flow is determined as 2240 m^3/day. The default values that provided in the blue cell are used for calculation in the solids content of sludge, type of thickener, and electricity use cells. Electricity use is assumed 110 kWh/day. CO_2 emissions from electricity used are found in 0.020 Mg/day. Scope 2 emissions are calculated as 7 Mg CO_2-eq/year.

Sludge from the thickening tanks is conveyed to anaerobic digestion unit. The amount of solids content does not change with thickening process, only the solid concentration is reduced by the sludge thickening. It is assumed that the VSS in thickened sludge was 70 % of TSS in sludge. Default SRT for aerobic digestion is assumed as 15 day. Assuming that the BOD of the mixed sludge solids is 50 % BOD in thickened sludge and it is calculated as 17950 kg/day. It is assumed that the VSS removal in anaerobic digestion is 60 %. The amount of biomass in anaerobic digestion is calculated by using the equation 3.10. The amount of methane is calculated using the equation 3.11. It is assumed that the conversion factor of the cell tissue of the final BOD is 1.42. The extinction coefficient (k_d) is assumed as 0.03 day^{-1}. There is assumed that the yield coefficient (Y) is 0.06 kg VSS⁄kg BOD. It is also assumed that the theoretical conversion factor 0.35 m^3 CH_4 per kg BOD.

$$P_x = \frac{\text{BOD in thickened sludge} * \text{BOD removal efficiency} * Y}{1 + k_d * \text{SRT}} \quad \textbf{3.10}$$

$$P_x = \frac{17950\,\text{kg BOD/d} * 0.70 * 0.06\,\text{kg VSS/kg BOD}}{1 + 0.03 * 15} = 520\,\text{kg VSS/day}$$

$$CH_4(m^3/d) = [(17950\,\text{kg BOD/day} * 0.70) - 1.42 * 520\,\text{kg VSS/day}] * 0.35\,m^3 CH_4/\text{kg BOD} \quad \textbf{3.11}$$

$$CH_4(m^3/d) = 11826\,m^3/\text{day}$$

It is assumed that the percent of CH_4 in biogas is 67 %. The amount of biogas is calculated 17650 m^3 biogas per day. VSS removed in anaerobic digester is calculated using the Equation 3.12.

$$35900\,\text{kg TSS/day} * 0.70\,\text{kg VSS/kg TSS} * 0.60 = 15078\,\text{kg VSS/day} \quad \textbf{3.12}$$

The amount of solids after digestion is calculated using the Equation 3.13. At 8 % solid concentration, sludge flow after digestion is calculated as 267 m^3/day.

$$\text{Solids mass} = \text{BOD in thickened sludge} + \text{Amount of biomass} - \text{VSS removed} \qquad \textbf{3.13}$$

$$\text{Solids mass} = 35900\ \text{kg/day} + 520\ \text{kg/day} - 15078\ \text{kg/day} = 21342\ \text{kg/day}$$

There are some options on anaerobic digestion worksheet in the method. Some inputs are required for the energy balance in the worksheet. The percent of biogas used for heat, biogas used to generate electricity, biogas flared are entered in corresponding cells. The worksheet provides default values for these inputs. The default values of biogas used for heat and biogas flared are given as 65 % and 35 % in the method. In this study, these values were assumed as zero to see the GHG emissions from anaerobic digestion clearly. Thus, biogas fugitive emissions are calculated as one hundred percent. Based on this it was assumed that the estimated CH_4 emissions from anaerobic digestion process are calculated as 60.552 Mg CO_2-eq per year. If biogas used to generate electricity and biogas flared are assumed as in default values, the estimation of net emissions consists of relatively large credits; debits total is calculated as 139 Mg CO_2 equivalents per year, and credits total is calculated as -2,223 Mg CO_2 equivalents per year.

Sludge flow after digestion is calculated as 267 m^3/day. Digestered sludge is conveyed to dewatering unit. It is considered that dewatering process has done by centrifuge. It is assumed that polymer is added to aid in the dewatering process. Polymer use is assumed as 53 kg per day, according to the method. CO_{2}-eq in polymer used is 0.5 Mg/day and these emissions are taken as scope 3 emissions by the method. The default value of electricity use is taken as 121 kWh/day in the method and CO_2 emissions from electricity used is calculated as 0.022 Mg CO_{2}-eq per day. The primary contributor is polymer for dewatering process. Total dewatering process emissions are estimated as 182 Mg CO_{2}-eq per year. The estimated emissions from polymer use are responsible for 95.6 % of the total estimated GHG emissions in dewatering process.

The amount of solid matter was calculated as 21342 kg/day. It is assumed that the specific gravity of sludge cake is 1170 kg/m^3. Therefore, the sludge cake volume is calculated as approximately 72 m^3/day. Solids content of sludge cake is assumed as 25 % according to the method. Type of composting operation is assumed as aerated static pile system. The method has asked that whether the sludge has been digested prior to composting. This scenario includes aerobic digestion unit. The percent of total nitrogen and total phosphorus are respectively assumed as 5 % and 1.9 % according to the default value of the method. The default value of total volatile solids is given as 51 %, and the percent of organic carbon is given as 29 % in the method. Compost use is replaced commercial fertilizer use according to the method. Volumetric ratio of amendment to sludge is 3 m^3 amendments per m^3 sludge. The default value of density of amendment is 250 kg/m^3 according to the worksheet. Solids content of composted sludge is assumed as 41 % according to the method. Total fuel use for composting equipment is calculated as 510 L diesel fuel per day by the method.

The CO_2 emissions from diesel used is calculated as 1.55 Mg CO_2-eq per day. The default value of electricity requirements of composting system is given as 3.240 kWh/day by the method, so CO_2 emissions from electricity used is calculated as 0.59 Mg CO_2-eq/day. CH_4 emitted from compost pile is calculated as to be zero by the method. N_2O emitted from compost pile is calculated as 0.021 Mg CO_2-eq per day and N_2O emitted from applying compost to soils is calculated as 0.0071 Mg CO_2 per day by the method. Total CO_2 emissions equivalents from released N_2O are calculated as 6.58 Mg CO_2-eq/day by the method.

Carbon sequestration from compost applied to soil is calculated as -4.50 Mg CO_2-eq/day by the worksheet. The fertilizer off-set credits from nitrogen applied to soil is given as -3.60 Mg CO_2-eq/day and from phosphorus applied to soil is given as -0.68 Mg CO_2-eq/day by the method. Scope 1 emissions occurs the CO_2 emissions from diesel used, CO_2 equivalents emissions from released N_2O and CO_2 equivalents from compost applied to soil. Scope 2 emissions are CO_2 emissions from electricity used. Scope 3 emissions include fertilizer off-set credits from nitrogen and phosphorus applied to soil. The estimate of net composting emissions consists of debits and credits. Scope 1 emissions are calculated as 1.323 Mg CO_2-eq/year; Scope 2 emissions are calculated as 214 Mg CO_2-eq/year and Scope 3 emissions are calculated as -1.564 Mg CO_2-eq/year by the method. The estimate of total GHG emissions in composting process is calculated as -26 Mg CO_2-eq/year.

Sludge quantity going to land application is calculated as 15 m^3/day by the method in composting worksheet. Type of biosolids to be land applied is selected as digested. The default value of total nitrogen and total phosphorus are respectively 5 % and 1.9 %. Percent dry weight of TVS and organic carbon are assumed as 51 % and 28.6 % according to the default values of the method. Average number of days biosolids is stored prior to land application is assumed as 25 day according to the method. It is assumed that the sludge replace commercial fertilizer where it is applied. Soil texture at land application sites is assumed as fine 50 % of fine-textured soils and 50 % coarse-textured soils.

The fuel used is used applying biosolids to land and the default value of fuel use is 10 L diesel fuel per day according to the method. CO_2 emissions from diesel used are calculated as 0.03 Mg/day. CO_2 emissions equivalents from released CH_4 are calculated as 0.07 Mg/day by the method. N_2O emitted from land application in fine-textured soils and from land application in coarse-textured soils are respectively calculated as 0.0034 Mg/day and 0.0007 Mg/day by the method. N_2O emitted from storage of biosolids prior to land application is calculated as 0.0002 Mg/day by the method. The CO_2 emissions equivalents from released N_2O are calculated as 0.05 Mg CO_2-eq/day. Carbon sequestration from biosolids applied to soil is calculated as -0.94 Mg CO_2 per day by the method. Fertilizer off-set credits from nitrogen applied to soil and from phosphorus applied to soil are respectively calculated as -0.75 Mg/day and -0.14 Mg/day by the method. Only the fertilizer off-set credits are scope 3 emissions, other emissions are scope 1 emissions. The total GHG emissions from land application process are calculated as -616 Mg CO_2-eq/year.

3.1.3 Scenario 3

Scenario 3 includes sludge thickening, anaerobic digestion, dewatering, alkaline stabilization, and finally land application process. The flow chart is shown in the

Figure 3.3. GHG emissions of sludge thickening process are the same as scenario 1. The amount of the mixed sludge is calculated as 35900 kg/day. The mixed sludge flow is determined as 2240 m^3/day. The default values that provided in the blue cell are used for calculation in the solids content of sludge, type of thickener, and electricity use cells. Electricity use is assumed 110 kWh/day, according to the default value of the method. CO_2 emissions from electricity used are found in 0.020 Mg/day. Scope 2 emissions are calculated as 7 Mg CO_2-eq/year.

Anaerobic digestion and dewatering operations is the same as scenario 2. When the biogas fugitive emissions were assumed to be 100 %, the estimated CH_4 emissions from anaerobic digestion process were calculated as 60.552 Mg CO_2-eq per year. If biogas used to generate electricity and biogas flared are assumed as in default values, the estimation of net emissions consists of relatively large credits; debits total is calculated as 139 Mg CO_2 equivalents per year, and credits total is calculated as -2,223 Mg CO_2 equivalents per year. The amount of solids after anaerobic digestion process was calculated as 21342 kg/day by using the equation 3.13. And at 8 % solid concentration, sludge flow after digestion was calculated using as 267 m^3/day.

Digestered sludge is conveyed to dewatering unit process. It is considered that dewatering process has done by centrifuge. It is assumed that polymer is added to aid in the dewatering process. Polymer use is assumed as 53 kg per day according to the default value of the BEAM methodology. According to the method, CO_2-eq in polymer used is 0.5 Mg/day and these emissions are taken as scope 3 emissions by the method. Electricity use is taken as 121 kWh/day according to the method and CO_2 emissions from electricity used is calculated as 0.022 Mg CO_2-eq/day. Total dewatering process emissions are estimated as 182 Mg CO_2-eq per year. The primary contributor is polymer for dewatering process. The estimated emissions from polymer use are responsible for 95.6 % of the total estimated GHG emissions in dewatering process.

Therefore, the dewatered sludge flow rate is calculated as approximately 72 m^3/day. The dewatered sludge is collected and then conveyed to the alkaline stabilization process. Solids content of sludge to be stabilized is assumed as 25 % according to the method. The default value of the amount of alkaline product added 3.6 Mg lime per day. CO_2 emissions equivalents from lime production are calculated as 3.2 Mg/day by the method. CO_2 emissions equivalents from lime production are calculated as 1183 Mg CO_2-eq per year and these emissions are scope 3 emissions. Electricity requirements of alkaline stabilization is assumed as 351 kWh/day according to the default value of the method and CO_2 emissions from electricity used are calculated as 0.06 Mg per day. These emissions from electricity used are scope 2 emissions. The total GHG emissions of alkaline stabilization process are calculated by the method as 1206 Mg CO_2-eq per year. The largest debit is from the lime production in the process. The estimated emissions from lime are responsible for 98 % of the total estimated GHG emissions in alkaline stabilization process.

Sludge quantity going to land application is calculated as 18 m^3/day by the method. Type of biosolids to be land applied is selected as limed. The default value of total nitrogen and total phosphorus are respectively 3.2 % and 1.9 %. Percent dry weight of TVS and organic carbon are assumed as 56 % and 31.4 % according to the default values of the method. The $CaCO_3$ equivalence is assumed as 25 % according to the default value of the method. Average number of days biosolids is stored prior to land application is assumed as 25 day according to the method. It is assumed that the sludge replace commercial fertilizer where it is applied. Soil texture at land application sites is assumed as fine 50 % of fine-textured soils and 50 % coarse-textured soils.

The fuel used is used applying biosolids to land and the default value of fuel use is 67 L diesel fuel per day according to the method. CO_2 emissions from diesel used are calculated as 0.19 Mg/day. CO_2 emissions equivalents from released CH_4 are calculated as 0.08 Mg/day by the method. N_2O emitted from land application in fine-textured soils and from land application in coarse-textured soils are respectively calculated as 0.0026 Mg/day and 0.0006 Mg/day by the method. N_2O emitted from storage of biosolids prior to land application is calculated as 0.0002 Mg/day by the method. The CO_2 emissions equivalents from released N_2O are calculated as 0.06 Mg CO_2-eq/day. Carbon sequestration from biosolids applied to soil is calculated as -1.13 Mg CO_2 per day by the method. Fertilizer off-set credits from nitrogen applied to soil and from phosphorus applied to soil are respectively calculated as -0.58 Mg/day and -0.17 Mg/day by the method. Only the fertilizer off-set credits are scope 3 emissions, other emissions are scope 1 emissions. The total GHG emissions from land application process are calculated as -384 Mg CO_2-eq/year.

3.1.4 Scenario 4

Scenario 4 includes sludge thickening, anaerobic digestion, dewatering, thermal drying, and landfill disposal process. The flow chart is shown in the Figure 3.4. GHG emissions of sludge thickening process are the same as scenario 1. The amount of the mixed sludge is calculated as 35900 kg/day. The mixed sludge flow is determined as 2240 m^3/day. The default values that provided in the blue cell are used for calculation in the solids content of sludge, type of thickener, and electricity use cells. Electricity use is assumed 110 kWh/day according to the default value of the method. CO_2 emissions from electricity used are found in 0.020 Mg/day. Scope 2 emissions are calculated as 7 Mg CO_2-eq/year.

Anaerobic digestion and dewatering operations is the same as scenario 2. When the biogas fugitive emissions were assumed to be 100 %, the estimated CH_4 emissions from anaerobic digestion process were calculated as 60.552 Mg CO_2-eq per year. If biogas used to generate electricity and biogas flared are assumed as in default values, the estimation of net emissions consists of relatively large credits; debits total is calculated as 139 Mg CO_2 equivalents per year, and credits total is calculated as -2,223 Mg CO_2 equivalents per year. The amount of solids after anaerobic digestion process was calculated as 21342 kg/day by using the equation 3.13. And at 8 % solid concentration, sludge flow after digestion was calculated using as 267 m^3/day.

Digestered sludge is conveyed to dewatering process. It is considered that dewatering process has done by centrifuge. It is assumed that polymer is added to aid in the dewatering process. Polymer use is assumed as 53 kg per day. CO_2-eq in polymer used is 0.5 Mg/day and these emissions are taken as scope 3 emissions by the method. Electricity use is taken as 121 kWh/day according to the method and CO_2 emissions from electricity used is calculated as 0.022 Mg CO_2-eq/day. Total dewatering process emissions are estimated as 182 Mg CO_2-eq per year. The largest debit is from the use of polymer to aid in the dewatering process. The estimated emissions from polymer use are responsible for 95.6 % of the total estimated GHG emissions in dewatering process.

The quantity of sludge cake is calculated as approximately 72 m^3/day. Solids content going to the thermal dryer is assumed as 25 % and coming out of dryer is assumed as 90 % according to the method. The value calculated by the method of natural gas use is 5504 m^3/day. CO_2 emissions from natural gas used are calculated as 10 Mg CO_2-eq per day. The value calculated by the method of electricity requirement of dryer is 3.852 m^3/day. CO_2 emissions from electricity used are calculated as 0.70 Mg CO_2-eq per year. Scope 1 emissions occurs CO_2 emissions from natural gas used and Scope 2 emissions occurs CO_2 emissions from electricity used. The total GHG emissions from thermal drying process are calculated as 4074 Mg CO_2-eq/year.

Quantity of sludge going to landfill disposal is assumed as 56 Mg/day. The default value of total nitrogen is 5 %. Sludge has been digested prior to landfill disposal. The default values of TVS and organic carbon are respectively 51 % and 29 % according to the method. CH_4 correction factor for landfill is assumed as according to the default value of the method. Quality of soil cover at landfill is assumed to be high, namely good organic matter content, supports vegetation well. Oxidation of CH_4 by soil cover (applies three years after placement of wastewater solids in landfill) is assumed as 25 % according to the default value of the method. CH_4 captured at landfill and flared, combusted or otherwise used (after three years) is assumed as 75 % according to the method. The percent of captured CH_4 used to generate electricity is assumed to be zero. The fraction of degradable organic carbon that can decompose is assumed as 80 % according to the default value of the method. The amount of decomposable TDOC decomposed in 3 years is assumed as 69.9 % according to the default value.

CH_4 released from first three years after landfilling and after three years are respectively calculated as 1.4 Mg/day and 0.11 Mg/day. CO_2 emissions equivalents from released CH_4 are calculated as 30.9 Mg/day. N_2O emitted from landfilled sludge is calculated as 0.017 Mg/day, and CO_2 emissions equivalents from released N_2O are calculated as 5.12 Mg/day. Carbon sequestration from undecomposed carbon from landfilled sludge is calculated as -2.98 Mg CO_2-eq/day. CO_2 emissions from biogas combustion are calculated as 1.21 Mg/day. The total GHG emissions from incineration process are calculated as 12.075 Mg CO_2-eq/year.

3.1.5 Scenario 5

Scenario 5 includes sludge thickening, anaerobic digestion, dewatering, thermal drying, and finally incineration process. The flow chart is shown in the Figure 3.5. GHG emissions of sludge thickening process are the same as scenario 1. The amount of the mixed sludge is calculated as 35900 kg/day. The mixed sludge flow is determined as 2240 m^3/day. The default values that provided in the blue cell are used for calculation in the solids content of sludge, type of thickener, and electricity use cells. Electricity use is assumed 110 kWh/day, according to the method. CO_2 emissions from electricity used are found in 0.020 Mg/day. Scope 2 emissions are calculated as 7 Mg CO_2-eq/year.

Anaerobic digestion and dewatering operations is the same as scenario 2. When the biogas fugitive emissions were assumed to be 100 %, the estimated CH_4 emissions from anaerobic digestion process were calculated as 60.552 Mg CO_2-eq per year. If biogas used to generate electricity and biogas flared are assumed as in default values, the estimation of net emissions consists of relatively large credits; debits total is calculated as 139 Mg CO_2 equivalents per year, and credits total is calculated as -2,223 Mg CO_2 equivalents per year. The amount of solids after anaerobic digestion process was calculated as 21342 kg/day by using the equation 3.13. And at 8 % solid concentration, sludge flow after digestion was calculated using as 267 m^3/day.

Digestered sludge is conveyed to sludge dewatering process. It is considered that dewatering process has done by centrifuge. It is assumed that polymer is added to aid in the dewatering process. Polymer use is assumed as 53 kg per day, according to the method. CO_2-eq in polymer used is 0.5 Mg/day and these emissions are taken as scope 3 emissions by the method. Electricity use is taken as 121 kWh/day according to the default value of the method and CO_2 emissions from electricity used is calculated as 0.022 Mg CO_2 equivalents per day. Total dewatering process emissions are estimated as 182 Mg CO_2-eq/year. The largest debit is from the use of polymer to aid in the dewatering process. The estimated emissions from polymer use are responsible for 95.6 % of the total estimated GHG emissions in dewatering process.

The quantity of sludge cake is calculated as approximately 72 m^3/day. Solids content going to the thermal dryer is assumed as 25 % and coming out of dryer is assumed as 90 % according to the method. The value calculated by the method of natural gas use is 5504 m^3/day. CO_2 emissions from natural gas used are calculated as 10 Mg CO_2-eq per day. The value calculated by the method of electricity requirement of dryer is 3852 m^3/day. CO_2 emissions from electricity used are calculated as 0.70 Mg CO_2-eq per year. Scope 1 emissions occurs CO_2 emissions from natural gas used and Scope 2 emissions occurs CO_2 emissions from electricity used. The total GHG emissions from thermal drying process are calculated as 4074 Mg CO_2-eq/year.

Solids content that coming out of thermal dryer is assumed as 90 %. Quantity of solid input to incinerator is 56 Mg/day-wet. The default value of total nitrogen is 4 % and total phosphorus is 1.5 %. Total volatile solids are assumed as 70 % according to the method. Type of incinerator is selected as fluidized bed. Recovery energy to electricity is assumed to be zero according to the method. The recovered energy as heat is assumed as 75 % according to the worksheet. Average high temperature of incineration is assumed as 850 ºC according to the default value of the method. The net natural gas used is calculated as -110 m^3 per day, and the CO_2 emissions from natural gas used is calculated as -0.21 Mg/day by the method. The net electricity used is calculated as 2800 kWh/day, and CO_2 emissions from electricity used is calculated as 0.51 Mg/day by the method. CO_2 emissions equivalents from released CH_4 are calculated as 0.01 Mg/day. N_2O emitted during incineration is calculated as 0.036 Mg/Day by the method. N_2O emission adjustment for moisture content of sludge is calculated as -0.018 Mg/day by the method. The CO_2 emissions equivalents from released N_2O are calculated as 5.58 Mg/day by the method. CO_2 emissions equivalents from burning sludge are calculated as 20.12 Mg/day. Scope 1 emissions occur CO_2 emissions from natural gas used, from released CH_4 and from released N_2O. Scope 2 emission occur CO_2 emissions from electricity used. The total GHG emissions of incineration process are calculated as 2151 Mg CO_2-eq/year.

3.1.6 Scenario 6

Scenario 6 includes sludge thickening, dewatering, incineration, and final disposal process. Sludge thickening is achieved by gravity thickening and followed by dewatering. The flow chart is shown in the Figure 3.6. GHG emissions of sludge thickening process are the same as scenario 1. The amount of the mixed sludge is calculated as 35900 kg/day. The mixed sludge flow is determined as 2240 m^3/day. The default values that provided in the blue cell are used for calculation in the solids content of sludge, type of thickener, and electricity use cells. Electricity use is assumed 110 kWh/day, according to the default value of the method. CO_2 emissions from electricity used are found in 0.020 Mg/day. Scope 2 emissions are calculated as 7 Mg CO_2-eq/year.

Thickened sludge flow was calculated as 897 m^3/day at 4 % concentration in scenario 1. Thickened sludge is conveyed to dewatering process. It is considered that dewatering process has done by centrifugation. It is assumed that polymer is added to aid in the dewatering process. Polymer use is assumed as 179 kg per day, according to the method. CO_2-eq in polymer used is 1.6 Mg/day and these emissions are taken as scope 3 emissions by the method. Scope 3 emissions from dewatering process are calculated as 588 Mg CO_2 equivalents per year. Electricity use is taken as 405 kWh/day according to the method and CO_2 emissions from electricity used is calculated as 0.073 Mg CO_2 equivalents per day. The primary contributor is polymer for dewatering process. Total dewatering process emissions are estimated as 615 Mg CO_2 equivalents per year.

Dewatered sludge cake is conveyed to the incineration process. The amount of the dewatered sludge is calculated as 34241 kg/day. The use of polymer per day in dewatering process is taken into account for this calculation. Solids capture efficiency is assumed as 95 % in dewatering process. There are assumed that the cake solid percentage is 25 % concentration and the specific gravity is 1170 kg/m^3. It is calculated that incinerated sludge is 856 m^3/day. The default value of total nitrogen is 4 % and total phosphorus is 1.5 %. Total volatile solids are assumed as 70 % according to the method. Type of incinerator is selected as fluidized bed. Recovery energy to electricity is assumed to be zero according to the method. The recovered energy as heat is assumed as 75 % according to the worksheet.

Average high temperature of incineration is assumed as 850 ºC according to the default value of the method. The net natural gas used is calculated as -1678 m^3 per day, and the CO_2 emissions from natural gas used is calculated as -3.19 Mg/day by the method. The net electricity used is calculated as 42800 kWh/day, and CO_2 emissions from electricity used is calculated as 7.75 Mg/day by the method. CO_2 emissions equivalents from released methane are calculated as 0.22 Mg/day. N_2O emitted during incineration is calculated as 0.546 Mg/Day by the method. N_2O emission adjustment for moisture content of sludge is calculated as -0.273 Mg/day by the method. The CO_2 emissions equivalents from released N_2O are calculated as 84.63 Mg/day by the method. CO_2 emissions equivalents from burning sludge are calculated as 307.59 Mg per day. Scope 1 emissions occur CO_2 emissions from natural gas used, from released CH_4 and from released N_2O. Scope 2 emissions occur

CO_2 emissions from electricity used. The total GHG emissions of incineration process are calculated as 32636 Mg CO_2-eq/year.

CHAPTER FOUR

RESULT AND DISCUSSION

The main objective of this thesis is the investigation of GHG emissions for different sludge treatment and disposal processes. When methodologies were examined, the BEAM method was considered to be the most suitable for the purpose of the thesis. Six sludge management scenarios for GHG emissions calculations were identified in the previous section of this thesis. The selected processes in these scenarios are widely used for sludge management. GHG emissions were estimated for each unit process in each of flow chart. The BEAM methodology was used for these calculations. As mentioned earlier, this method is divided into unit processes rather than focusing on complete management scenarios.

GHG emission estimations from each unit process in a sludge management scenario and total GHG emissions for that scenario can be seen in the BEAM method. The methodology has stated that it is easier to evaluate the accuracy of default values and the emission factors that have the greatest impacts on GHG emissions by separating unit processes. The method provides emission factors and default values for users, and emission calculations were made according to these values. This section of the thesis includes a comparison with the total GHG emissions from different sludge management scenarios. Table 4.1 provides the opportunity to compare the total GHG emissions for each scenario.

Table 4.1 Total GHG emissions from each scenario

Scenario	Total GHG Emission
Scenario 1	423 Mg CO_2-eq/year
Scenario 2	-2.536 Mg CO_2-eq/year
Scenario 3	-1.068 Mg CO_2-eq/year
Scenario 4	14.254 Mg CO_2-eq/year
Scenario 5	4.330 Mg CO_2-eq/year
Scenario 6	33.258 Mg CO_2-eq/year

The six scenarios were compared regarding the GHG emitted. The second scenario is the best option regarding the global warming impact. In comparison with systems, incineration without stabilization processes such as aerobic or anaerobic digestion appears to be the worst option. The GHG mitigation aspects of this biosolids application were not considered in the emissions calculations but could be further investigated as it may be represent an opportunity to decrease net GHG emissions from this management scenario.

In scenario 1, the largest source of GHG emissions is aerobic digestion process and its associated electricity requirements of the digesters. Using default values in the method for aerobic digestion process, it is estimated that net GHG emissions from digestion are 641 Mg CO_2 equivalents per year. The second largest source of GHG emissions is dewatering process, because of polymer used. The use of polymer creates significant indirect emissions. The estimated emissions from only polymer use are 276 Mg CO_2 equivalents per year. Typically land application unit process provides a net carbon credit, which equates to -493 Mg CO_2 equivalents per year.

Scenario 1 and scenario 2 are compared to each other, the difference between GHG emissions from aerobic and anaerobic digestion will be seen clearly. Anaerobic digestion unit process provides net carbon credit, offsetting GHG emissions from other parts of the program, which equates to -2084 Mg CO_2 equivalents per year. The largest source of GHG debits in scenario 2 is dewatering process and its associated electricity requirements of the digesters. It is calculated above that GHG emissions from dewatering process are 182 Mg CO_2 equivalents per year. Using default values for anaerobic digestion, it is estimated that net GHG emissions from digestion are -2536 Mg CO_2 equivalents per year.

When scenario 2 and scenario 3 are compared to each other, GHG emissions from composting and alkaline stabilization processes can be benchmarked. Emissions during thickening and dewatering are identical because treatments are the same. Typically a composting process provides carbon credit, offsetting GHG emissions from other parts of the program. Alkaline stabilization process causes a significant

GHG emission debit. A small amount of alkaline stabilization emissions is emitted from electricity used; a large part is due to lime production. It is calculated above that the estimated GHG emissions in alkaline stabilization is 1206 Mg CO_2 equivalents per year. The method has noted that the alkaline stabilization can be achieved using recycled lime substitutes including cement kiln dust and fly ash. Incorporating recycled lime substitutes eliminates the indirect emissions associated with the use of hydrated lime, and would substantially decrease GHG emissions from this unit process.

In comparison with scenario 4 to scenario 5, GHG emissions from landfilling process are much more than the incineration process. In scenario 4, the estimated landfilling process emissions are responsible for approximately 85 % of the estimated net GHG emissions. It has clearly seen that the largest source of GHG emissions in scenario 4 is landfilling process. After the landfilling process, thermal drying is the second largest source of GHG emissions in this scenario. The first largest source of GHG emissions is the thermal drying process and its associated natural gas used, which equates to 4074 Mg CO_2 equivalents per year in scenario 5. The second largest source of GHG emissions is the incineration process, which equates to 2151 Mg CO_2 equivalents per year in scenario 5. Additional credits of emissions approximately –2,084 Mg CO_2 equivalents per year are achieved by anaerobic digestion in this scenario.

In comparison with other scenarios, scenario 6 appears to be the worst option. The calculated incineration process emissions are responsible for approximately 98 % of the estimated net GHG emissions in scenario 6. The CO_2 emissions equivalents from released N_2O are responsible for approximately 98 % the estimated emissions of incineration process. The method has emphasized that the incineration temperature is above 900 ºC, N_2O emissions are likely minimal.

In general, higher net GHG emissions were associated with scenarios that use thermal drying, incineration or landfill disposal in their management practices. Thermal drying requires the use of a substantial amount of energy. The natural gas used is responsible for approximately 94 % of thermal drying process in scenario 5. Incineration process emits substantial N_2O emissions. Landfill disposal process generates substantial CH_4 and N_2O emissions. The method has emphasized that the lower net GHG emissions were associated with biosolids management programs that conduct land application due to the potential to offset the use of chemical fertilizers and to sequester carbon. The calculations are representative from an environmental point of view and should be compared with economic or social dimensions to give a global approach in waste management. To perform a complete analysis of the economic and social work should be completed by a Life Cycle Assesment (LCA).

CHAPTER FIVE
CONCLUSION

This study serves as a window to an understanding of investigation of GHG emissions for different sludge treatment and disposal processes. This thesis was undertaken in sequential stages. The first stage involved a literature and background review. The existing protocols, guideline documents, and calculation tools that are applicable to GHG emissions reporting were examined. The literature review involved a synthesis of GHG emissions from possible unit processes associated with solids processing and biosolids management. GHG emissions from wastewater treatment plant processes were investigated. Different sludge treatment and disposal processes and their GHG emissions were defined in detail. Potential GHG emissions were discussed for each unit sludge management process. The information gathered from the literature formed the basis for the development stage of the thesis. Different alternative flow charts were created for different sludge management options. The GHG emissions were estimated for each unit process in each flow chart.

As a result of the work done on the subject of this thesis, it is observed that the estimation of GHG emissions from different sludge management options has recently started investigating. GHG accounting and management tools that were given in the Section 1 with a little detail are prerequisites to achieve carbon emission reduction targets. The existing researches have shown that the sludge treatment and disposal processes constitute a significant amount of total GHG emissions from WWTPs. While IPCC, EPA and others have worked to estimate emissions from wastewater treatment, there are not widely-accepted, standardized guidelines to estimate emissions from WWTPs. It obviously seems that there is a dearth of information for sludge management. Sludge treatment and disposal should be examined in detail on the issue of their emissions. There are limited data and information related to GHGs and new technologies within sludge management area. There are economic and social implications to considering GHG emission impacts. The calculations in Section 3 were representative from an environmental point of view and should be compared with economic or social dimensions to give a global approach in waste management. To perform a complete analysis of the economic and social work should be completed by a Life Cycle Assesment (LCA).

A number of restrictions of this thesis should be mentioned that the study concerned the carbon footprint of sludge treatment and disposal processes only. Therefore, a general and simple scenario for biological wastewater treatment plant was considered. For future researches, the influence of wastewater treatment options on the footprint of sludge treatment and disposal could be examined. The influence of various factors like climate conditions, soil structure or sludge characteristics on the emission calculations also was not taken in detail. The default values given in the BEAM method or other resources were used in the calculation. For comparing the GHG emissions that came from different sludge treatment and disposal processes, six scenarios were created for different sludge management options in this study. The existing and currently employed wastewater treatment facilities and sludge management options in provinces can be a topic for future researches. This will reduce the uncertainty and increase the accuracy in the scenario comparisons.

Concerns regarding climate change and the likelihood of more stringent GHG emission regulations have resulted in sludge generators interested in evaluating sludge management projects based on the potential to minimize GHG emissions. Opportunities to reduce GHG emissions were not taken into account and discussed in this study. For instance of these opportunities includes increasing energy efficiencies in processes such as electricity, heat, fossil fuels; collecting digester gas and utilization to offset purchased energy requirements; increasing land application process to obtain credits through carbon sequestration. It may be a separate topic for future researches.

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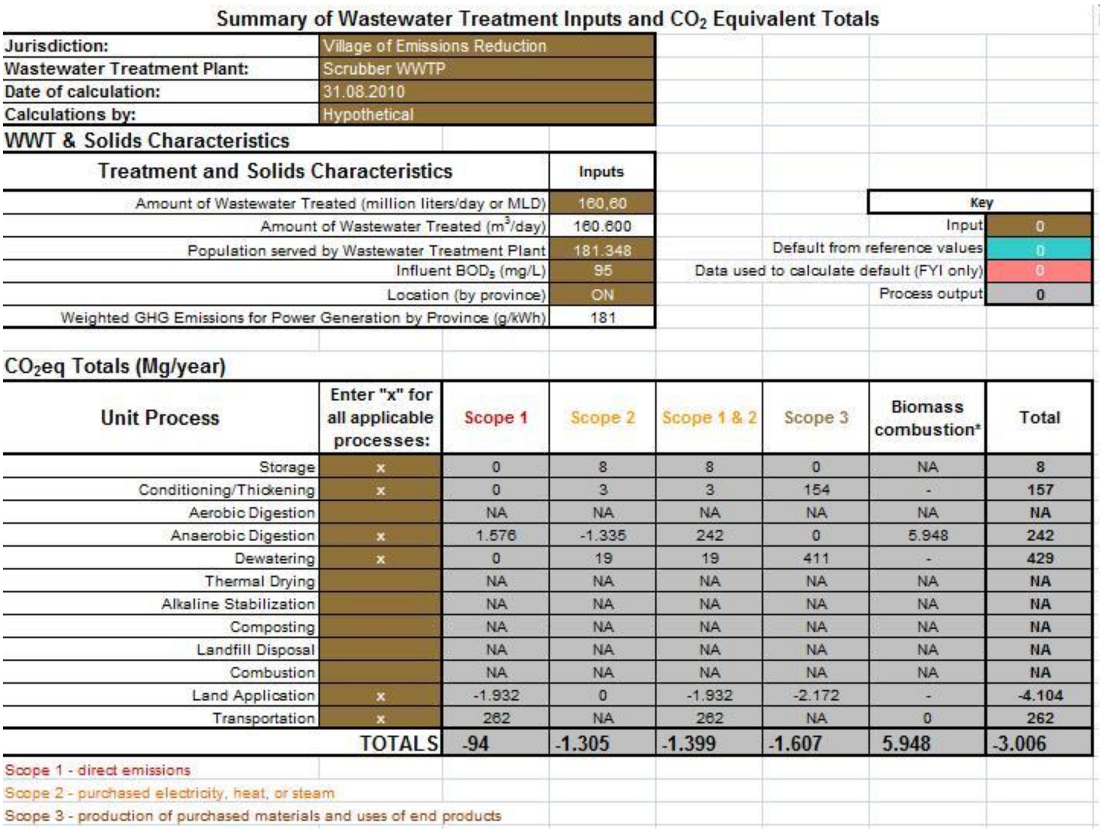
APPENDICES – THE BEAM METHOD (Sylvis, 2009).

Worksheet #1 – Data Entry



Summary of Wastewater Treatment Inputs and CO_2 Equivalent Totals

Jurisdiction:	Village of Emissions Reduction
Wastewater Treatment Plant:	Scrubber WWTP
Date of calculation:	31.08.2010
Calculations by:	Hypothetical

WWT & Solids Characteristics

Treatment and Solids Characteristics	Inputs
Amount of Wastewater Treated (million liters/day or MLD)	160,60
Amount of Wastewater Treated (m^3/day)	160.600
Population served by Wastewater Treatment Plant	181.348
Influent BOD_5 (mg/L)	95
Location (by province)	ON
Weighted GHG Emissions for Power Generation by Province (g/kWh)	181

Key	
Input	0
Default from reference values	0
Data used to calculate default (FYI only)	0
Process output	0

CO_2eq Totals (Mg/year)

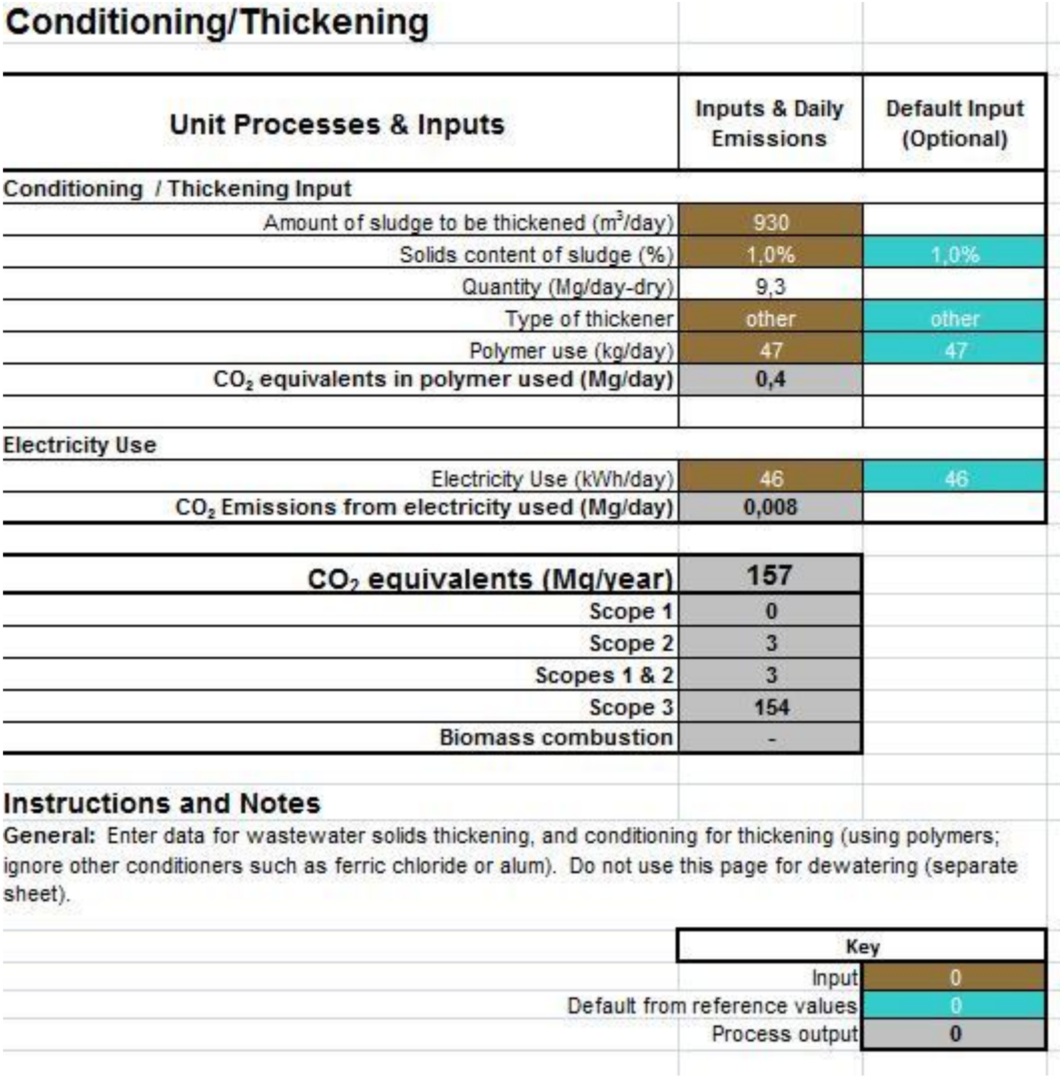
Unit Process	Enter "x" for all applicable processes:	Scope 1	Scope 2	Scope 1 & 2	Scope 3	Biomass combustion*	Total
Storage	x	0	8	8	0	NA	8
Conditioning/Thickening	x	0	3	3	154	-	157
Aerobic Digestion		NA	NA	NA	NA	NA	NA
Anaerobic Digestion	x	1.576	-1.335	242	0	5.948	242
Dewatering	x	0	19	19	411	-	429
Thermal Drying		NA	NA	NA	NA	NA	NA
Alkaline Stabilization		NA	NA	NA	NA	NA	NA
Composting		NA	NA	NA	NA	NA	NA
Landfill Disposal		NA	NA	NA	NA	NA	NA
Combustion		NA	NA	NA	NA	NA	NA
Land Application	x	-1.932	0	-1.932	-2.172	-	-4.104
Transportation	x	262	NA	262	NA	0	262
	TOTALS	-94	-1.305	-1.399	-1.607	5.948	-3.006

Scope 1 - direct emissions

Scope 2 - purchased electricity, heat, or steam

Scope 3 - production of purchased materials and uses of end products

A Unit Process Worksheet – Conditioning/Thickening



Conditioning/Thickening

Unit Processes & Inputs	Inputs & Daily Emissions	Default Input (Optional)
Conditioning / Thickening Input		
Amount of sludge to be thickened (m^3/day)	930	
Solids content of sludge (%)	1,0%	1,0%
Quantity (Mg/day-dry)	9,3	
Type of thickener	other	other
Polymer use (kg/day)	47	47
CO_2 equivalents in polymer used (Mg/day)	**0,4**	
Electricity Use		
Electricity Use (kWh/day)	46	46
CO_2 Emissions from electricity used (Mg/day)	**0,008**	

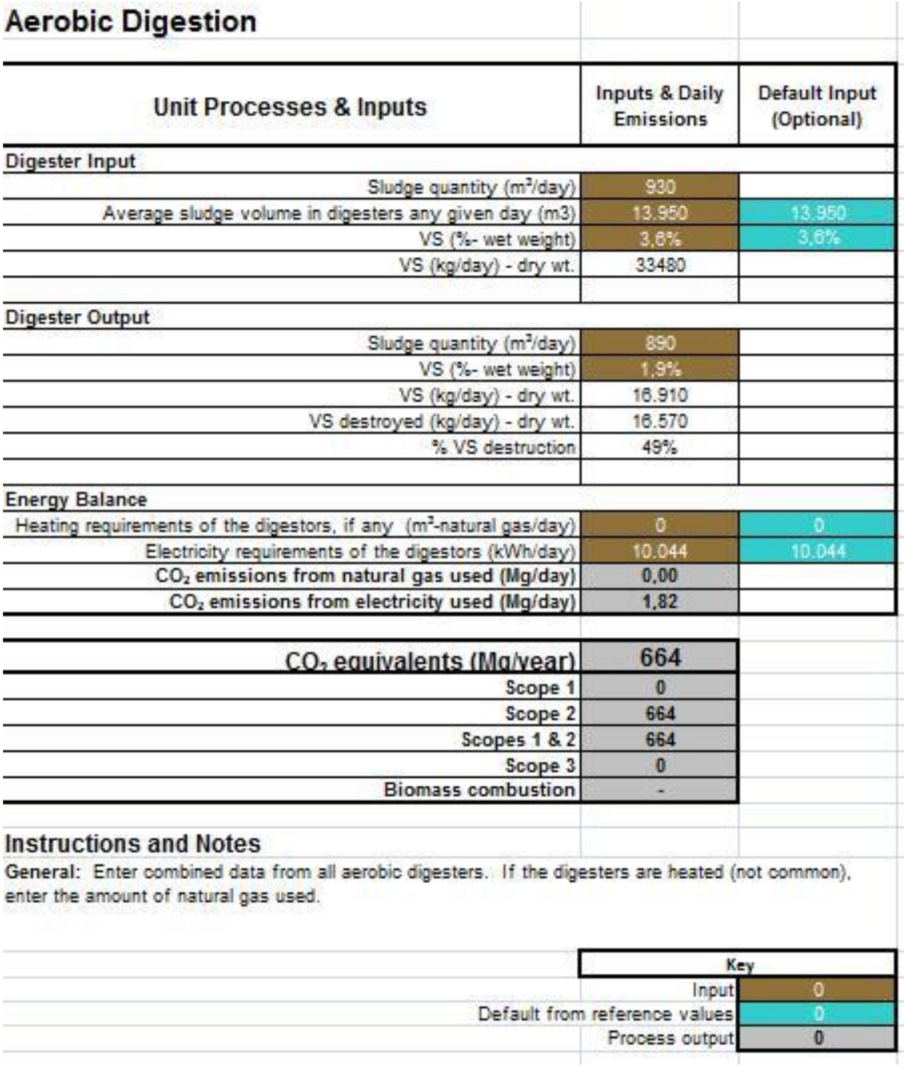
CO_2 equivalents (Mg/year)	**157**
Scope 1	**0**
Scope 2	**3**
Scopes 1 & 2	**3**
Scope 3	**154**
Biomass combustion	**-**

Instructions and Notes

General: Enter data for wastewater solids thickening, and conditioning for thickening (using polymers; ignore other conditioners such as ferric chloride or alum). Do not use this page for dewatering (separate sheet).

Key	
Input	0
Default from reference values	0
Process output	**0**

A Unit Process Worksheets – Aerobic Digestion



Aerobic Digestion

Unit Processes & Inputs	Inputs & Daily Emissions	Default Input (Optional)
Digester Input		
Sludge quantity (m^3/day)	930	
Average sludge volume in digesters any given day (m3)	13.950	13.950
VS (%- wet weight)	3,6%	3,6%
VS (kg/day) - dry wt.	33480	
Digester Output		
Sludge quantity (m^3/day)	890	
VS (%- wet weight)	1,9%	
VS (kg/day) - dry wt.	16.910	
VS destroyed (kg/day) - dry wt.	16.570	
% VS destruction	49%	
Energy Balance		
Heating requirements of the digestors, if any (m^3-natural gas/day)	0	0
Electricity requirements of the digestors (kWh/day)	10.044	10.044
CO_2 emissions from natural gas used (Mg/day)	**0,00**	
CO_2 emissions from electricity used (Mg/day)	**1,82**	

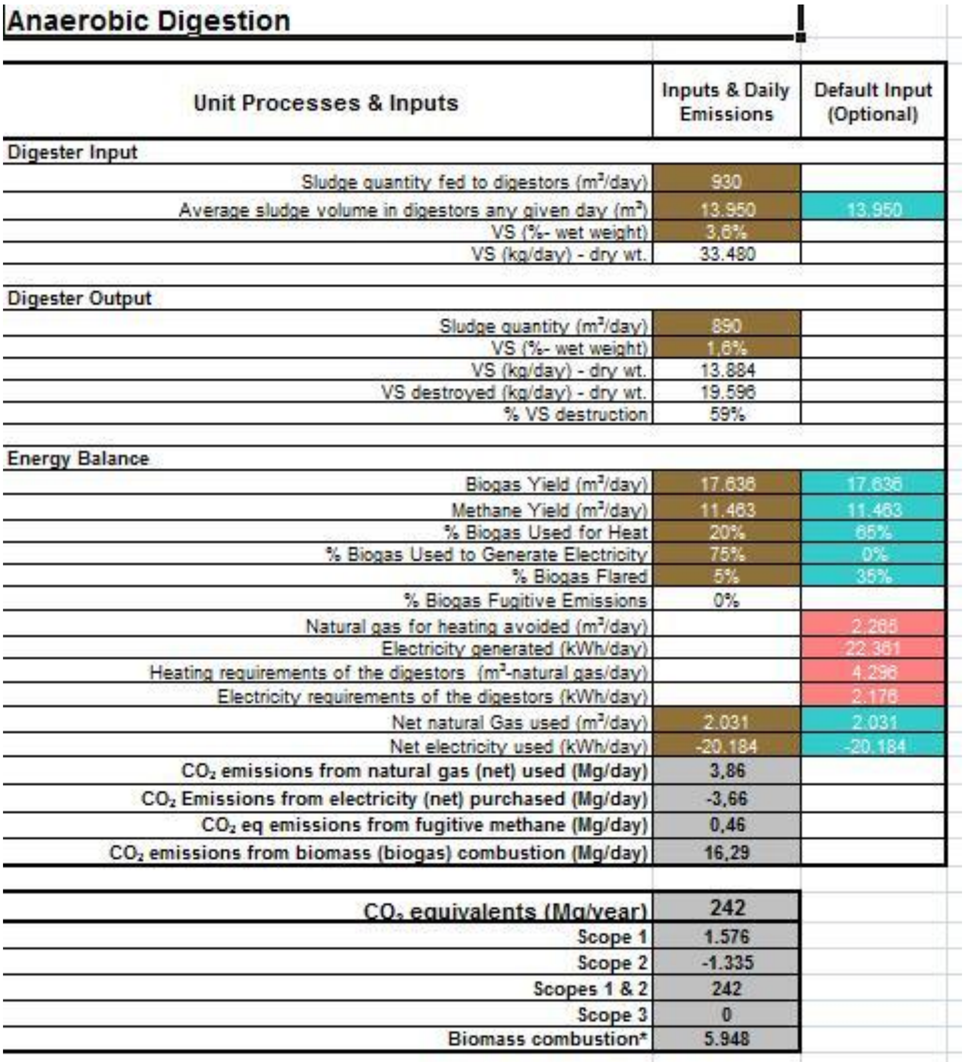
CO_2 equivalents (Mg/year)	664
Scope 1	**0**
Scope 2	**664**
Scopes 1 & 2	**664**
Scope 3	**0**
Biomass combustion	**-**

Instructions and Notes

General: Enter combined data from all aerobic digesters. If the digesters are heated (not common), enter the amount of natural gas used.

Key	
Input	0
Default from reference values	0
Process output	0

A Unit Process Worksheets – Anaerobic Digestion

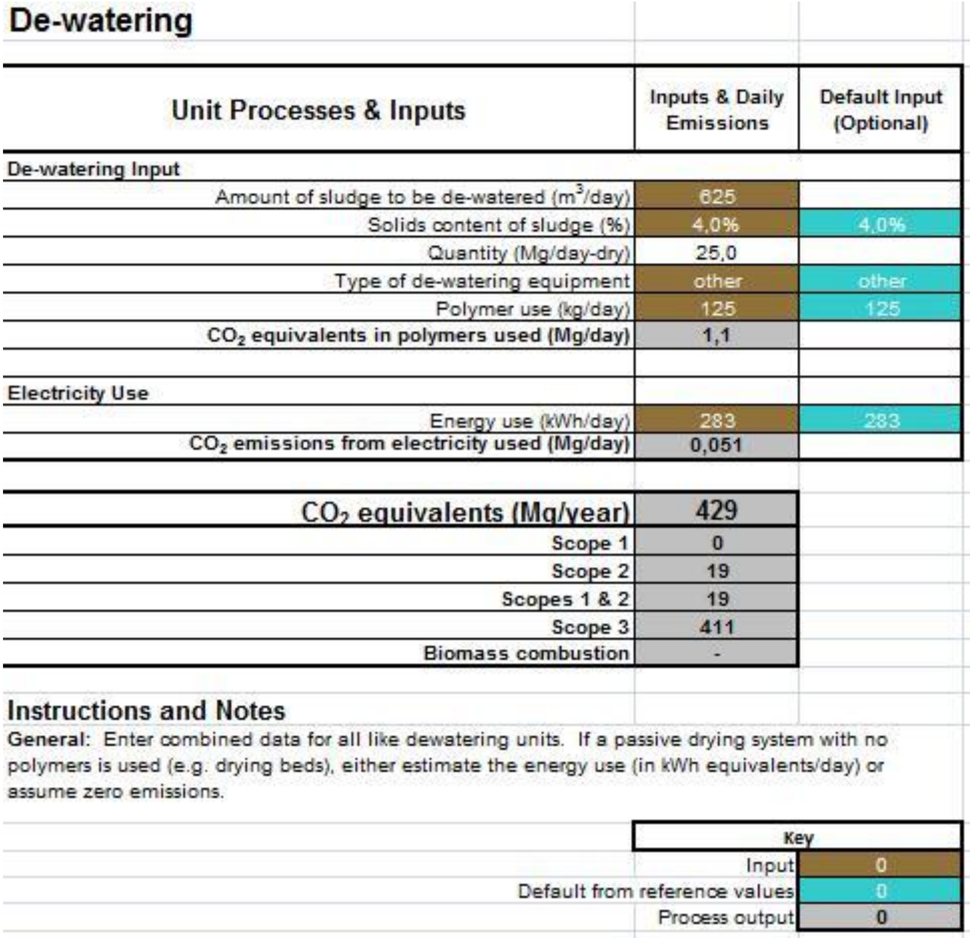


Anaerobic Digestion

Unit Processes & Inputs	Inputs & Daily Emissions	Default Input (Optional)
Digester Input		
Sludge quantity fed to digestors (m^3/day)	930	
Average sludge volume in digestors any given day (m^3)	13.950	13.950
VS (%- wet weight)	3,6%	
VS (kg/day) - dry wt.	33.480	
Digester Output		
Sludge quantity (m^3/day)	890	
VS (%- wet weight)	1,6%	
VS (kg/day) - dry wt.	13.884	
VS destroyed (kg/day) - dry wt.	19.596	
% VS destruction	59%	
Energy Balance		
Biogas Yield (m^3/day)	17.636	17.636
Methane Yield (m^3/day)	11.463	11.463
% Biogas Used for Heat	20%	65%
% Biogas Used to Generate Electricity	75%	0%
% Biogas Flared	5%	35%
% Biogas Fugitive Emissions	0%	
Natural gas for heating avoided (m^3/day)		2.265
Electricity generated (kWh/day)		22.361
Heating requirements of the digestors (m^3-natural gas/day)		4.296
Electricity requirements of the digestors (kWh/day)		2.176
Net natural Gas used (m^3/day)	2.031	2.031
Net electricity used (kWh/day)	-20.184	-20.184
CO_2 emissions from natural gas (net) used (Mg/day)	**3,86**	
CO_2 Emissions from electricity (net) purchased (Mg/day)	**-3,66**	
CO_2 eq emissions from fugitive methane (Mg/day)	**0,46**	
CO_2 emissions from biomass (biogas) combustion (Mg/day)	**16,29**	

CO_2 equivalents (Mg/year)	**242**
Scope 1	**1.576**
Scope 2	**-1.335**
Scopes 1 & 2	**242**
Scope 3	**0**
Biomass combustion*	**5.948**

A Unit Process Worksheets – Dewatering



De-watering

Unit Processes & Inputs	Inputs & Daily Emissions	Default Input (Optional)
De-watering Input		
Amount of sludge to be de-watered (m^3/day)	625	
Solids content of sludge (%)	4,0%	4,0%
Quantity (Mg/day-dry)	25,0	
Type of de-watering equipment	other	other
Polymer use (kg/day)	125	125
CO_2 equivalents in polymers used (Mg/day)	**1,1**	
Electricity Use		
Energy use (kWh/day)	283	283
CO_2 emissions from electricity used (Mg/day)	**0,051**	

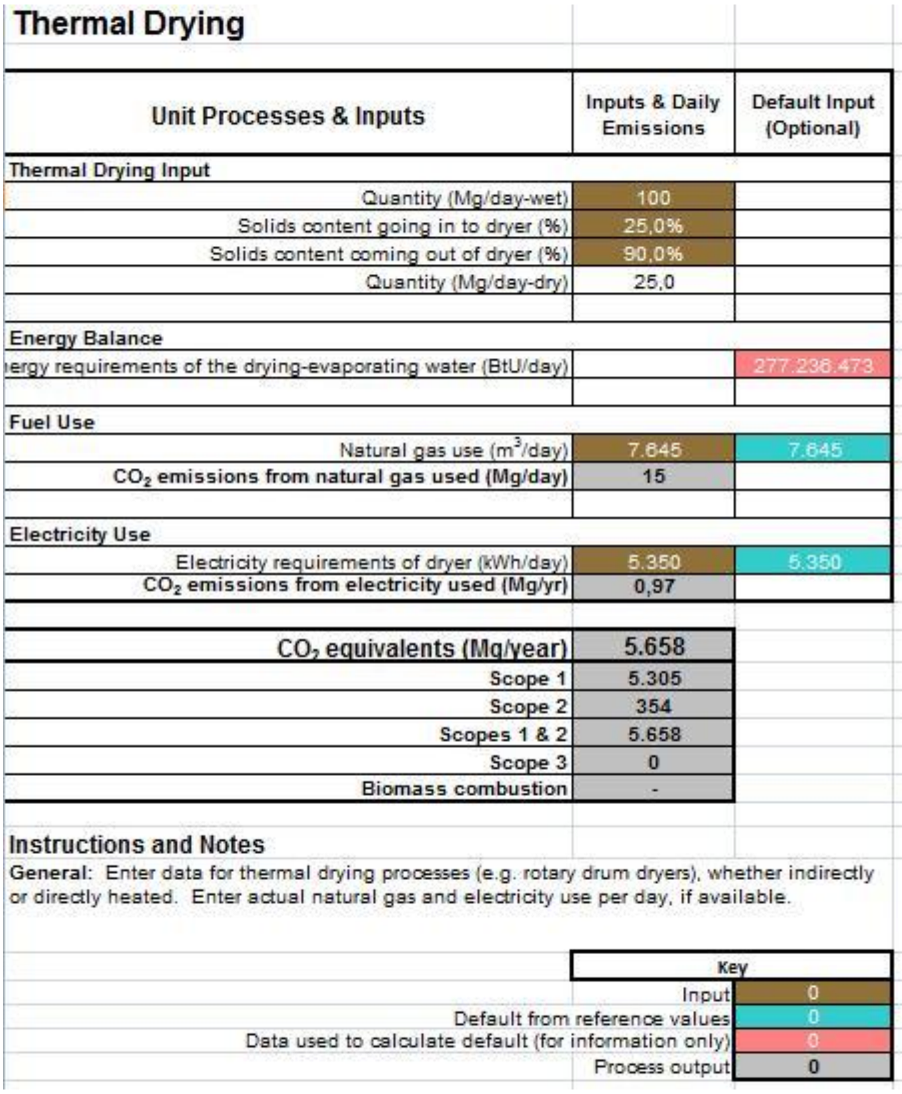
CO_2 equivalents (Mg/year)	429
Scope 1	**0**
Scope 2	**19**
Scopes 1 & 2	**19**
Scope 3	**411**
Biomass combustion	**-**

Instructions and Notes

General: Enter combined data for all like dewatering units. If a passive drying system with no polymers is used (e.g. drying beds), either estimate the energy use (in kWh equivalents/day) or assume zero emissions.

Key	
Input	0
Default from reference values	0
Process output	**0**

A Unit Process Worksheets – Thermal Drying



Thermal Drying

Unit Processes & Inputs	Inputs & Daily Emissions	Default Input (Optional)
Thermal Drying Input		
Quantity (Mg/day-wet)	100	
Solids content going in to dryer (%)	25,0%	
Solids content coming out of dryer (%)	90,0%	
Quantity (Mg/day-dry)	25,0	
Energy Balance		
ergy requirements of the drying-evaporating water (BtU/day)		277.236.473
Fuel Use		
Natural gas use (m^3/day)	7.645	7.645
CO_2 emissions from natural gas used (Mg/day)	**15**	
Electricity Use		
Electricity requirements of dryer (kWh/day)	5.350	5.350
CO_2 emissions from electricity used (Mg/yr)	**0,97**	

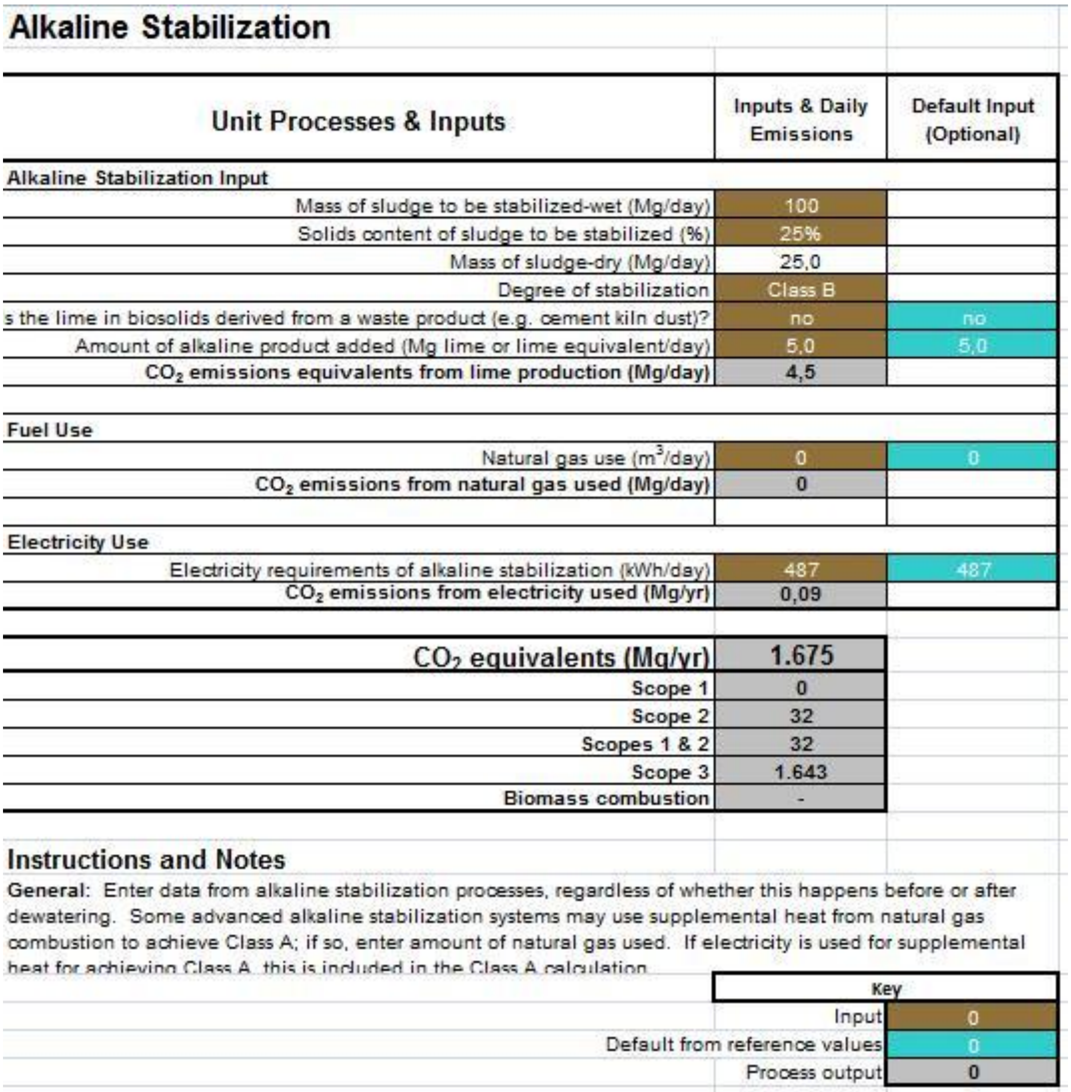
CO_2 equivalents (Mg/year)	**5.658**
Scope 1	**5.305**
Scope 2	**354**
Scopes 1 & 2	**5.658**
Scope 3	**0**
Biomass combustion	**-**

Instructions and Notes

General: Enter data for thermal drying processes (e.g. rotary drum dryers), whether indirectly or directly heated. Enter actual natural gas and electricity use per day, if available.

Key	
Input	0
Default from reference values	0
Data used to calculate default (for information only)	0
Process output	**0**

A Unit Process Worksheets – Alkaline Stabilization



Alkaline Stabilization

Unit Processes & Inputs	Inputs & Daily Emissions	Default Input (Optional)
Alkaline Stabilization Input		
Mass of sludge to be stabilized-wet (Mg/day)	100	
Solids content of sludge to be stabilized (%)	25%	
Mass of sludge-dry (Mg/day)	25,0	
Degree of stabilization	Class B	
s the lime in biosolids derived from a waste product (e.g. cement kiln dust)?	no	no
Amount of alkaline product added (Mg lime or lime equivalent/day)	5,0	5,0
CO_2 emissions equivalents from lime production (Mg/day)	**4,5**	
Fuel Use		
Natural gas use (m^3/day)	0	0
CO_2 emissions from natural gas used (Mg/day)	**0**	
Electricity Use		
Electricity requirements of alkaline stabilization (kWh/day)	487	487
CO_2 emissions from electricity used (Mg/yr)	**0,09**	

CO_2 equivalents (Mg/yr)	**1.675**
Scope 1	**0**
Scope 2	**32**
Scopes 1 & 2	**32**
Scope 3	**1.643**
Biomass combustion	**-**

Instructions and Notes

General: Enter data from alkaline stabilization processes, regardless of whether this happens before or after dewatering. Some advanced alkaline stabilization systems may use supplemental heat from natural gas combustion to achieve Class A; if so, enter amount of natural gas used. If electricity is used for supplemental heat for achieving Class A, this is included in the Class A calculation.

Key	
Input	0
Default from reference values	0
Process output	**0**

A Unit Process Worksheets – Composting

Composting

Unit Processes & Inputs	Inputs & Daily Emissions	Default Input (Optional)
Feedstock Input		
Material type	sludge	
Quantity of sludge going to composting (Mg/day-wet)	100	
Solids content (%)	25,0%	
Quantity of sludge going to composting (Mg/day-dry)	25,0	
Sludge density (kg/m^3)	950	950
Volume of sludge going to composting (m^3/day)	105	
Has the sludge been digested prior to composting?	no	no
Total nitrogen (%-dry weight)	4,0%	4,0%
Total phosphorus (%-dry weight)	1,5%	1,5%
Total volatile solids - TVS (%-dry weight)	70,0%	70,0%
Organic carbon (%-dry weight)	39,0%	39%
Will compost use replace commercial fertilizer use where it is applied?	yes	yes
Volumetric ratio of amendment to sludge (m^3 amendment:m^3 sludge, as is)*	3	3
Amendment grinding on-site?	yes	yes
Volume of sludge in compost (%)	25%	
Volume of amendment in compost (%)	75%	
Density of amendment (kg/m^3)**	250	250
Quantity of amendment going to composting (Mg/day-wet)	79	
Blended Feedstock Characteristics		
C:N	31	31
Solids content (%)	41%	41%
Type of composting operation	ASP	
Are active composting piles covered or is the air from them treated through a biofilter?	yes	yes
Fuel Use		
Grinding (L-diesel fuel/day)		261
Setting up and breaking down piles (L-diesel fuel/day)		447
Total fuel use for composting equipment (L-diesel fuel/day)	708	708
Applying compost to land (L-diesel fuel/day)	67	67
CO_2 Emissions from Diesel used (Mg/day)	**2,15**	
Electricity Use		
Electricity requirements of composting system (kWh/day)	4.500	4.500
CO_2 Emissions from Electricity used (Mg/day)	**0,82**	
Methane Emissions		
CH_4 emitted from compost pile (Mg/day)	0,00	
CO_2 Emissions equivalents from released CH_4 (Mg/day)	**0,00**	
Nitrous Oxide Emissions		
N_2O emitted from compost pile (Mg/day)	0,000	
N_2O emitted from applying compost to soils (Mg/day)	0,0079	
CO_2 Emissions equivalents from released N_2O (Mg/day)	**0,00**	
Carbon Sequestration		
From compost applied to soil (Mg CO_2/day)	**-6,25**	
Fertilizer Off-set Credits		
From nitrogen applied to soil (Mg CO_2/day)	**-4,00**	
From phosphorus applied to soil (Mg CO_2/day)	**-0,75**	

CO_2 equivalents (Mg/year)	**-2.933**
Scope 1	**-1.497**
Scope 2	**298**
Scopes 1 & 2	**-1.200**
Scope 3	**-1.734**
Biomass combustion	**-**

Instructions and Notes

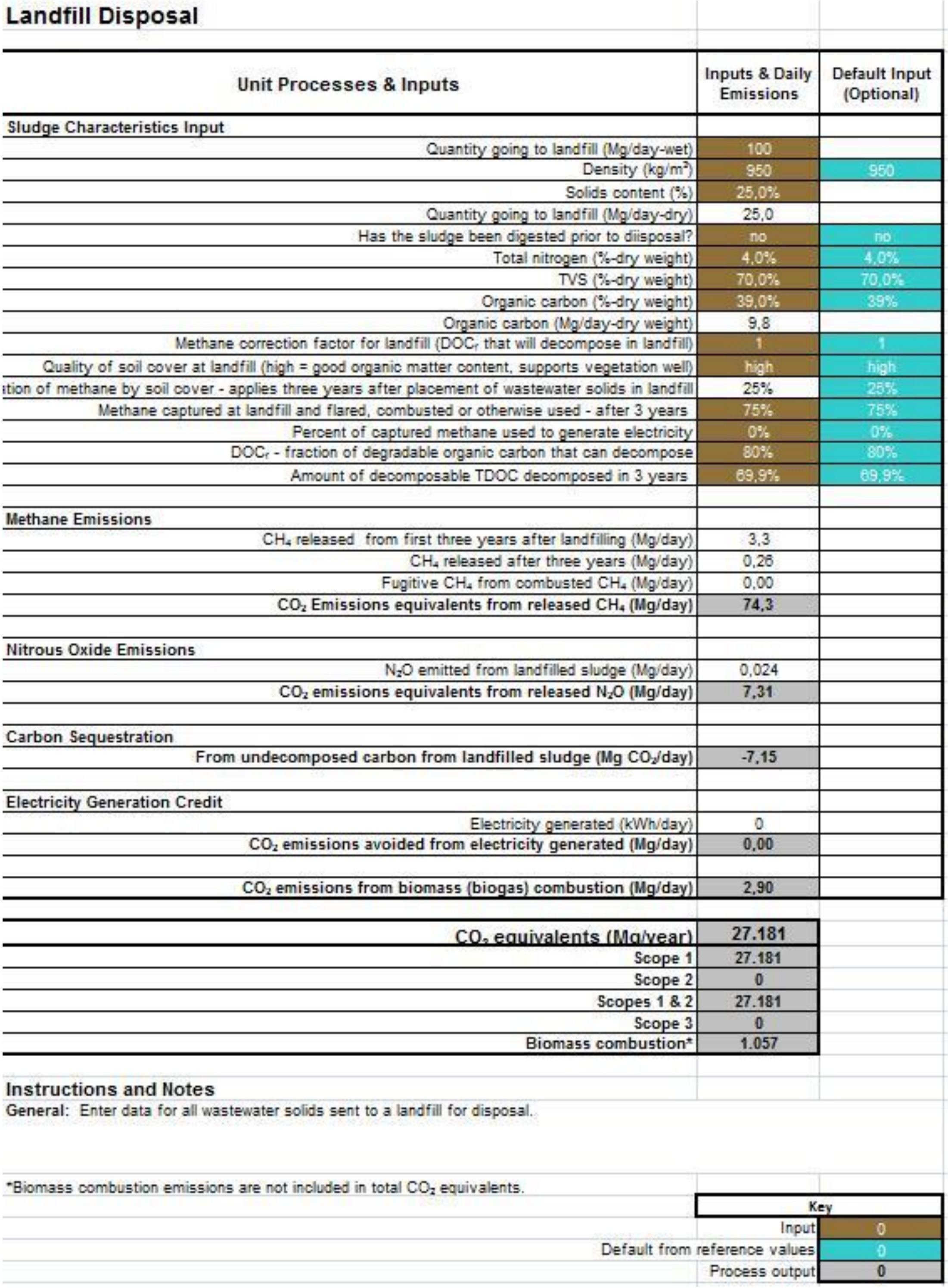
General: Enter data for all solids that were composted. Whenever possible use data from local measurements.

*For this row, if entering a local value, enter in both the blue and orange cells.

**Default is for density of sawdust.

Key	
Input	0
Default from reference values	0
Data used to calculate default (for information only)	0
Process output	0

A Unit Process Worksheets – Landfill Disposal



Landfill Disposal

Unit Processes & Inputs	Inputs & Daily Emissions	Default Input (Optional)
Sludge Characteristics Input		
Quantity going to landfill (Mg/day-wet)	100	
Density (kg/m^3)	950	950
Solids content (%)	25,0%	
Quantity going to landfill (Mg/day-dry)	25,0	
Has the sludge been digested prior to diisposal?	no	no
Total nitrogen (%-dry weight)	4,0%	4,0%
TVS (%-dry weight)	70,0%	70,0%
Organic carbon (%-dry weight)	39,0%	39%
Organic carbon (Mg/day-dry weight)	9,8	
Methane correction factor for landfill (DOC$_f$ that will decompose in landfill)	1	1
Quality of soil cover at landfill (high = good organic matter content, supports vegetation well)	high	high
tion of methane by soil cover - applies three years after placement of wastewater solids in landfill	25%	25%
Methane captured at landfill and flared, combusted or otherwise used - after 3 years	75%	75%
Percent of captured methane used to generate electricity	0%	0%
DOC$_f$ - fraction of degradable organic carbon that can decompose	80%	80%
Amount of decomposable TDOC decomposed in 3 years	69,9%	69,9%
Methane Emissions		
CH$_4$ released from first three years after landfilling (Mg/day)	3,3	
CH$_4$ released after three years (Mg/day)	0,26	
Fugitive CH$_4$ from combusted CH$_4$ (Mg/day)	0,00	
CO$_2$ Emissions equivalents from released CH$_4$ (Mg/day)	**74,3**	
Nitrous Oxide Emissions		
N$_2$O emitted from landfilled sludge (Mg/day)	0,024	
CO$_2$ emissions equivalents from released N$_2$O (Mg/day)	**7,31**	
Carbon Sequestration		
From undecomposed carbon from landfilled sludge (Mg CO$_2$/day)	**-7,15**	
Electricity Generation Credit		
Electricity generated (kWh/day)	0	
CO$_2$ emissions avoided from electricity generated (Mg/day)	**0,00**	
CO$_2$ emissions from biomass (biogas) combustion (Mg/day)	**2,90**	

CO$_2$ equivalents (Mg/year)	**27.181**
Scope 1	**27.181**
Scope 2	**0**
Scopes 1 & 2	**27.181**
Scope 3	**0**
Biomass combustion*	**1.057**

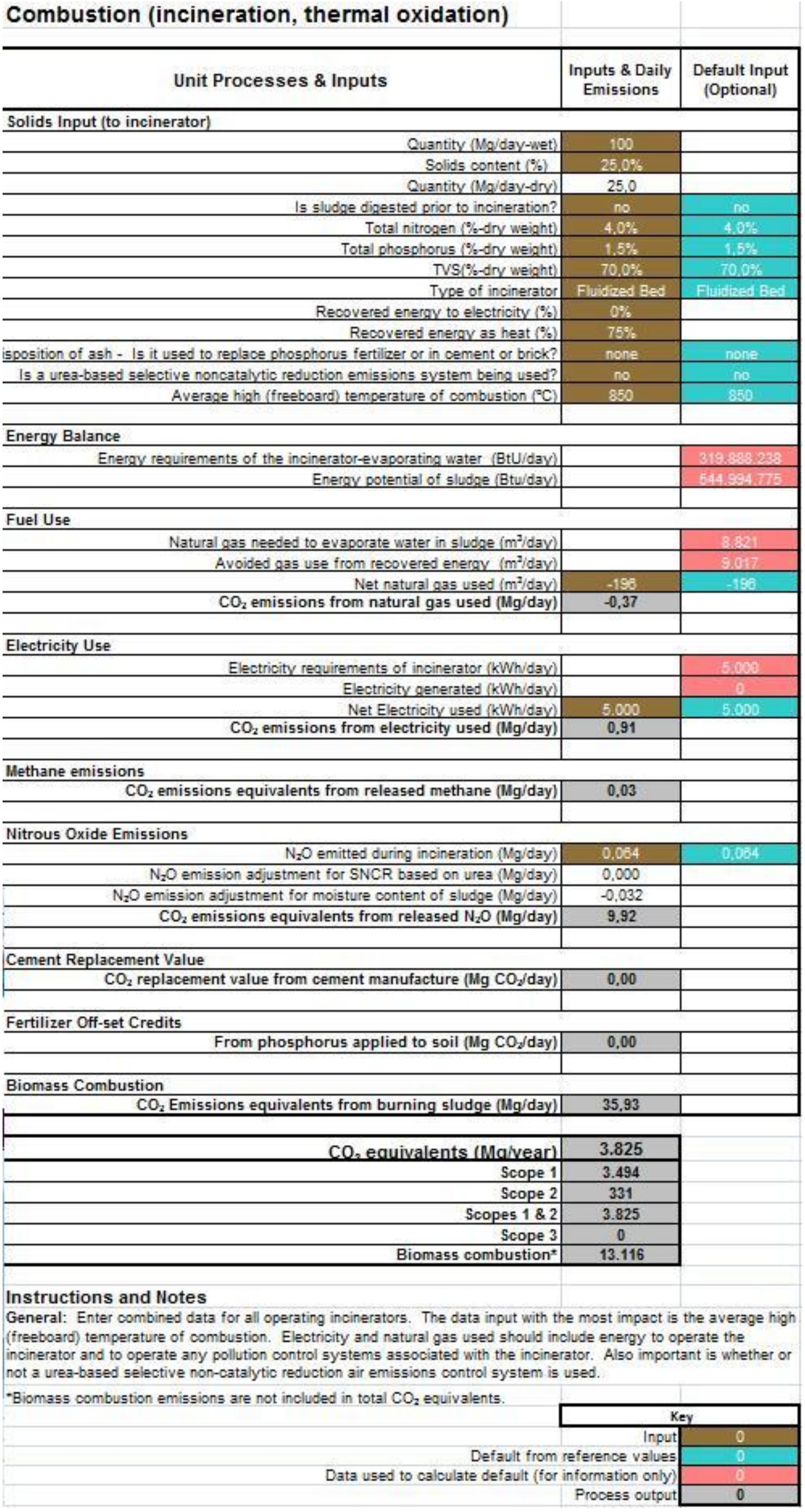
Instructions and Notes

General: Enter data for all wastewater solids sent to a landfill for disposal.

*Biomass combustion emissions are not included in total CO$_2$ equivalents.

Key	
Input	0
Default from reference values	0
Process output	**0**

A Unit Process Worksheets – Incineration



Combustion (incineration, thermal oxidation)

Unit Processes & Inputs	Inputs & Daily Emissions	Default Input (Optional)
Solids Input (to incinerator)		
Quantity (Mg/day-wet)	100	
Solids content (%)	25,0%	
Quantity (Mg/day-dry)	25,0	
Is sludge digested prior to incineration?	no	no
Total nitrogen (%-dry weight)	4,0%	4,0%
Total phosphorus (%-dry weight)	1,5%	1,5%
TVS(%-dry weight)	70,0%	70,0%
Type of incinerator	Fluidized Bed	Fluidized Bed
Recovered energy to electricity (%)	0%	
Recovered energy as heat (%)	75%	
isposition of ash - Is it used to replace phosphorus fertilizer or in cement or brick?	none	none
Is a urea-based selective noncatalytic reduction emissions system being used?	no	no
Average high (freeboard) temperature of combustion (°C)	850	850
Energy Balance		
Energy requirements of the incinerator-evaporating water (BtU/day)		319.888.238
Energy potential of sludge (Btu/day)		544.994.775
Fuel Use		
Natural gas needed to evaporate water in sludge (m^3/day)		8.821
Avoided gas use from recovered energy (m^3/day)		9.017
Net natural gas used (m^3/day)	-196	-196
CO_2 emissions from natural gas used (Mg/day)	**-0,37**	
Electricity Use		
Electricity requirements of incinerator (kWh/day)		5.000
Electricity generated (kWh/day)		0
Net Electricity used (kWh/day)	5.000	5.000
CO_2 emissions from electricity used (Mg/day)	**0,91**	
Methane emissions		
CO_2 emissions equivalents from released methane (Mg/day)	**0,03**	
Nitrous Oxide Emissions		
N_2O emitted during incineration (Mg/day)	0,064	0,064
N_2O emission adjustment for SNCR based on urea (Mg/day)	0,000	
N_2O emission adjustment for moisture content of sludge (Mg/day)	-0,032	
CO_2 emissions equivalents from released N_2O (Mg/day)	**9,92**	
Cement Replacement Value		
CO_2 replacement value from cement manufacture (Mg CO_2/day)	**0,00**	
Fertilizer Off-set Credits		
From phosphorus applied to soil (Mg CO_2/day)	**0,00**	
Biomass Combustion		
CO_2 Emissions equivalents from burning sludge (Mg/day)	**35,93**	

CO_2 equivalents (Mg/year)	**3.825**
Scope 1	**3.494**
Scope 2	**331**
Scopes 1 & 2	**3.825**
Scope 3	**0**
Biomass combustion*	**13.116**

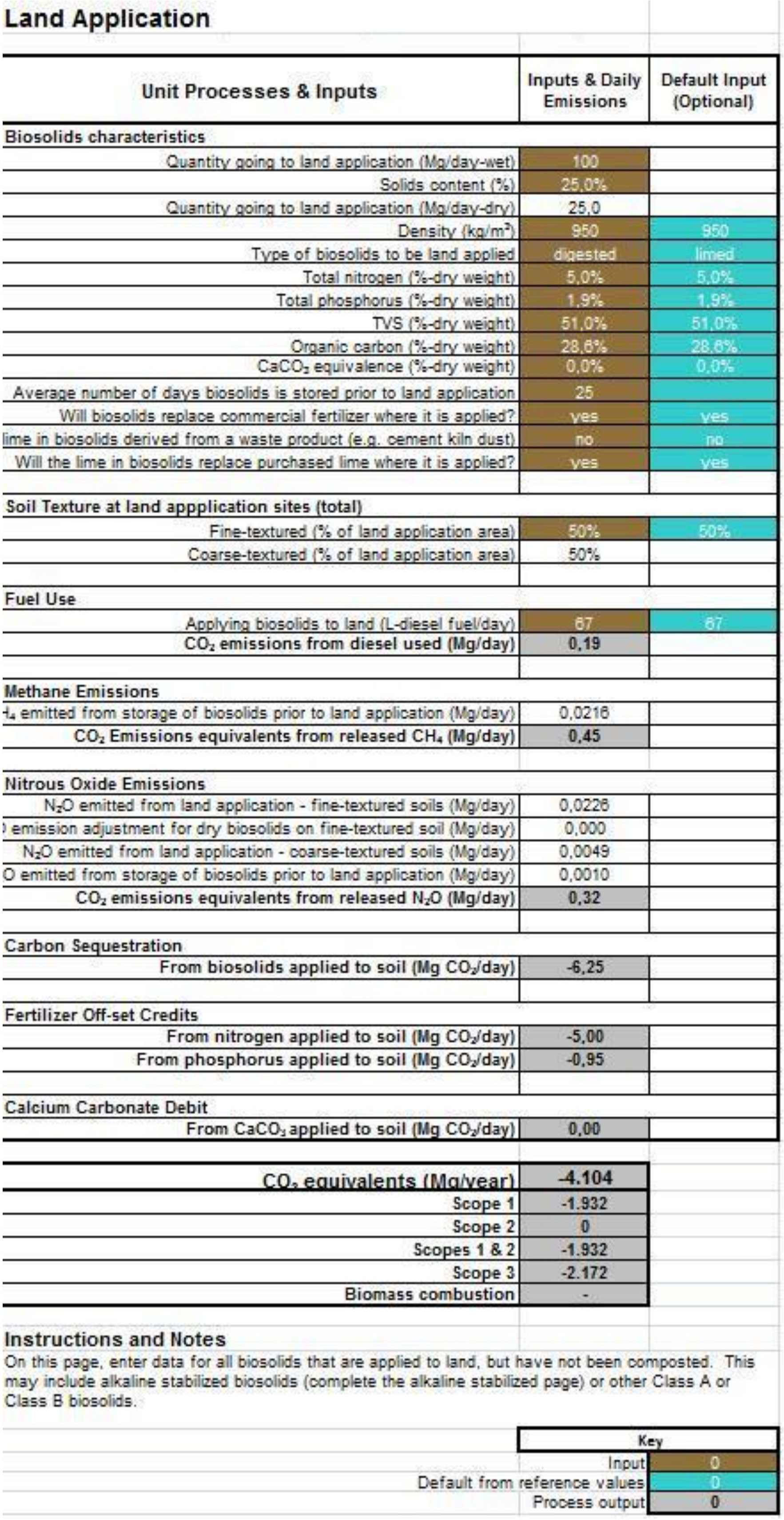
Instructions and Notes

General: Enter combined data for all operating incinerators. The data input with the most impact is the average high (freeboard) temperature of combustion. Electricity and natural gas used should include energy to operate the incinerator and to operate any pollution control systems associated with the incinerator. Also important is whether or not a urea-based selective non-catalytic reduction air emissions control system is used.

*Biomass combustion emissions are not included in total CO_2 equivalents.

Key	
Input	0
Default from reference values	0
Data used to calculate default (for information only)	0
Process output	0

A Unit Process Worksheets – Land Application



Land Application

Unit Processes & Inputs	Inputs & Daily Emissions	Default Input (Optional)
Biosolids characteristics		
Quantity going to land application (Mg/day-wet)	100	
Solids content (%)	25,0%	
Quantity going to land application (Mg/day-dry)	25,0	
Density (kg/m^3)	950	950
Type of biosolids to be land applied	digested	limed
Total nitrogen (%-dry weight)	5,0%	5,0%
Total phosphorus (%-dry weight)	1,9%	1,9%
TVS (%-dry weight)	51,0%	51,0%
Organic carbon (%-dry weight)	28,6%	28,6%
$CaCO_3$ equivalence (%-dry weight)	0,0%	0,0%
Average number of days biosolids is stored prior to land application	25	
Will biosolids replace commercial fertilizer where it is applied?	yes	yes
lime in biosolids derived from a waste product (e.g. cement kiln dust)	no	no
Will the lime in biosolids replace purchased lime where it is applied?	yes	yes
Soil Texture at land appplication sites (total)		
Fine-textured (% of land application area)	50%	50%
Coarse-textured (% of land application area)	50%	
Fuel Use		
Applying biosolids to land (L-diesel fuel/day)	67	67
CO_2 emissions from diesel used (Mg/day)	**0,19**	
Methane Emissions		
H_4 emitted from storage of biosolids prior to land application (Mg/day)	0,0216	
CO_2 Emissions equivalents from released CH_4 (Mg/day)	**0,45**	
Nitrous Oxide Emissions		
N_2O emitted from land application - fine-textured soils (Mg/day)	0,0226	
O emission adjustment for dry biosolids on fine-textured soil (Mg/day)	0,000	
N_2O emitted from land application - coarse-textured soils (Mg/day)	0,0049	
O emitted from storage of biosolids prior to land application (Mg/day)	0,0010	
CO_2 emissions equivalents from released N_2O (Mg/day)	**0,32**	
Carbon Sequestration		
From biosolids applied to soil (Mg CO_2/day)	**-6,25**	
Fertilizer Off-set Credits		
From nitrogen applied to soil (Mg CO_2/day)	**-5,00**	
From phosphorus applied to soil (Mg CO_2/day)	**-0,95**	
Calcium Carbonate Debit		
From $CaCO_3$ applied to soil (Mg CO_2/day)	**0,00**	

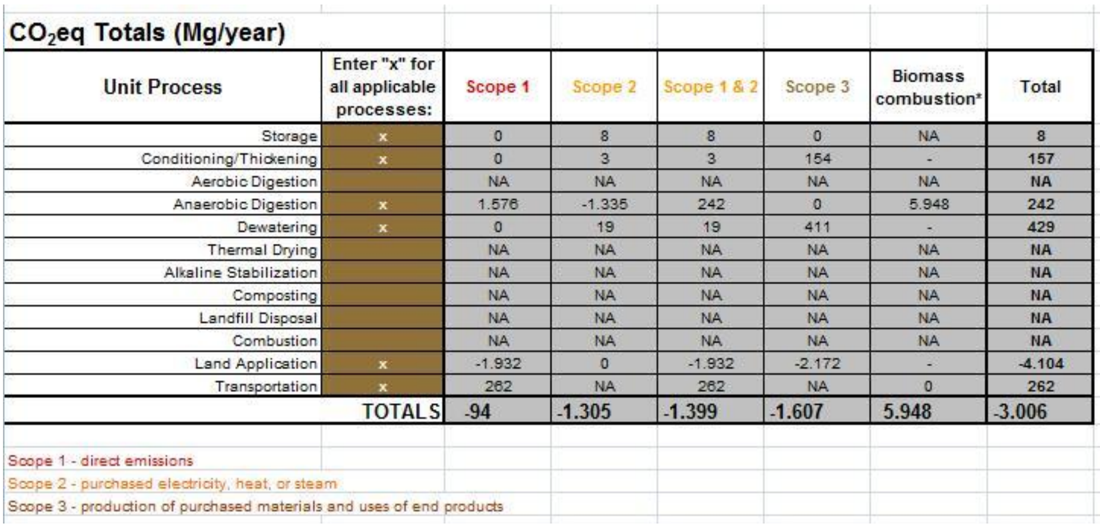
CO_2 equivalents (Mg/year)	**-4.104**
Scope 1	**-1.932**
Scope 2	**0**
Scopes 1 & 2	**-1.932**
Scope 3	**-2.172**
Biomass combustion	**-**

Instructions and Notes

On this page, enter data for all biosolids that are applied to land, but have not been composted. This may include alkaline stabilized biosolids (complete the alkaline stabilized page) or other Class A or Class B biosolids.

Key	
Input	0
Default from reference values	0
Process output	**0**

Viewing Entire Program Results



CO_2eq Totals (Mg/year)

Unit Process	Enter "x" for all applicable processes:	Scope 1	Scope 2	Scope 1 & 2	Scope 3	Biomass combustion*	Total
Storage	x	0	8	8	0	NA	8
Conditioning/Thickening	x	0	3	3	154	-	157
Aerobic Digestion		NA	NA	NA	NA	NA	NA
Anaerobic Digestion	x	1.576	-1.335	242	0	5.948	242
Dewatering	x	0	19	19	411	-	429
Thermal Drying		NA	NA	NA	NA	NA	NA
Alkaline Stabilization		NA	NA	NA	NA	NA	NA
Composting		NA	NA	NA	NA	NA	NA
Landfill Disposal		NA	NA	NA	NA	NA	NA
Combustion		NA	NA	NA	NA	NA	NA
Land Application	x	-1.932	0	-1.932	-2.172	-	-4.104
Transportation	x	262	NA	262	NA	0	262
	TOTALS	-94	-1.305	-1.399	-1.607	5.948	-3.006

Scope 1 - direct emissions

Scope 2 - purchased electricity, heat, or steam

Scope 3 - production of purchased materials and uses of end products