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Carbon Dioxide and Methane Emissions from Different Wastewater Treatment Scenarios

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Carbon Dioxide and Methane Emissions from Different Wastewater Treatment Scenarios

Master of Science Thesis

by

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Abstract

Since the era of industrialization, concentrations of greenhouse gases (GHGs) have tremendously increased in the atmosphere, as a result of the extensive use of fossil fuels, deforestation, improper waste management, transport, and other economic activities (Boer, 2008).This has led to a great accumulation of greenhouse gases, forming a blanket around the Earth which contributes in the so-called “Global Warming”.

Over the last decades, wastewater treatment has developed strongly and has become a very important asset in mitigating the impact of domestic and industrial effluents on the environment. There are many different forms of wastewater treatment, and one of the most effective treatment technology in terms COD, N and P removal, activated sludge is often criticized for its high energy use. Some other treatment concepts have a more "green" image, but it is not clear whether this image is justified based on their greenhouse gas emission. This study focuses on the estimation of GHG emissions of four different wastewater treatment configurations, both conventional and innovative systems namely: (1) Harnaschpolder, (2) Sneek, (3) EIER-Ouaga and (4) Siddhipur. This analysis is based on COD mass balance, the Intergovernmental Panel on Climate Change (IPCC) 2006 guidelines for estimating CO_2 and CH_4, and literature review. Furthermore, the energy requirements for each of the systems were estimated based on energy survey.

The study showed that an estimated daily average of 87 g of CO_2 equivalent, ranging between 38 to 192 g, was derived to be the per capita CO_2 emission for the four different wastewater treatment scenarios. Despite the fact that no electrical energy is used in the treatment process, the GHG emission from EIER-Ouaga anaerobic pond systems is found to be the highest compared to the three other scenarios analysed. It was estimated 80% higher than the most favourable scenario (Sneek). Moreover, the results indicate that the GHGs emitted from these WWTPs are 97% lower compared to other anthropogenic sources like the public transport sector. The innovative sanitation scenarios were found to cause less environmental burden in terms of energy and GHGs.

Nevertheless, to ensure a positive impact of these treatment systems, an optimum biogas reuse (for the production of electricity and heat), the source separation of human excreta (to disburden the wastewater treatment processes) should be introduced to reduce their GHG emissions.

Keywords: Carbon dioxide, greenhouse gases, methane, wastewater treatment technologies.

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Dedication

To my late father Moumouni Ali

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List of Symbols

ANNAMOX	Anaerobic ammonia oxidation
AS	Activated sludge
BOD	Biochemical Oxygen Demand
Cap	Capita
CO_2	Carbon dioxide
CO_2 equiv.	Carbon dioxide equivalent
COD	Chemical Oxygen Demand
CH_4	Methane
d	day
DO	Dissolve Oxygen
EF	Emission Factors
FCCC	Framework Convention on Climate Change
g	gram
GC	Gas Chromatography
GHG	Greenhouse Gas
GHGs	Greenhouse Gases
GWP	Global Warming Potential
IPCC	Intergovernmental Panel on Climate Change
kg	kilogram
kWh	Kilo Watt hour
MDG	Millennium Development Goal
N	Nitrogen
N_2O	Nitrous oxide
˚ C	Degree Celsius
P	Phosphorus
PPBV	Part per billion by volume
PPMV	Part per million by volume
t	Ton
TSS	Total Suspended Solids
UASB	Upflow Anaerobic Sludge Blanket
UN	United Nations
UNDP	United Nations Development Program
UNEP	United Nations Environment Programme
US EPA	United States Environmental Protection Agency
VFAs	Volatile Fatty Acids
WWTP	Wastewater Treatment Plant
yr	year

1. INTRODUCTION

1.1. Background

According to the Environmental Engineering Dictionary and Directory, the term "environment" encompasses all that surrounds man, including the land, the water and the atmosphere. In pursuit of satisfying human needs, man impacts the environment. Particularly, most of man's activities result in the production of atmospheric gases, such as carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), which are referred to as Greenhouse Gases (GHGs). Burning of fossil fuels (in large part for transport), deforestation and waste management are among the activities that most produce GHGs (**Table 1.1)**. Of the GHGs, the most important is CO_2, due to its abundance in the atmosphere and high Heat-retaining power. These GHGs contribute to a rise in temperature at the Earth's surface, commonly known as Global Warming (IPCC, 2006).

Energy released by the sun gets to the earth's surface in the form of radiant light. The bulk of this energy is not absorbed by the atmosphere, since it allows the transmission of light. However, about half of the Sun's energy that reaches the Earth is absorbed by the surface as heat. Part of this is eventually radiated back into the atmosphere in the form of infrared radiation. GHGs are not permeable to infrared radiation and instead absorb it and pass it on as heat to the other gases of the atmosphere. The surface and lower atmosphere are warmed because of the GHGs and this makes our life on Earth possible. Yet, the increased concentration of GHGs in the atmosphere forms a blanket around the planet that impedes the escape of energy from the Earth's surface and atmosphere, thus leading to excessive rise in temperature.

Table 1.1: Greenhouse Gas emissions by sector (IPCC, 2006)

Sector	Emission per year (%)
Power stations	21.3
Industrial processes	16.8
Transportation fuels	14
Agricultural by products	12.5
Fossil fuel retrieval, processing, and distribution	11.3
Land use and biomass burning	10
Waste treatment and disposal	**3.4**
Residential, commercial, and others sources	10.3

Environmental pollution has been in existence, way back from man's earliest civilization down to the industrial revolution. The situation is getting worse despite concerted efforts by scholars. According to the last assessment by the Intergovernmental Panel on Climate Change, the warming of the climate is unequivocal and accelerating (IPCC, 2007).It has also been found that temperatures have risen by 0.74˚C on average over the last 100 years, with most of the warming occurring in the last 50 years. Further measurements of carbon dioxide concentrations in the atmosphere indicate an increase from a pre-industrial value of 278 parts per million (ppm) to 379 ppm in 2005 (**Table 1.2**) which lead to the global warming.

Table1.2: characteristics of the principal greenhouse gases (*Margarita and Scarlette*, 2007)

Gas	Mean life (years)	Pre-industrial concentration	Concentration in 1990	Global warming Potential (%)	Annual increase (%)
CO_2	50-200	280 ppmv	360 ppmv	45-61	1.5
CH_4	10	790 ppbv	1720 ppbv	16	1.3
N_2O	130-200	288 ppbv	312 ppbv	5	0.25-0.3

Almost all researchers acknowledge Global Warming, but some disagree that CO_2 is the causal agent (Ball, 1983; Shaviv and Dekel, 2008; Wheeler, 2001). Some go as far as stating that the theory of man-made global warming is all nonsense, since none of the studies have shown clear evidence that attribute the observed climate changes to the specific cause of increase in GHGs (Kroonenberg, 1994; Lindzen, 2006; William, 2004).

The standard measurements of Antarctic or Greenland ice caps of atmospheric CO_2 concentrations show that before the Industrial Revolution levels were about 280 ppmv then started increasing afterwards up to 380 ppmv. Therefore, according to the theory of man-made global warming, industrial growth caused the temperature rise. Al Gore, former vice president of United States of America clearly pointed out that there is a complex relationship between CO_2 and temperature, but reiterated that when there is more carbon dioxide the temperature rises (F**igure 1.1**). The figure shows historical CO_2 (right axis) and reconstructed temperature (as a difference from the mean temperature for the last 100 years) records based on Antarctic ice cores, providing data for the last 800,000 years (Falkowski *et al.*, 2000).

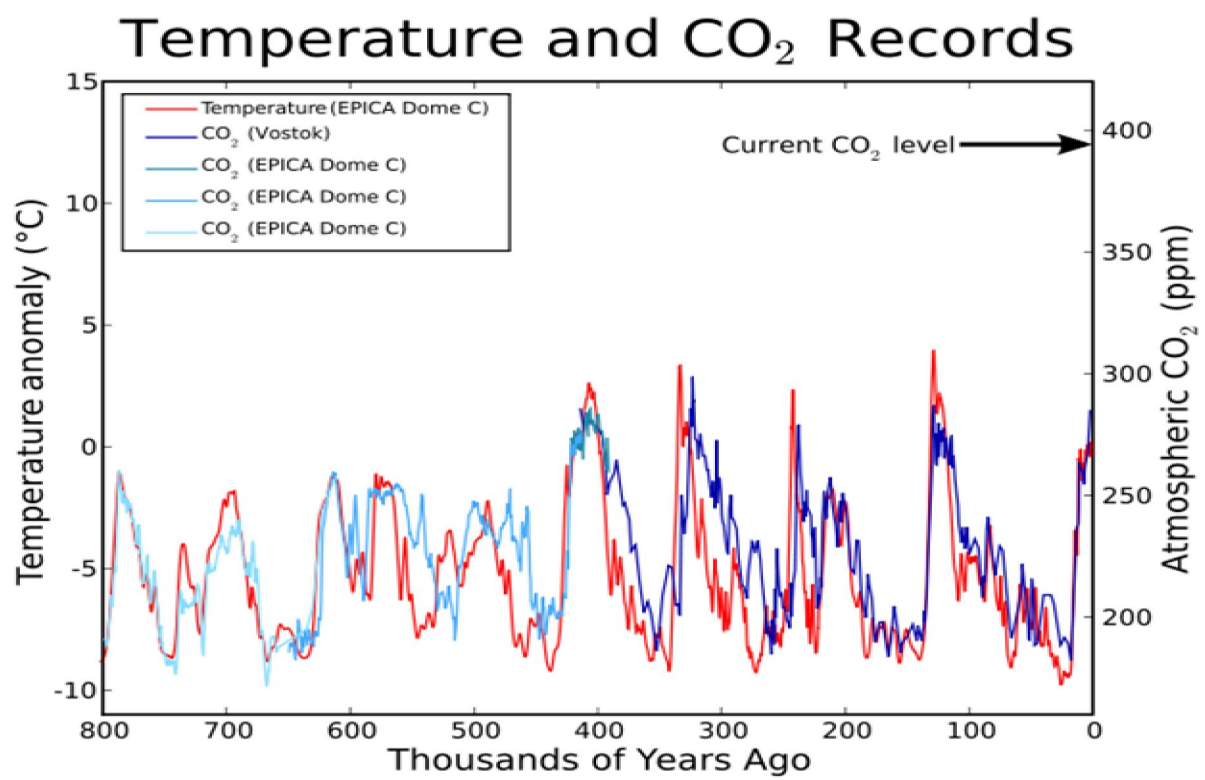


Figure1.1: Relationship between carbon dioxide and temperature

Even though it is not 100% sure that global warming is caused by GHGs emissions, it is obvious that the natural balance is disturbed. The consequences of global warming are enormous and include sea-level rise, shifts in growing seasons, and increasing frequency and intensity of extreme weather events, such as storms, floods and droughts (IPCC, 2007). There is an urgent need to reduce emissions of these GHGs. Companies in developed countries need to pay for their emissions since they cannot comply with the emission level in their own countries, it is easier for them to reduce the emissions in other countries than in their own efficient plants. Many programs have been initiated to reduce the emissions of GHGs and to mitigate their effects, because of the general consensus that excess GHGs cause global warming and climate change. For instance, the Kyoto Protocol which is an amendment to the United Nations Framework Convention on Climate Change (UNFCC) is an international and legally binding agreement to reduce GHG emissions in the signatory countries. The Clean Development Mechanism (CDM) and the Joint Implementation (JI) are both mechanisms of the agreement that offer organisations the opportunity to earn extra income by receiving Carbon Credits and at the same time reducing GHG emissions.

One of the areas contributing to the total GHG emissions is wastewater treatment, because it involves removal of organic material. Moreover, with the introduction of stricter effluent standards, it is certain that wastewater treatment plants will play a major role in total GHG emissions (**Table 1.3)** (Hospido *et al.*, 2007). It also implies that these climate effects will be more pronounced as a result of high material and energy consumption as well as involving the generation of waste in the plants. In the process of treating wastewater, methane, carbon dioxide, nitrous dioxide, and other harmful gases are generated in parts of these systems, primary settling tanks, biological tanks, secondary clarification tanks, sludge holding tanks, and sludge transfer lines (Czeplel *et al.*, 1993).

Table 1.3: Greenhouse emissions from wastewater treatment

Type of system	GHG production	References
Aerobic systems		
Conventional activated sludge (Galicia, Spain)	11.1 to 13.8 kg CO_2 equiv./ person/year	(Hospido *et al.,* 2007)
Conventional activated sludge (Sweden)	12 kg CO_2 equiv./ person /year	(Kärrman and Jőnsson, 2001)
Anaerobic systems		
Open lagoons	143.25 kg CO_2 per m^3 of wastewater	(Show and Lee, 2008)
Anaerobic granular-sludge systems	36.4 kg CO_2 per m^3 of wastewater	(Show and Lee, 2008)
Algae-based anaerobic pond	0.46 g CH_4/m^2/day	(Van der Steen *et al.*, 2004)
Duckweed-based anaerobic pond reactor	0.20 g CH_4/m^2/day	(Van der Steen *et al.,* 2004)

Many attempts have been developed to address these new challenges (strict effluent standards and GHG emissions). Some are energy-intensive (conventional water and wastewater management) and others emit large amounts of GHGs (solid waste management). According to Lee (2007), 0.3 to 0.6 kWh is required to treat one cubic meter of wastewater using the membrane bioreactor and 0.2 to 0.4 kWh/m^3 is needed when using the conventional activated sludge (Amy, 2008). In addition to the high energy consumption, the waste management sector has proved to contribute about 3 to 4 percent of the annual global anthropogenic (man-made) GHG emission (IPCC, 2006).

One of the mitigation measures is to apply wastewater treatment options that consume less energy. For instance, a new concept in sanitation aims to offer sustainable alternatives for a number of elements in the urban water cycle. A key sustainability aspect is the aim of recycling nutrients and organic matter via urban, peri-urban and rural agriculture, while making minimal use of natural resources (e.g. water, chemicals and energy). It is often thought that Ecological Sanitation ("EcoSan") by definition uses less energy, and is therefore cleaner with respect to GHG emissions. However, because of the large scale of modern WWTPs, there are also some benefits to expect from this new sanitation. Artificial inorganic fertilizer can be largely replaced by the sanitized EcoSan products. In this system, human excrement is sanitized without water via urine-diverting dehydration toilets (UDDTs), or composting systems and greywater is treated via natural processes for use in agriculture, fish-farming and other applications.

In this regard, various strategies have been developed to face the new challenges of climate change and phosphate shortage. Nevertheless, most research (Chen and Lin, 2008; Lovett *et al.*, 2008; Margarita and Scarlette, 2007; Rasheed, 2008; Vanotti *et al.*, 2008) has concentrated on GHG emissions from conventional waste management, while largely neglecting innovative sanitation practices. The calculation of the overall emissions of each system is a major challenge.

An important starting point for the systematic analysis of sanitation systems is a precise definition of the goal and scope. In Chapter 2, a detailed review of the principal greenhouse gases and their effects is outlined. Different sanitation systems and their potential contributions to the emissions of GHGs are also discussed, together with an overview of methods for estimating GHG emissions. Chapter 3 describes the methodology used in estimating CO_2 and CH_4 and in estimating the amount of energy used in the selected scenarios. The materials used, the data sources and assumptions made are also pointed out. Chapter 4 presents the results from the analysis of the GHG emissions for each of the four systems. The results were also discussed and compared with other sectors. Finally, Chapter 5 summarizes the results and conclusions and recommendations were drawn.

1.2. Research Objectives

This study seeks to analyze four different wastewater treatment configurations: a modern conventional urban wastewater system, a waste stabilization pond system, and two innovative sanitation concepts for separate treatment of urine, faeces, and greywater in order to compare and estimate their ecological impacts on the environment, in terms of energy use and emissions of CH_4 and CO_2. The carbon footprint of each scenario will be calculated, in tons of CO_2 per capita per year.

The goal is to compare different methods and to increase the knowledge on alternative sanitation systems so as:

- To estimate the energy saving and potential GHG emissions for each of the four identified treatment systems.
- To analyze the potential of different sanitation concepts to reduce the emission of GHGs.
- To determine the best combination of sustainable sanitation that produces an optimal reduction of GHG emissions and energy use.

1.3. Research Questions

- How much carbon dioxide and methane are emitted in each of these four wastewater treatment scenarios?
- What are the energy requirements for each of these scenarios?
- How can different scenarios of new sanitation concepts be developed and compared to arrive at an optimal reduction of GHG emissions?
-

1.4. Research Scope

Sanitation in large complex systems is a multi-step process in which waste is managed from the point of generation to the point of reuse or ultimate disposal. This research concentrates on treatment of domestic sewage. Both on-site and off-site solutions are dealt with in the study. Furthermore, treatment processes and energy requirement for the processes are analyzed.

This research analyses the GHG emissions of the following four sanitation systems, focusing on methane and carbon dioxide:

- Full-scale activated sludge plant with biological phosphorus removal. This research considers a full scale plant as one that covers a whole city. An example is Harnaschpolder wastewater treatment plant in Delft, The Netherlands, with capacity 1.3 million.
- Decentralized sanitation and reuse system. In this category, only part of an urban setting or city is being considered. The case studied is in Sneek, the Netherlands, with a conceptual wastewater treatment plant where blackwater and greywater are treated separately treated by an Upflow Anaerobic Sludge Blanket (UASB)-septic tank, Anaerobic Ammonia Oxidation (Anammox), A-B process, and struvite precipitation technologies.
- Waste stabilization ponds system in a warm climate. There are three principal types of waste stabilization pond commonly used in warm climates, namely anaerobic ponds, facultative ponds and maturation ponds. These are usually arranged in series: Anaerobic followed by facultative, then one or two maturation ponds before the water is discharged. The case study of EIER-Ouagadougou, Burkina Faso pilot wastewater treatment plant is considered.
- Urine-diverting dehydration toilet (UDDT) system, where urine and faecal matter are kept separate and treated separately. The case study is located in Siddhipur, Nepal.

Further in this study and for the sake of simplicity the four scenarios are named as followed:

1. **Harnaschpolder** for the full scale activated sludge of Harnaschpolder WWTP in Delft, Netherlands.
2. **Sneek** for the conceptual decentralized WWTP in Sneek, Netherlands.
3. **EIER-Ouaga** for the pilot waste stabilisation pond in Ouagadougou, Burkina Faso
4. **Siddhipur** for the urine-diverting dehydration toilet (UDDT) system in Siddhipur, Nepal

Impacts of the production of construction materials and energy used during construction are excluded. This simplification is based on previous research showing that operational impacts are more important than construction impacts (Lundie *et al.*, 2004).

Therefore stronger focus is given to unit operations of biological treatment processes where large amounts of CO_2 and CH_4 are expected (**Figure 1.2**).

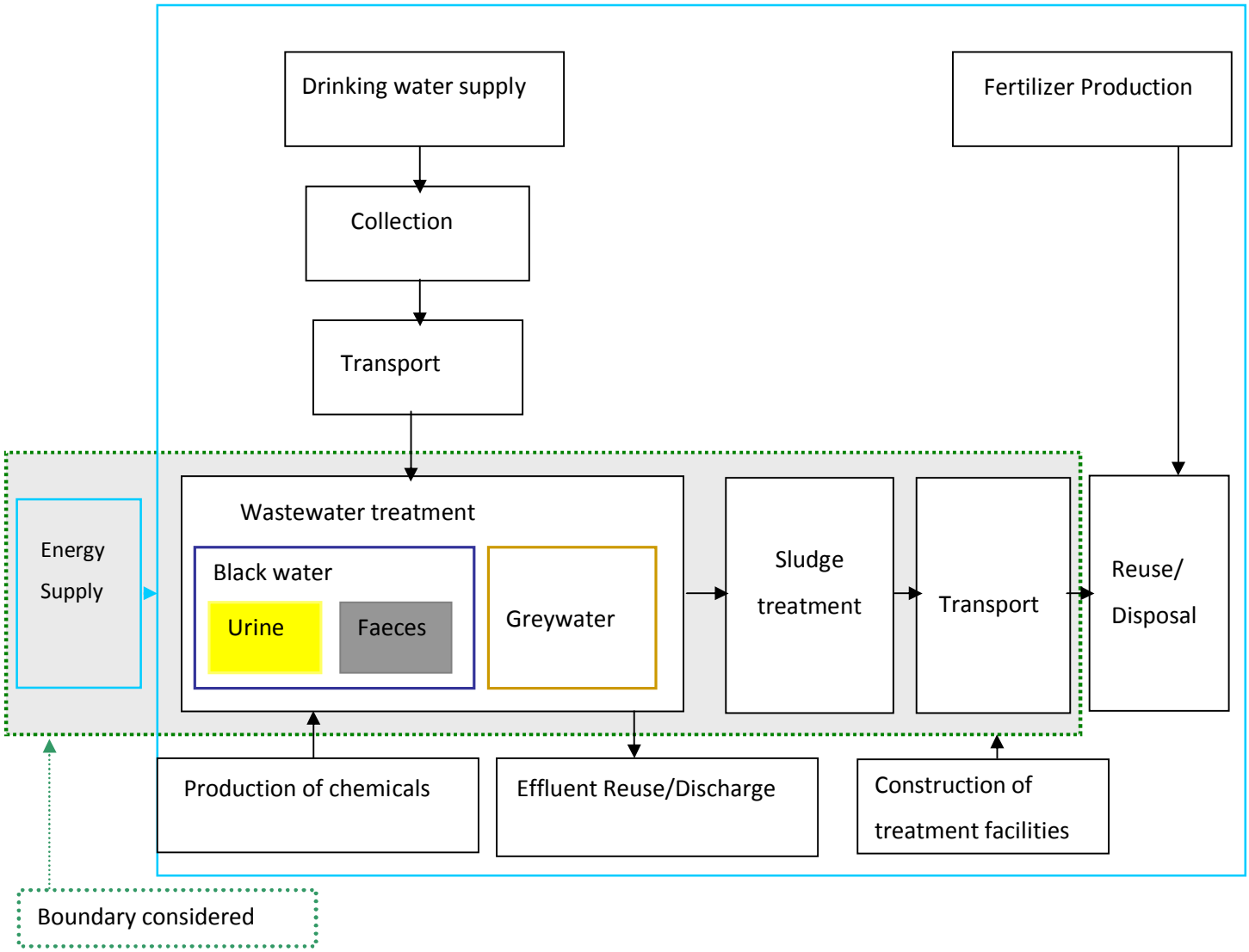


Figure 1.2: A simplified sketch of the parts of wastewater treatment systems, showing the boundary of the systems being considered in this study (green frame)

In **Figure 2.16** the flowchart of the emissions in the full chain of sanitation system and that of producing fossil fuel energy as a reference are defined.

2. LITERATURE REVIEW

In this chapter, a detailed review of principal greenhouse gases and their effects is outlined. Different sanitation systems and their potential contribution to the emissions of GHGs are discussed. An overview of various methods to estimate GHG emissions is also presented.

2.1. Greenhouse Gases (GHGs)

2.1.1. Definition of GHGs

GHGs are those gaseous constituents of the atmosphere, both natural and anthropogenic, that absorb and emit radiation at specific wavelengths within the spectrum of thermal infrared radiation emitted by the Earth's surface, the atmosphere itself, and by clouds. This property causes the Greenhouse Effect.

GHGs are essential to maintaining the temperature of the Earth; without them the planet would be so cold as to be uninhabitable. However, an excess of GHGs can raise the temperature of a planet to lethal levels, as on Venus where the 90 bar partial pressure of carbon dioxide (CO_2) contributes to a surface temperature of about 467°C. GHGs are produced by many natural and industrial processes (Wikipedia).

According to the IPCC (2001), "there is new and stronger evidence that most of the warming observed over the last 50 years is attributable to human activities". The changes are happening faster than any purely natural process and the expected impacts are as unprecedented. Higher temperatures combined with changes in rainfall and water run-off will profoundly affect both natural and human systems. The consequences of this climate change include: reduced food security, loss of life due to catastrophic floods, homelessness, submerging of land due to rising sea level, and increased deaths from diseases such as malaria.

2.1.2 Anthropogenic GHGs

Anthropogenic compounds are compounds created or produced due to human activities (Pankratz, 2001). In disposing of organic materials in landfills, anaerobic bacteria degrade these materials, producing predominantly CH_4 and CO_2. The produced CH_4 is considered anthropogenic CH_4 even though it is derived from biogenic sources since the CH_4 would not have been produced if the materials had not been deposited in a landfill (Rasheed, 2008).

2.1.3. Biogenic GHGs

A compound is considered biogenic when it directly results from natural processes. For instance, the CO_2 released from a landfill may be considered biogenic since it would have been produced by natural decomposition of the organic materials, even if they were not placed in a landfill. Some of the carbon in the organic materials stored in the landfill, due to organic materials is not completely decomposed by anaerobic bacteria.

The storage of carbon would not occur under natural conditions where all the organic materials would degrade to carbon dioxide, thus a landfill may be considered an anthropogenic carbon sink. The capture and combustion of CH_4 from landfills eliminates the release of CH_4 and CO_2 produced is biogenic because it is equivalent to that which would have been produced from natural decomposition of the organic waste materials. The use of the landfill CH_4 as a renewable fuel offsets the GHG emissions that would have been produced from burning non-renewable fossil fuels (Rasheed, 2008).

2.1.4. The Global Warming Potential (GWP)

GWP is an indicator of the Greenhouse Effect caused by the emission of climate-active gases (e.g. CO_2, CH_4, and N_2O) into the atmosphere. Climate change is a global phenomenon and poses serious risks to many regions in the world. The characterization factors are taken from the Intergovernmental Panel on Climate Change (IPCC, 2007) and describe the potential for global warming equivalent to CO_2 as a reference, thus CO_2 is 1, CH_4 is 21, and N_2O is 310. The factors are related to a time horizon of 100 years (GWP_{100a}). CO_2 from renewable sources (e.g. biogas from faeces digestion combusted in a central heating plant) does not increase global warming and is therefore not taken into account as being relevant for climate change.

2.1.5. Global Carbon Cycle

The carbon cycle may be described as the biogeochemical cycle by which carbon is exchanged among the biosphere, pedosphere, geosphere, hydrosphere and atmosphere of the Earth. The cycle is usually thought of as four major reservoirs of carbon interconnected by pathways of exchange. These reservoirs are: The plants; the terrestrial biosphere, which is usually defined to include fresh water systems and non-living organic material, such as soil carbon; the oceans, including dissolved inorganic carbon and living and non-living marine biota; and the sediments including fossil fuels (Wikipedia).

The annual exchanges of carbon among these reservoirs occur because of various chemical, physical, geological, and biological processes. The ocean contains the largest active pool of carbon near the surface of the Earth, but the deep ocean part of this pool does not rapidly exchange with the atmosphere (**Figure 2.1**). The global carbon cycle is affected by human activities and is coupled to other climatological and biogeochemical processes (**Table 2.1**).

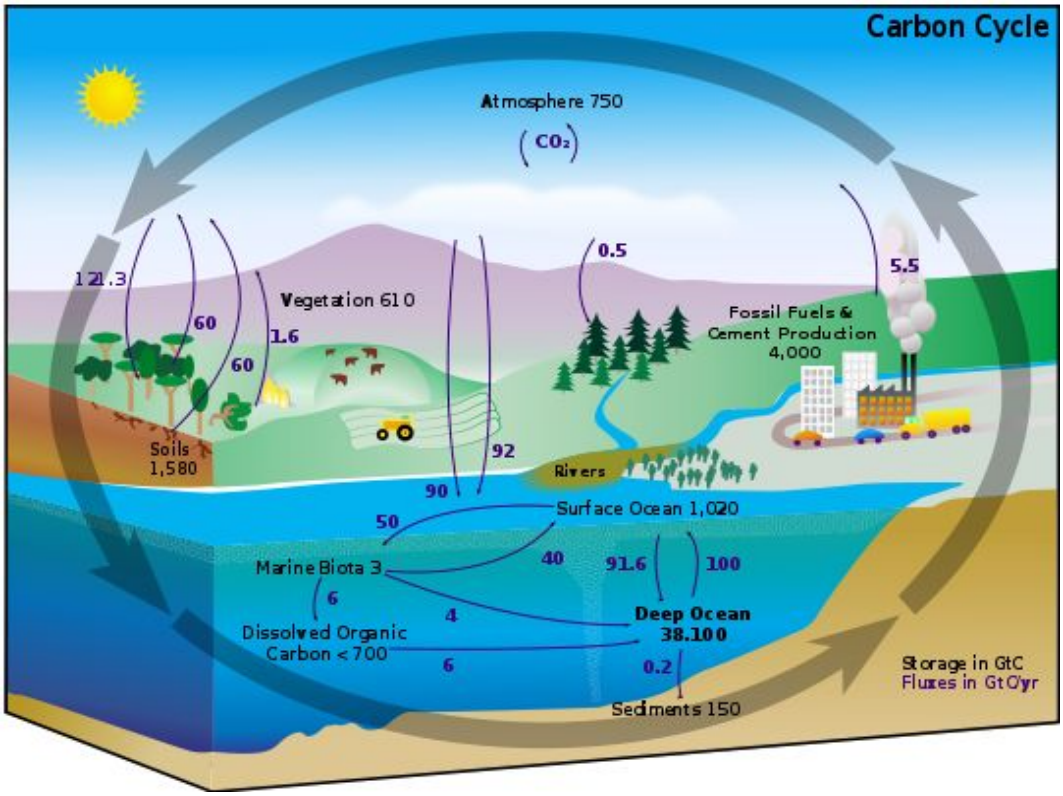


Figure 2.1: A global view of the carbon cycle

http://en.wikipedia.org/wiki/File:Carbon_cycle-cute_diagram.svg

Table 2.1: Carbon pools in the major reservoirs on Earth (Falkowski *et al.*, 2000)

Pools	Quantity (Giga tons)
Atmosphere	720
Oceans	38,400
Total Inorganic	37,400
Surface Layer	670
Deep Layer	36,730
Total Organic	1,000
Lithosphere	
Sedimentary Carbonates	>60,000,000
Kerogens	15,000,000
Terrestrial Biosphere (Total)	2,000
Living Biomass	600-1,1,000
Dead Biomass	1,200
Aquatic Biosphere	1-2
Fossil fuels	4,130
Coal	3,510
Oil	230
Gas	140
Others (Peat)	250

2.1.6. Principal Greenhouse Gases

On Earth, the most abundant GHGs are, in order of relative abundance: water vapour, carbon dioxide, methane, nitrous oxide, ozone, and chlorofluorocarbons (CFCs).

It is important to note that this is a combination of the strength of the Greenhouse Effect of each gas and its abundance. For instance, methane is a much stronger greenhouse gas than CO_2, it is about 21 times more heat absorptive, but is present in much smaller concentrations (Wikipedia).

2.1.6.1 Water Vapour

This is the most important GHG, but it will not be considered in the rest of this analysis because it is present in a relatively constant amount that is not affected by modern human activities.

2.1.6.2 Carbon Dioxide (CO_2)

CO_2 is the most important and abundant GHG that is produced by people. Human activity is not only producing more CO_2 but is also severely damaging the capacity of the Earth to absorb it via natural sinks, such as forests and oceanic plankton. While CO_2 occurs naturally, its concentration in the atmosphere is rapidly increasing due to the burning of fossil fuels like coal, oil and natural gas, plus the burning of forests.

Climate change research points to the direct effect of human activities on the chemical composition of the global atmosphere (IPCC, 2008). In addition, observations of parallel trends in the atmospheric abundances of the $^{13}CO_2$ isotope (Dongarrà and Varrica, 2002) and molecular oxygen (O_2) uniquely identified the increase of CO_2 with anthropogenic sources, particularly fossil fuel burning, cement manufacturing, and deforestation. It is estimated that approximately 27 Gton C have been added to the atmosphere from the burning of fossil fuels since 1850. The present anthropogenic release is about 6 Gton C per year, which is also 100 times the amount released every year by all the volcanoes in the world (Dongarrà and Varrica, 2002). Of the total anthropogenic CO_2 emissions, about half accumulates in the atmosphere. The remainder is being removed by a combination of natural processes. Such a large injection of anthropogenic CO_2 into the atmosphere has caused, during the last 150 years, an increase of the CO_2 level of about 27%.

Massive destruction of forests worldwide results in many fewer trees to take up CO_2. Moreover, the stored CO_2 in the trees is released into the atmosphere, compounding the problem. Thus damage to the planet's carbon sinks through deforestation and ozone layer depletion makes a direct contribution to the enhanced Greenhouse Effect. Atmospheric CO_2 is part of this global carbon cycle and therefore its fate is a complex function of many biogeochemical processes.

Through photosynthesis, trees take up CO_2 from the air. The destruction of forests releases CO_2, thus increasing its levels in the atmosphere. Until some 50 years ago, most of the CO_2 from deforestation was released from temperate zones, but now tropical deforestation is the largest source (Jarvis and Linder, 2000). Tropical forests are being cut and burned for farming, mining and cattle grazing. These activities increase the amount of CO_2 in the atmosphere and also contribute to the loss of biodiversity every year.

According to the IPCC (2006), and Falkowski et al, (2000), CO_2 concentrations in the atmosphere have increased by about 33% since the pre-industrial times, and could double by the year 2065. The IPCC (1996) stated that a doubling of CO_2 would lead to a global temperature rise of 1.5 to 4.5^{o}C.

2.1.6.3 Methane (CH_4)

Methane is the principal natural gas obtained from oil wells and is used for cooking and industrial purposes, including the production of chemical urea for use as an agricultural fertilizer. It is a major GHG, because of its strong global warming potential. Its primary source is the anaerobic decomposition of organic matter in biological systems, such as solid waste and wastewater treatment systems, decomposition of animals, and wetland rice cultivation. It is also a by-product of coal mining incomplete combustion of fossil fuels, and the distribution of petroleum and natural gas. Methane production is dependent on several environmental variables, such as temperature, substrate type and quality, and depth of water table (Stadmark and Leonardson, 2005). In addition, according to Joabsson *et al*, (1999), presence and species composition of vascular plants can affect CH_4 exchange between wetland ecosystems and the atmosphere, because plants affect important aspects of CH_4 dynamics, for instance, production, consumption and transport.

In general, approximately 80% of methane is produced biologically and the principal sources are rice paddies, wetlands, sediments, enteric fermentation, animal waste treatment and landfills under low redox potential conditions by obligate anaerobes (Chatterjee, 2000). The atmospheric concentration of CH_4 has increased by about 50% since the pre-industrial times. The IPCC (2001) stated that over half of the current CH_4 flux in the atmosphere has anthropogenic origins, with agriculture, fossil fuels, and waste disposal being the biggest contributors, while El-Fadel and Massoud (2001) stated that only 30% of the total CH_4 emissions are from natural sources. Methane also escapes from natural gas deposits. CH_4 is abiotically removed from the atmosphere by reacting with hydroxyl radicals (OH) to produce methyl radicals and water vapour and in the stratosphere with chlorine to produce methyl radicals and hydrochloric acid (Reeburgh *et al.*, 1996).

The IPCC (2006) estimates that the atmospheric concentration of CH_4 (with a GWP 21 to 23 times greater than that of CO_2) has increased by 150% to 1,745 ppb since pre-industrial times. Each molecule persists in the atmosphere for about 10 years (Reeburgh *et al.*, 1996). The atmospheric concentrations of CH_4 have more than doubled since the pre-industrial times and according to Stephen (2004) it could double again by 2050 if appropriate measures are not instituted to curtail the current trends.

2.1.6.4 Nitrous oxide (N_2O)

Nitrous oxide (N_2O) is a significant contributor to Global Warming and the destruction of the ozone layer (Wu *et al.*, 2009). It has an atmospheric lifetime of about 120 years, a global warming potential of 310 relative to CO_2 over a 100 year time horizon, and is responsible for about 5% of anticipated warming (IPCC, 2001). The amount of N_2O in the atmosphere is increasing at a rate of only about 0.3% year (Wu *et al.*, 2009).

Anthropogenic sources of N_2O include agricultural soils, fossil fuel combustion, nitric acid production, municipal solid waste, wastewater treatment, combustion and burning of biomass (Chatterjee, 2000). N_2O can be produced during nitrification, and denitrification dissimilatory, reduction of NH_4, NO_3, and chemo-denitrification. Nitrification is the oxidation of NH_4 or NH_3 to NO_3 via NO_2, which is achieved by two steps: first, ammonia-oxidizing bacteria form nitrite, and then nitrite-oxidizing bacteria convert it to nitrate. There are two possible mechanisms of N_2O production during nitrification. Certain nitrifying bacteria generate N_2O from the reduction of NO_2 under oxygen-limited conditions. Alternatively, N_2O can be also produced by chemical decomposition of NO_2 or various reactions of the intermediates formed during NH_4 oxidation (Henze *et al.*, 2008).

The emission of nitrous oxide from WWTPs is relatively small (3% of the estimated total anthropogenic N_2O emission), but is a significant factor (26%) in the GHG footprint of the total water chain. Nitrous oxide is emitted predominantly in the aerated zones, but it remains unclear whether nitrifying or denitrifying micro-organisms are the main source of N_2O emissions (Wu *et al.*, 2009).

According Wu *et al*, (2009), the main operational parameters leading to N_2O emission in WWTPs are: first, the low dissolved oxygen concentration in the nitrification and denitrification stage, second, the increased nitrite concentrations in both the nitrification and denitrification stage, and, third, a low COD/N ratio in the denitrification stage.

The tendency of WWTPs to decrease their energy consumption by decreasing aeration could be adverse with respect to the Greenhouse Effect: even though it decreases CO_2 emission, this could be counteracted by the increased N_2O emission, due to its 310-fold stronger GWP. Rapidly changing process conditions lead to increased N_2O emission, but adaptation can occur if systems repeatedly experience

dynamic conditions. There are indications that growth of nitrifiers and denitrifers on internal storage compounds can lead to N_2O emission, but the mechanism is unclear and scientific findings are contradictory.

2.1.6.5 Ozone (O_3)

Ozone is a powerful GHG, particularly formed in the lower atmosphere (near the ground) from vehicular pollution in the sunlit air. It is produced by the reaction of sunlight on air containing hydrocarbons and nitrogen oxides that react directly at the source of the pollution or many kilometres downwind. The atmospheric lifetime of tropospheric ozone is about 22 days; its main removal mechanisms are deposition on the ground, producing OH, and by reactions with OH and the peroxy radical HO_2 (Wu *et al.*, 2007).

Ozone has been present at the ground level since before the Industrial Revolution; but current peak concentrations are now far higher than the pre-industrial levels. Even background concentrations, well away from sources of pollution, are substantially higher. This increase in ozone raises further concern, because in the upper troposphere it acts as a GHG, absorbing some of the infrared energy emitted by the Earth. The GWP of ozone is difficult to quantify because of its non-uniform concentrations across the globe. However, according to IPCC Third Assessment Report (2001), the radioactive forcing of tropospheric ozone is about 25% that of CO_2 in other words, very low.

2.1.6.6 Chlorofluorocarbons (CFCs)

CFCs are responsible for depletion of stratospheric ozone, but also contribute to the Greenhouse Effect. According to Wu et al, (2009), chlorofluorocarbons are to be phased out totally by 2010 by all countries. It has been reported that industrialized countries have already phased out the use of chlorofluorocarbons.

On the other hand, Hydro fluorocarbons, per fluorocarbons, and sulphur hexafluoride are synthetic, powerful greenhouse gases that are emitted from a variety of industrial processes. Fluorinated gases are sometimes used as substitutes for ozone depleting substances (ODS) (i.e. CFCs, HCFCs, and halons). US EPA (2009) reported that these gases are typically emitted in smaller quantities, but because they are powerful GHGs, they are sometimes referred to as High Global Warming Potential gases.

2.2. Wastewater Treatment and GHGs Sources

The sources of GHGs are from diverse sectors. The major anthropogenic sources of GHG emissions include power stations, industrial processes, transport, agricultural by-products, and land-use-related activities. Industrial and municipal wastewaters are also a source of GHG emissions. Collection and treatment of wastewater are a source of CO_2, CH_4, and N_2O. Similarly, the sludge generated as a by-product of treatment can further undergo microbial decomposition to CH_4 and N_2O. **Figure 2.2** depicts annual GHG emissions by sector.

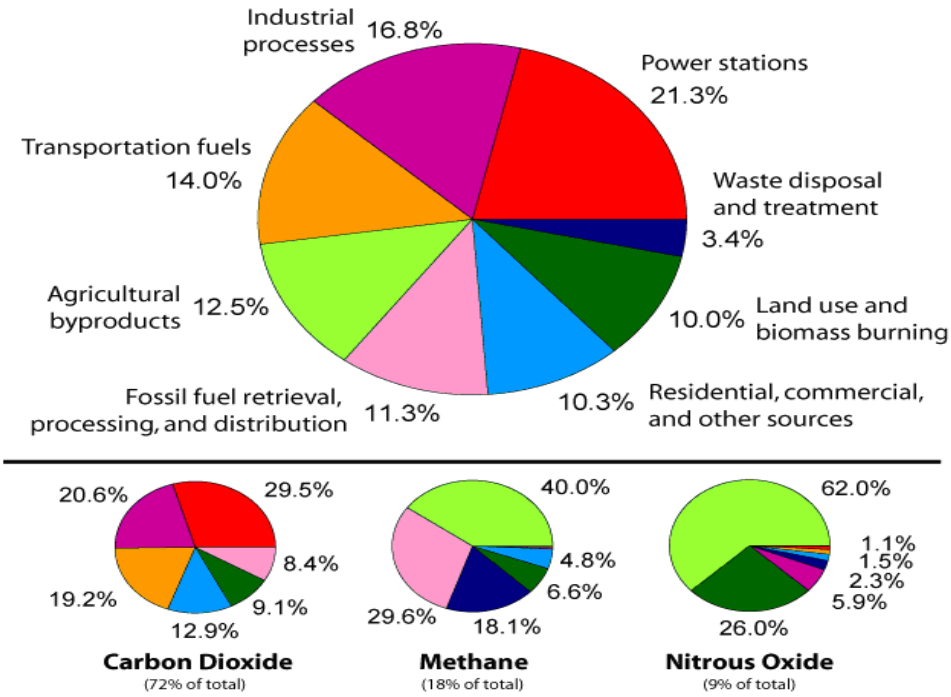


Figure 2.2: Annual GHG emissions by sector
www.globalwarmingart.com/images/e/e0/Greenhouse_Gas_by_Sector.png

2.2.1. Emission of Greenhouse Gases

Generally, GHGs are generated from energy industries, livestock, forestry, agriculture and waste. Greenhouse Gases are also available in the atmosphere in small quantities and they are contributing to Global Warming through their accelerated generation as a result of anthropogenic activities.

The main GHG emissions from waste sectors are

• Wastewater (CH_4, CO_2, and N_2O)

- Landfill (CH_4, and CO_2)
- Open dump (CH_4, and CO_2)
- Uncontrolled burning (CO_2)

Table 2.2: IPCC, 2001a states Human activities which cause GHG emission

GHG	Emission by volume	Human Activities
CO_2	70-72 %	Primarily through the burning of fossil fuels, rapid deforestation
CH_4	About 20%	Fossil fuels [gas pipe line leak, coal mines], Agriculture [rice & cattle farming], industries, solid waste disposal sites
N_2O	6-7%	Agricultural fertilizers, industrial processes, burning fossil fuels, wastewater, composting

2.2.2. Direct and Indirect Measures to avoid GHG

There are a number of ways to avoid the production of GHGs in waste management (**Table 2.3)**. Indirect measures to reduce GHG emissions include decreased waste generation, lower raw material consumption, reduced energy demand and fossil fuel avoidance.

Table 2.3: Direct and Indirect Measures to avoid CH_4 emission (Rasheed, 2008)

Direct Measures to avoid CH4 Emission	Indirect Measures to avoid CH4	Indirect measures to reduce GHGs in general
Landfill CH_4 recovery	Material recovery of recyclable waste	Decreased waste generation
Optimized wastewater treatment	Recycling of greywater	Lower raw materials consumption
Controlled aerobic composting	Waste prevention or Waste minimization	Fossil fuel avoidance
Thermal process such as incineration to convert waste to energy	Reuse of energy produced	Reduced energy demand in general

2.3. Clean Development Mechanisms (CDM)

2.3.1. The Concept of CDM

The Clean Development Mechanism (CDM) and Joint Implementation (JI) are two "flexibility mechanisms" of the Kyoto Protocol intended to allow countries to receive credits for investments in GHG reduction projects anywhere in the world. In both cases, approved methodologies must be used to estimate the emission reduction that the project will achieve against an established baseline. The methodologies for performing these calculations are a product of international agreement, and as such should be considered in developing GHG estimation (IPCC, 2006).

2.3.2. Carbon Trading

Since GHGs are uniformly mixed in the Earth's atmosphere, they impact the climate of the whole world. This fact provides the economic justification for international cooperation on climate change projects and project-based emission trading. This cooperation makes economic sense for the reason that emissions reduction in developing countries costs less than in industrialized countries (Rasheed, 2008).

In the wastewater sector, Rossi *et al*, (2001) proposed a strategy that developed countries could adopt to exchange carbon credits with countries that do not have full wastewater treatment and/or energy recovery. The traditional driving force for the treatment in developed areas is public health and environmental preservation. All these benefits could be exported to developing countries, and can be advantageous for both parties, since the developed countries can obtain carbon emission credits (based on the emissions that the developing country would cause by not performing wastewater treatment) in exchange for exporting wastewater treatment technologies. The receiving urban area would receive public health, environmental, as well as economic benefits (the recovered energy remains in the area, reducing the local demand for fossil fuels, and with additional improvements for the fishing and tourism industries). Equivalent CO_2 emissions from urban wastewater treatment in underdeveloped countries amount to 1.4% of the non-fossil fuel related emissions. Since no country experiences a shortage of wastewater, this strategy for trading (or, better, exchanging) is applicable to all countries. Countries that have ratified the Kyoto Protocol have an additional compelling motive. Performing full wastewater treatment in all urban areas worldwide has substantial economic incentives, but is also a necessity and an obligation towards the sustainable management of the global environment (Rossi *et al.*, 2001).

2.4. Urban Water Systems

Urban areas are part of the wider catchment and interact with the water resources upstream and downstream. There are mainly two approaches of water management in the urban water cycle; the conventional and the new management concept.

2.4.1. Conventional Approach to Urban Water Management

Over a century, the idea of urban drainage has been to remove wastewater from users to prevent unhygienic conditions and to remove storm water to avoid damage from flooding. All this is being done with the aim of not harming the environment (Kärrman, 2001). However, during the last decade the conventional systems (**Figure 2.3**) have been increasingly criticized from the point of view of sustainability. Sustainability is generally based on six important criteria are namely: Socio-cultural, Technical function, Economy, Physical environment, Health, and Institutional. Since different institutions are responsible for the management of each subsystem, analysis of the urban water cycle (UWC) should be done with a catchment perspective, because problems encountered in the UWC may have their origin in the catchment operation of the urban water cycle, causing problems downstream (Steen, 2007).

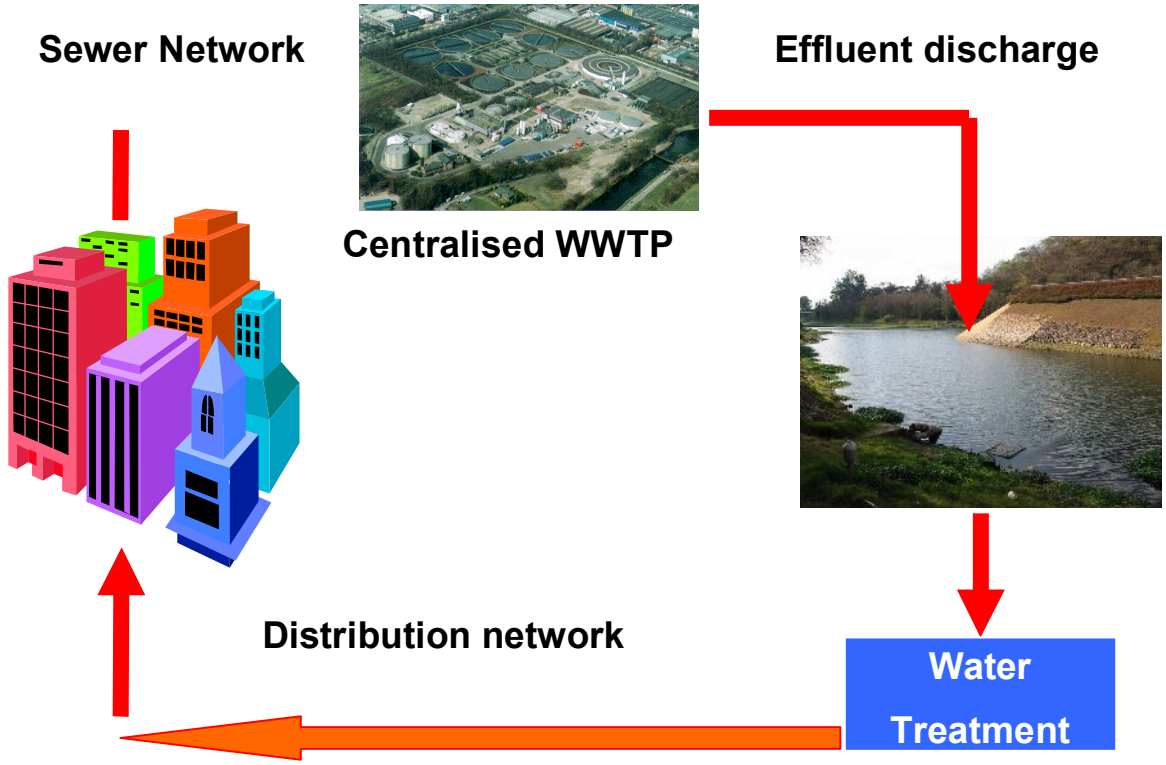


Figure 2.3: Conventional approach of urban water cycle (Hubbert, 2008)

2.4.2. Innovative Approaches to Urban Water Management

To prepare the urban centres of the world for future changes and global pressures (population growth, climate change, land use change etc.), it is believed that a sustainable and integrated urban water management is necessary to address these changes (Steen, 2007).

Analysis of the entire urban water system will lead to the identification of opportunities that are not apparent when sub-systems are analysed separately.

- Water Demand Management will reduce cost of Wastewater Treatment and/or will improve WWTP effluent quality and save energy.
- More reuse opportunities will be identified (industry, agriculture, urban landscaping).

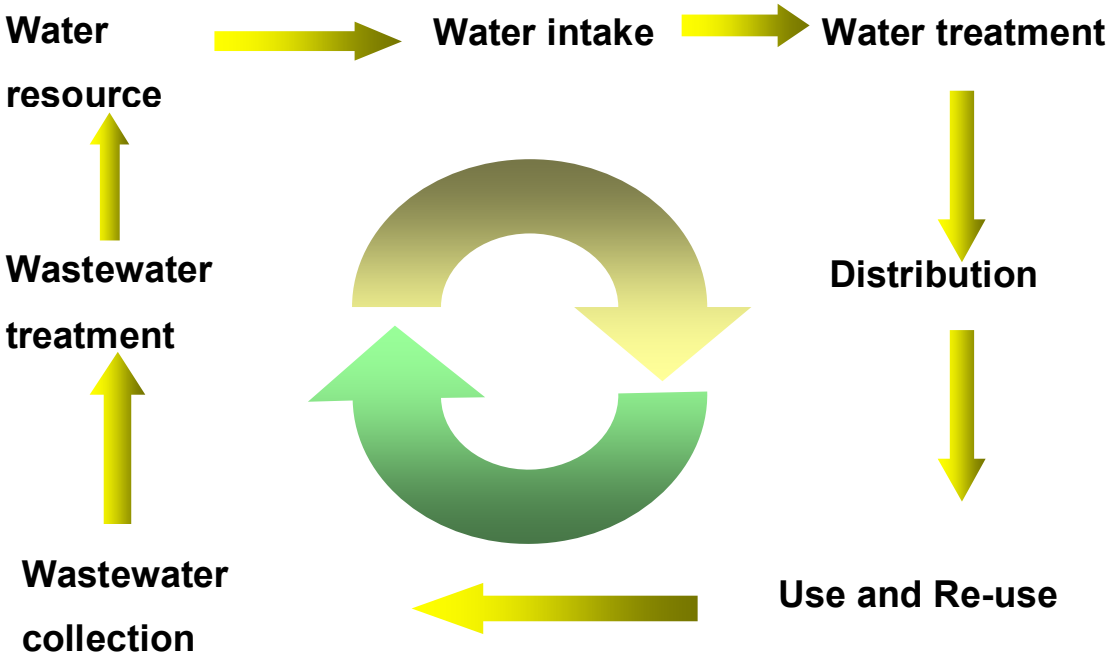


Figure 2.4: Innovative approach of urban water cycle (Steen, 2007)

In this new approach, the management of the urban water cycle and its individual stages is done in an integrated way, which means that management of on stage takes into account interactions with other stages. Management of one stage may well be through changing something in another stage.

2.5. Overview of Sanitation Systems

Sanitation, which is a sub-system of the urban water cycle, is a large and complex system. It is a multi-step process in which wastes are managed from the point of generation to the point of use or ultimate disposal.

However, there are two main approaches to sanitation systems. The first one is the traditional (conventional) way of managing our wastes, "flush-and-discharge" and "drop-and-store", while the second one may be adapted to the category of "sanitize-and-recycle", known as Ecological Sanitation (EcoSan) (Esrey *et al.*, 1998).

2.5.1. Conventional Sanitation Systems

Every community produces both liquid and solid wastes and air emissions. The liquid waste (wastewater) is essentially the water supply to the community after it has been used in a variety of applications. From the standpoint of sources of generation, wastewater may be defined as a combination of the water-borne wastes removed from residences, institutions, and commercial and industrial establishments, together with such groundwater, surface water, and storm water as may get mixed in. The amount of wastewater and pollutants from households varies from country to country. These variations are influenced by the climate, socio-economic factors, household technology and other considerations (**Table 2.4**).

It is undeniable that sewage has long been considered a potential health risk and a nuisance to urban agglomerations (Henze *et al.*, 2008).

Table 2.4: Variation in Wastewater Parameters across Different Countries (Metcalf and Eddy, 2003)

Country	Parameters (g/capita/day)				
	BOD	TSS	TKN	NH3-N	Total P
Brazil	55 – 68	55 – 68	8 – 14	ND	0.6 – 1
Denmark	55 – 68	82 – 96	14 – 19	ND	1.5 - 2
Egypt	27 – 41	41 – 68	8 – 14	ND	0.4 – 0.6
Germany	55 – 68	82 – 96	11 – 16	ND	1.2 – 1.6
Greece	55 – 60	ND	ND	8 – 10	1.2 – 1.5
India	27 – 41	ND	ND	ND	ND
Italy	49 – 60	55 – 82	8 – 14	ND	0.6 – 1
Japan	40 – 45	ND	1 – 3	ND	0.15 – 0.4
Palestine	32 – 68	52 – 72	4 – 7	3 – 5	0.4 – 0.7
Sweden	68 – 82	82 – 96	11 – 16	ND	0.8 – 1.2
Turkey	27 – 50	41 – 68	8 – 14	9 – 11	0.4 – 2
Uganda	55 – 68	41 – 55	8 -14	ND	0.4 – 0.6
United States	50 - 120	60 - 150	9 – 22	5 – 12	2.7 – 4.5

[ND = Not Determined]

When untreated wastewater accumulates and become anaerobic, the decomposition of organic matter it contains will lead to nuisance conditions including the production of malodorous gases, such as hydroxide sulphide (H_2S), and some GHGs (CH_4, CO_2, N_2O). Furthermore, untreated wastewater contains numerous pathogenic microorganisms that reside in the human intestinal tract. Wastewater also contains nutrients, which can stimulate the growth of aquatic plants, and may contain toxic compounds that potentially may be mutagenic or carcinogenic. For these reasons, the immediate and nuisance-free removal of wastewater from its sources of generation, followed by treatment, reuse, or disposal into the environment is necessary to protect public health and the environment (Metcalf and Eddy, 2003).

The historical development of wastewater treatment technology has led to an ever-expanding sequence of treatment steps, and a significant increase in the cost of building and operating treatment plants. Moreover, operating treatment plants often require advanced skills and knowledge (Zhang, 2008).

In the beginning, sedimentation was sufficient. However, it led to severe environmental impacts on the receiving waters and therefore biological wastewater treatment was then developed. Biological treatment was firstly aimed at the biodegradation of the organic matter. Soon, it became obvious that high concentration of ammonia caused oxygen depletion in the receiving water. Thus, a nitrification process, based on the oxidation of ammonia to nitrogen, was introduced. Still, the water quality in rivers deteriorated due to eutrophication. Denitrification and phosphorus removal technologies were added as further treatment steps. Disinfection technology to lower the concentration of bacteria and viruses is considered as an additional step in order to protect the quality of the receiving waters (Henze *et al.*, 2008).

There exists a large variety of conventional wastewater treatment processes, and the most common ones are:

- Activated sludge systems
- Stabilization ponds
- Anaerobic reactors
- Land disposal systems
- Aerobic biofilm reactors

Zhang (2008) implied another critical technological concern is the terminal product generated by the treatment approach currently applied. The traditional processes are focused on conversion of the wastewater constituents into inorganic products such as carbon dioxide (CO_2) and water (H_2O). However, it would be economically and ecologically far more advantageous to focus the treatment process on the production of resources, e.g., methane (CH_4), fertilizer, energy CHP (cogeneration of heat and power).

In the following sections, we will discuss the main treatment options in the wastewater sector.

2.5.1.1 Activated Sludge Systems

The activated sludge process is the most commonly used technology for biological wastewater treatment to remove COD, N, and P. It consists of two stages: a biological stage (anaerobic, anoxic and aerobic tanks) and a physical stage (clarifiers) (**Figure 2.5**). Segregation of the bioreactor into anaerobic, anoxic,

and aerobic zones distinguishes biological nutrient removal (BNR) systems from other activated sludge systems. Anaerobic zones allow for selection of phosphorus accumulating organisms (PAOs), thereby increasing the phosphorus content of the mixed liquor suspended solid (MLSS) and allowing phosphorus removal in the waste solids. Anoxic zones allow for denitrification, thereby removing nitrogen as N_2. Aerobic zones are necessary for the growth of nitrifying bacteria and PAOs (Brjdanovic, 2008).

Activated sludge systems have been successfully used for carbon removal for almost a century. In recent decades, activated sludge nutrient removal has been explored, tested and widely introduced. The growing public concern for environmental protection has led to the implementation of continuously increasing effluent standards. Research towards new techniques for upgrading treatments plants without the need for expansion of existing volumes has therefore advanced.

Several processes and technologies have been studied and proposed to activated sludge market over recent years: SHARON, a simple system for N-removal over nitrite (Ahn, 2006), Anammox (fully autotrophic N-removal) (Waki *et al.*, 2007); CANON, combination of nitrification and anaerobic ammonia oxidation (Third *et al.*, 2001) etc…

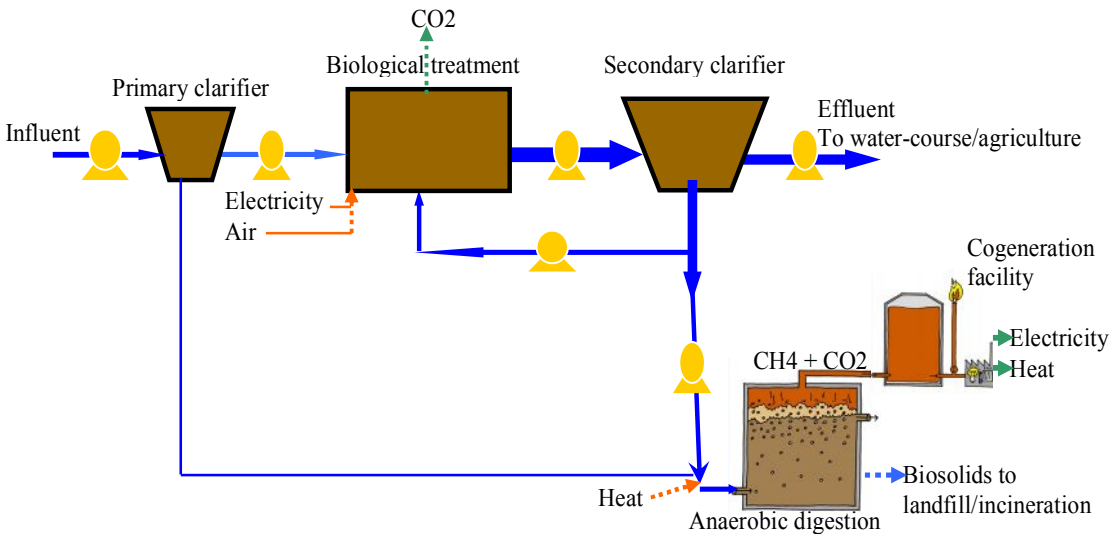


Figure 2.5: Schematic of a typical activated wastewater treatment plant

Despite their successful application, activated sludge systems also impact negatively the environment. One of the major impacts of activated sludge treatment option is their high energy consumption, which

indirectly emits CO_2 via the burning of fossils fuels. Aeration is an essential process in the majority of wastewater treatment plants and accounts for 45 to 75% of their energy expenditure (Henze *et al.*, 2008). Another impact of activated sludge systems is the emission of GHGs (CO_2, CH_4, and N_2O). First, in the aerobic oxidation tanks, organic molecules are metabolized to CO_2 and H_2O, which go directly to the atmosphere. Second, the ammonia in the wastewater undergoes subsequent transformations. In the process of nitrification, the ammonia is oxidized to nitrite and the nitrite to nitrate. In the process of denitrification the nitrate are reduced to nitrogen gas. In both of these processes, N_2O is produced. Then, the third and last aspect of impact can be positive or negative, depending on whether the gases (CH_4 and CO_2) are collected or not during the anaerobic digestion of the sludge.

2.5.1.2 Stabilization Ponds

Stabilization ponds are units specially designed and built with the purpose of treating sewage. However, the construction is simple and is principally based on earth movement for digging, filling and embankment preparation. This treatment system consists of a series of Anaerobic, Facultative, and Maturation ponds (**Figure 2.6**).

Wastewater treatment via stabilisation ponds refers to the aerobic or anaerobic degradation of organic matter; since both aerobic and anaerobic bacteria contribute to waste stabilisation. The oxygen required for aerobic stabilisation is produced by photosynthesis, and waste stabilisation ponds are therefore typical natural systems which do not require any electricity for oxygen input (Marcos and Carlos Augusto, 2005). Aside from their effective BOD removal, waste stabilization ponds are also simple and cheap to build, operate and maintain; they have low (if any) energy requirements, and sludge management is simple. They are widespread due to their very effective removal of pathogens, and their effluent is therefore suitable for reuse.

On the other hand, this treatment option impacts negatively on the environment. For instance: large areas are required, the performance is strongly affected by temperature, there is a low degree of operational control, and finally they have a high potential for producing malodorous gases, especially at the anaerobic ponds.

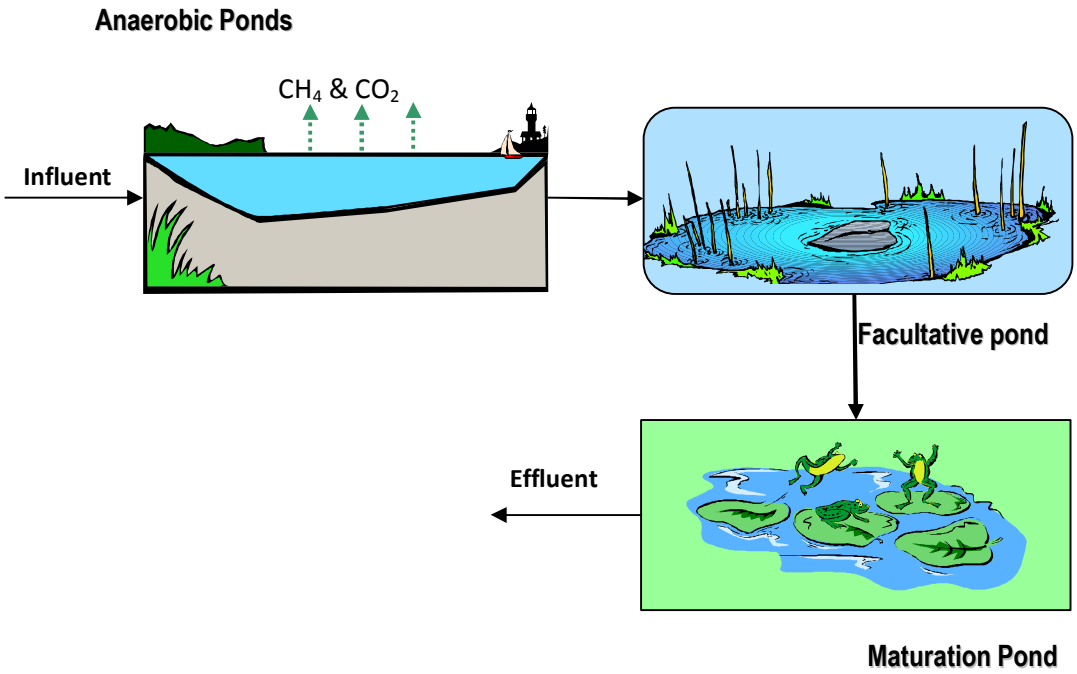


Figure 2.6: Schematic views of waste stabilization ponds

2.5.1.3 Anaerobic Reactors

The fermentation process in which organic material is degraded and biogas (composed of mainly CH_4 and CO_2) is produced, is referred to as anaerobic digestion. Anaerobic digestion processes occur in many places where organic material is available and redox potential is low (zero oxygen). This is typically the case in the stomachs of ruminants, in marshes, sediments of lakes and ditches, municipal landfills, or even municipal sewers.

Generally, the anaerobic process involves four key biological and chemical stages: hydrolysis, acidogenesis, acetogenesis and methanogenesis.

The simplified reaction sequences of the four key processes are represented and discussed below:

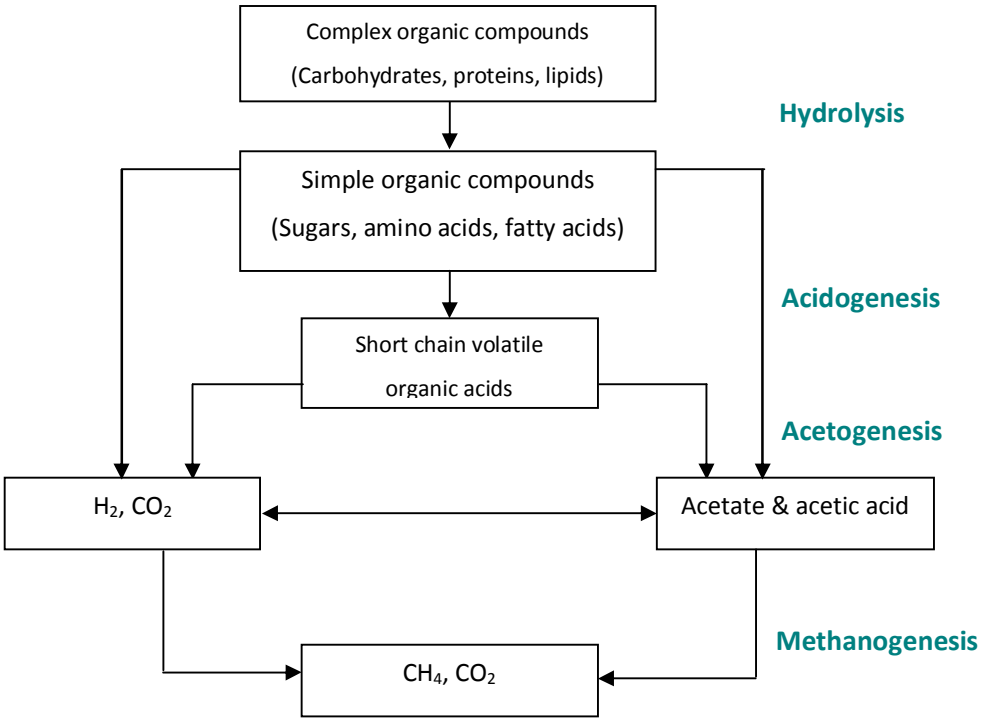


Figure 2.7: Reaction sequence for the anaerobic digestion of complex macromolecules
(Haandel and Lettinga**,** 1994)

♦ **Hydrolysis**

In this first step of the anaerobic process, long-chain polymeric and complex organic molecules are broken down into smaller ones, such as carbohydrates, proteins, lipids and dissolving the smaller molecules into solution. Through hydrolysis, the complex organic molecules are broken down into simple sugars, amino acids, and fatty acids. The resultant molecules are subsequently used in the second stage of the anaerobic process: acidogenesis. The acetate and hydrogen produced in this stage can be consumed directly by methane-producing bacteria (methanogens). In practice, the speed of this step can be limiting for the overall rate of anaerobic digestion. For example, the conversion rate of lipids becomes very slow below 20˚C (Haandel and Lettinga, 1994).

♦ **Acidogenesis**

This second step of this biological process involves the further breakdown of the remaining components by acidogenic bacteria. Here, a soluble mix of short-chain volatile fatty acids (VFAs), such as acetic, alcohols, formic, propionic, lactic acids and acetates are created, along with ammonia, carbon dioxide

and hydrogen sulphide, and other by-products. This fermentation is carried out by a diverse group of bacteria, most of which are obligate anaerobes.

♦ **Acetogenesis**

The third stage in anaerobic digestion is acetogenesis. In this step, the products of acidogenesis are further digested by acetogens to produce largely acetic acid, as well as carbon dioxide and hydrogen; the key substrates for methanogens (methane-producing bacteria) in the final stage of anaerobic digestion. This stage regulates the cumulative concentrations of VFAs, which affect the subsequent stage.

♦ **Methanogenesis**

The final stage of anaerobic digestion is the biological process of methane formation. In this case, methane-producing bacteria take up the intermediate products of the preceding stages and convert them into the two most important GHGs (CH_4 and CO_2) and water. Methanogenesis is sensitive to both high and low pHs and occurs between pH 6.5 and pH 8. According to Haandel and Lettinga (1994), methanogenesis is often the rate limiting of the entire anaerobic digestion process because it has a cell 'doubling time' of a few days compared with the few hours required for acetogenic bacteria. The following simplified generic equation may represent the overall anaerobic processes (Haandel and Lettinga, 1994):

$$C_x H_y O_z + (\frac{4x + y - 2z}{4}) * H_2O \rightarrow (\frac{4x - y - 2z}{8}) * CO_2 + (\frac{4x - y - 2z}{8}) * CH_4$$

Where: $C_xH_yO_z$ is the organic matter.

There are many types of anaerobic reactors. This section only presents the most widely applied design for domestic sewage treatment:

♦ Anaerobic filter

The organic pollutant is converted anaerobically (**Figure 2.7**) by bacteria that grow attached to a support medium (usually stones) in the reactor (**Figure 2.8**). The system requires a primary sedimentation tank (frequently septic tanks). The sludge production is low and the excess that is already stabilised can be reused or disposed of.

In most of these types of system the GHGs (CH_4, CO_2, and N_2O) produced are emitted directly into the atmosphere. Therefore, they contribute to the actual GHGs concentration in the atmosphere.

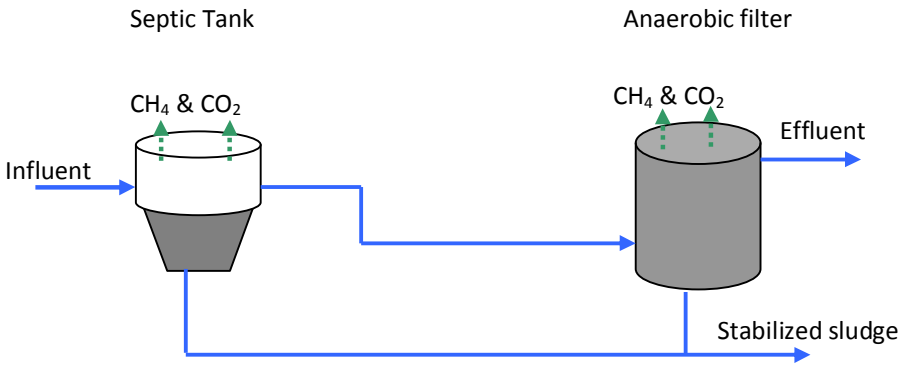


Figure 2.8: Schematic view of an anaerobic filter system

♦ UASB (Upflow Anaerobic Sludge Blanket) reactor

The BOD is converted anaerobically (**Figure 2.7**) by bacteria dispersed in the reactor. The liquid flow is upwards. The upper part of the reactor is divided into settling and gas collection zones (**Figure 2.9**). The settling zone allows the exit of clarified effluent in the upper part and the return of the solids (biomass) by gravity to the system, increasing its concentration in the reactor. Among the gases formed are CH_4, CO_2 and H_2S, which are collected and used to produce electricity. The system has no primary sedimentation, the sludge production is low, and the excess sludge is already thickened and stabilised.

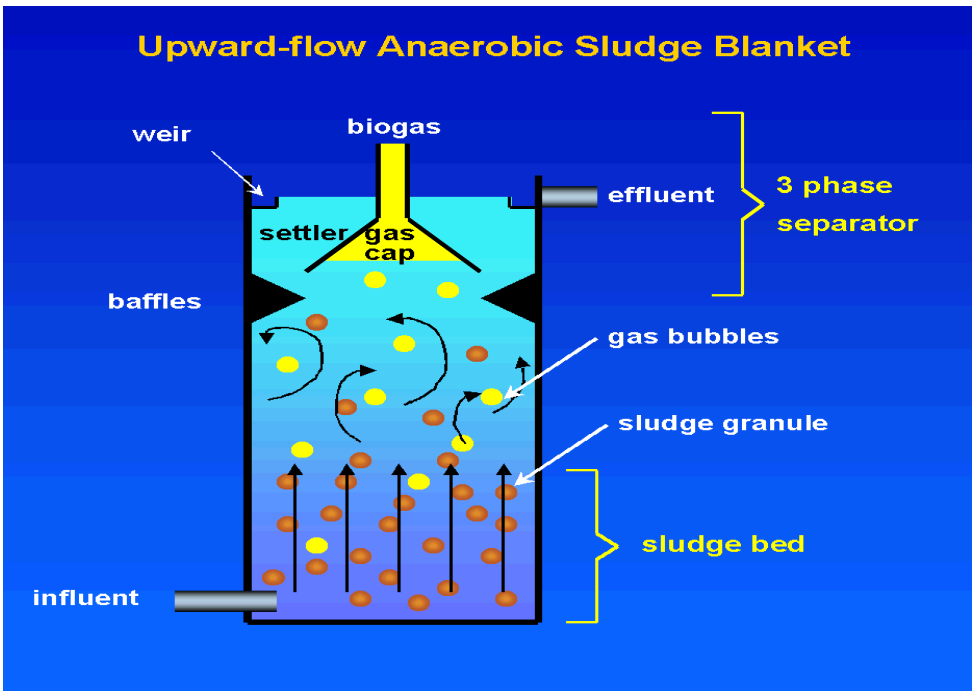


Figure 2.9: The upward-flow anaerobic sludge bed (UASB) reactor concept
www.uasb.org/discover/agsb.htm#history

2.5.1.4 Land Disposal Systems

- The most common destinations for the final disposal of treated liquid effluents are water courses and sea. However, land disposal is also a viable process, applied in various locations around the world.
- Land application of wastewater leads to groundwater recharge and or to evapotranspiration. Sewage supplies the plants with water and nutrients.
- Various mechanisms in the soil are responsible for the removal of the pollutants (Marcos and Carlos Augusto, 2005):
  - ♦ Physical (settling, filtration, radiation, volatilisation, dehydration);
  - ♦ Chemical (oxidation and chemical reactions, precipitation, adsorption, ion exchange, complexation, photochemical breakdown);
  - ♦ Biological (biodegradation and predation).
- The most common types of land application are :
  - ♦ Soil-based systems, i.e. Soil Aquifer Treatment (SAT);
  - ♦ Water-based systems, i.e. Constructed Wetlands (CW).

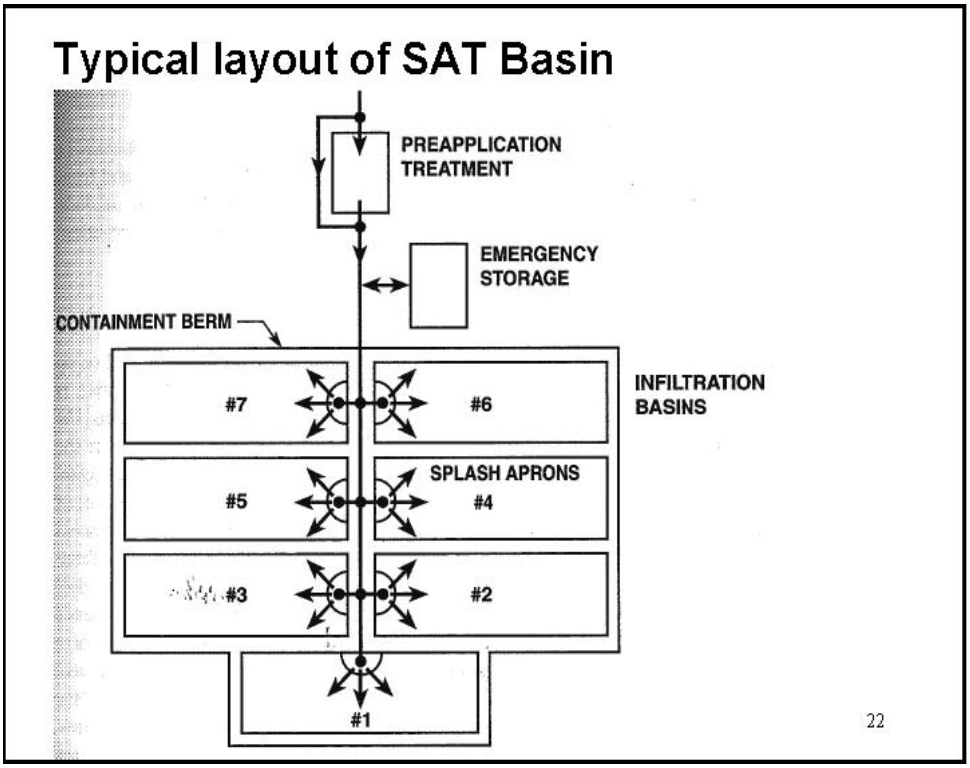


Figure 2.10: Layout of soil aquifer treatment system (Sharma and Amy, 2008)

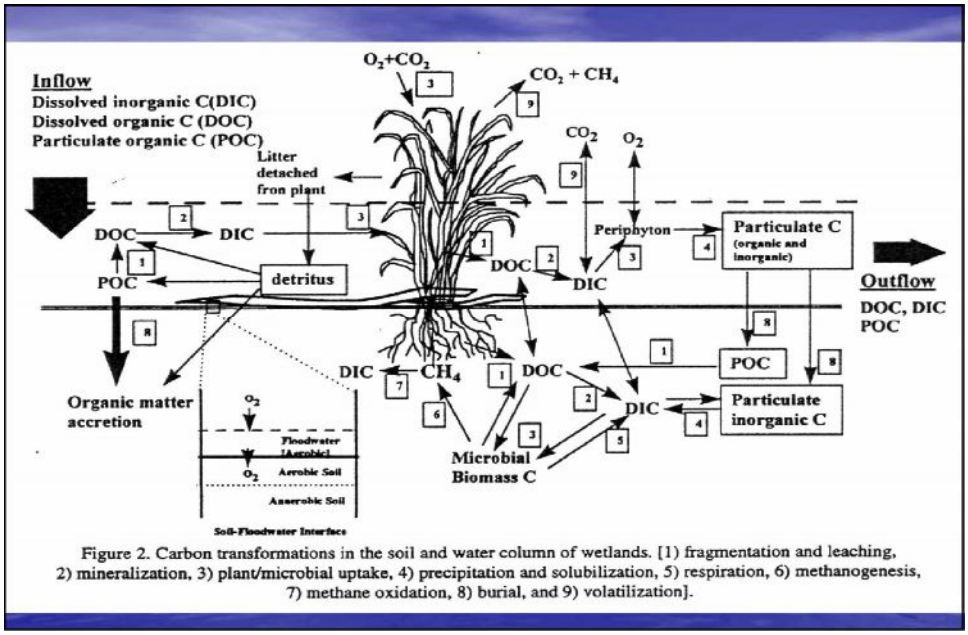


Figure 2. Carbon transformations in the soil and water column of wetlands. [1) fragmentation and leaching, 2) mineralization, 3) plant/microbial uptake, 4) precipitation and solubilization, 5) respiration, 6) methanogenesis, 7) methane oxidation, 8) burial, and 9) volatilization].

Figure 2.11: Organic matter transformation in constructed wetlands systems (Rousseau, 2008)

Despite their advantages to remove pathogens from wastewater, to recharge groundwater, land application systems are also known to be sources of GHG (CH_4, CO_2, N_2O) emissions in the atmosphere (Picek *et al.*, 2007).

On the other hand, constructed wetlands (CWs) are widely used for wastewater treatment and have many advantages, including low cost and easy operation and maintenance (Inamori *et al.*, 2008). CWs may provide both aerobic and anaerobic conditions conducive to microorganism-mediated removal of organic contaminants and nutrients, especially nitrogen. However, the sustainable operation of the system depends upon a highly effective conversion of pollutants to gaseous products undergoing anaerobic and aerobic processes, which produce gases including N_2O and CH_4 (**Figure 2.11**).

2.5.2. Innovative Sanitation Systems

2.5.2.1 Ecological Sanitation (EcoSan)

♦ **The Concept of EcoSan**

Ecological Sanitation, known as "EcoSan", is an alternative to conventional sanitation. It is based on an ecosystem approach, a holistic view of material flows. Human urine and faeces are regarded as a valuable resource to be recycled, not to be disposed as a waste. It is a new philosophy, or paradigm shift, concerning how people should best interact with the environment.

EcoSan is not a single, specific technology; but rather a concept that advocates closing the loop of nutrients between sanitation and agriculture, while still breaking the loop of disease transmission (Esrey *et al.*, 1998). EcoSan also uses natural processes to achieve these goals (**Figure 2.12**).

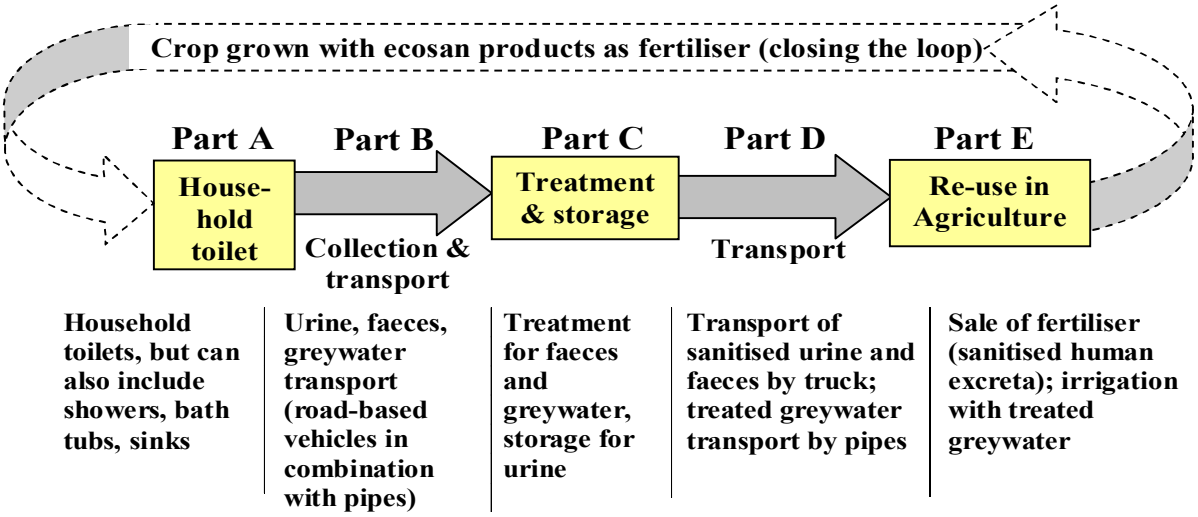


Figure 2.12: Summary of the concept of EcoSan (Ronteltap, 2008)

2.5.2.2 EcoSan Based on Dehydration

In a Urine-diverting Dehydration Toilet (UDDT) faeces are dried with the help of absorbent dry material, ventilation, and sometimes heat (Esrey *et al.*, 1998). Dehydration vaults or receptacles are used to collect, store and dry faeces, which will should be protected against external moisture entering, while urine and anal cleansing water are diverted elsewhere (Tilley *et al.*, 2008).

The use of specialized collection devices (squatting pans or seat risers), which divert urine for storage in a separate container, allows the faeces to be dehydrated fairly easily. UDDTs have various local names

and variations, including the Vietnamese Double Vaults (**Figure 2.13**).

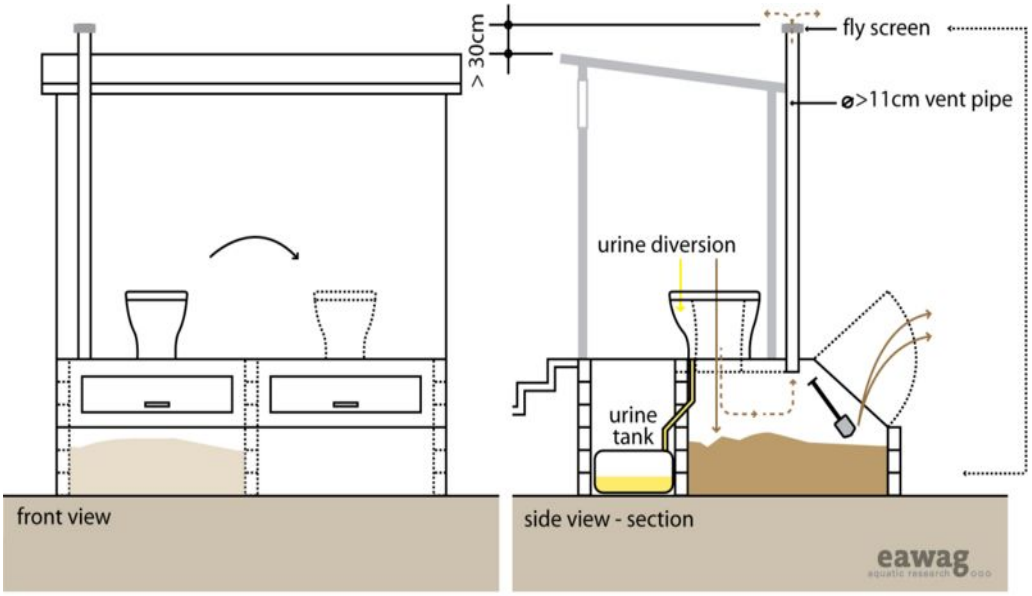


Figure 2.13: Urine diverting dehydration toilet (AKVO)

2.5.2.3 EcoSan Based on Composting

Composting refers to the process by which biodegradable components (organic matter) are biologically decomposed, under controlled, aerobic conditions, by microorganisms (mainly bacteria and fungi). This technology usually requires four main parts (Tilley *et al.*, 2008):

- A reactor (storage chamber);
- A ventilation unit to provide oxygen and allow gases (CO2, water vapour) to escape;
- A leachate collection system; and
- An access door to remove the mature product as shown in the figure below.

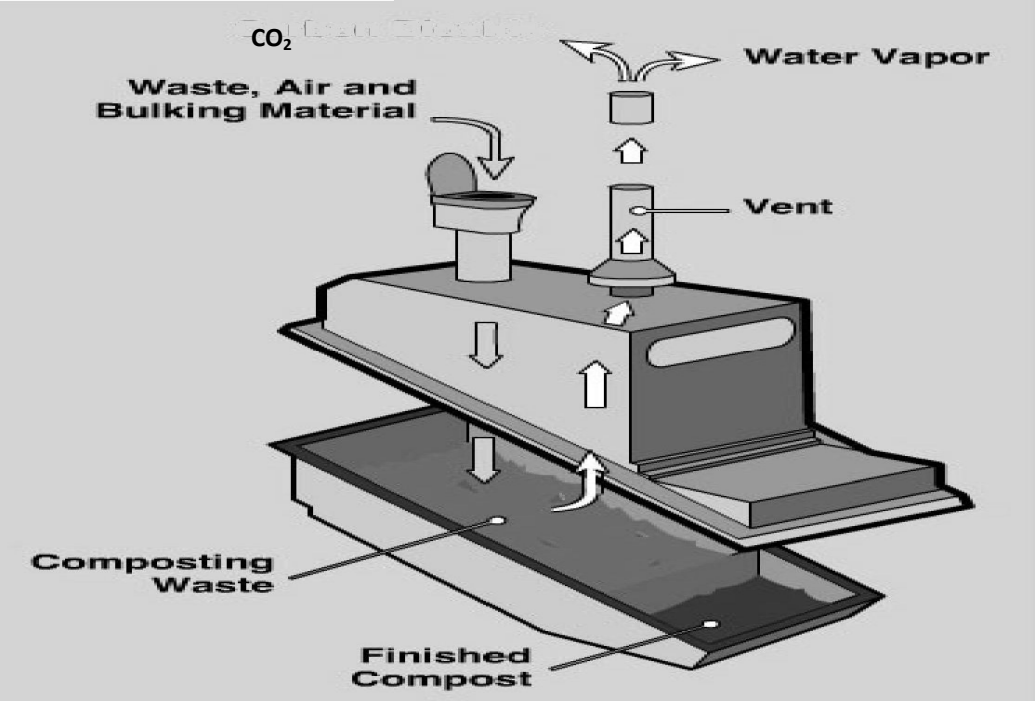


Figure 2.14: composting chamber with a UDDT (Dinuccio *et al.*, 2008)

Various configurations exist for a composting chamber, including continuous systems and batch systems: The “Clivus Multrum” single vault composting toilet in Sweden; the “Carousel” multiple-vault composting toilet in Norway; the “Sirdo Seco” solar heated composting toilet in Mexico, are some few examples (Esrey *et al.*, 1998). The composting chamber can be constructed above or below ground (depending on local conditions), and a UDDT can also be used as a user interface.

For urban centres, composting in receptacles is a popular method of recycling the food waste, faeces and portion of municipal solid waste, thus reducing the amount sent to landfills (USEPA, 2000). Composting is a biological process which reduces the volume and mass of solid organic wastes, while producing a safe, stabilized and nutrient-rich soil amendment (Adhikari *et al.*, 2009). It also reduces emissions of GHGs and generates less leachate.

2.5.2.4 EcoSan and Millennium Development Goals (MDGs)

EcoSan can contribute very directly to the achievement of MDGs 1, 4 and 7 (**Table 2.5**). Most the developing countries can note afford the expensive centralized WWT, and more than 40% of the world population are living in those countries. Therefore, it believes that applying quick Ecosan solutions will make such a great impact in the achievement of the MDGs.

Table 2.5: Contributions of EcoSan to MDGs

MDG	Quick Win Solution	EcoSan contribution
Goal 1: Eradicate extreme poverty and hunger	Affordable fertilisers Training in health & farming	Sanitised human excreta to be reused as fertiliser and soil conditioner
Goal 4: Reduce child mortality	Faster, decentralized implementation	Better nutrition; Control of water-borne diseases
Goal 7: Ensure environmental sustainability	Access to sanitation for schools; Provide soil nutrients	Reduced demand for chemical fertilisers; Less GHGs; Biogas for energy; Improved living conditions in slums

Adapted from: (von Münch *et al.* 2006)

2.6. Overview of Energy Used in Sanitation Systems

2.6.1. Energy and MDGs

Energy is central to sustainable development and poverty reduction efforts. It affects all aspects of development: social, economic, and environmental, including livelihoods, access to water, agricultural productivity, health, population levels, education, and gender related issues. None of the Millennium Development Goals (MDGs) can be met without major improvement in the quality and quantity of energy services in developing countries (Klemes and Pierucci, 2008).

Global Warming is increasingly becoming recognized as one of Humanity's major technological, social, and political challenges, and it is closely related to energy generation and exploitation. Klemes and Pierucci (2008) stated that between 1900 and 1955 the average rate of global energy use rose from

about 1 to 2 Tera Watts (TW). However, between 1955 and 1999, energy use rose from 2 TW to about 12 TW. Furthermore, it was estimated in 2006 that an additional 16% growth in primary energy use worldwide had occurred. Klemes and Pierucci (2008) quoted recommendations provided by the UK Royal Commission on Environmental Pollution and subsequently supported by others in the UK. They conclude that we need to reduce CO2 emissions by over 50% to stabilize impacts on Global Warming. Then, they concluded that one way in which this problem could be addressed is by judicious use of process intensification technology. This is defined as "any engineering development that leads to a substantially smaller, cleaner, safer and more energy-efficient technology".

2.6.2. The Cumulative Energy Demand (CED)

The CED is a measure for the use of primary energy for a certain product or service, including all relevant preparatory inputs, such as the production of raw materials, transport, etc. All forms of primary energy are considered, including non-renewable energy sources (e.g., fossil fuels, uranium) and renewable ones (e.g., solar or wind power). An index usually indicates if a certain form of CED is meant (e.g. CED_{fossil} for fossil fuels only). This indicator summarizes the energy demand for a product or service and is based on large databases, where CED has been calculated for a multitude of materials, electric power generation processes, modes of transport, etc. CED is relatively easy to determine and hence is seen as a simple indicator to assess the overall environmental impacts related to energy demand.

2.6.3. Energy Survey in the Treatment Process of Wastewater

Energy surveys can vary in complexity, but a complete energy audit should answer the following questions:

- How much electricity is being used and at what time of the day?
- How much is the utility charging for power?
- How efficient is the equipment?
- Can a change in the process result in improving energy use?

According to the US Environmental Protection Agency Bureau of Land & Water Quality (October 2002) Newsletter, there are three general levels of energy surveys:

- a **desktop survey** which involves an analysis of billing data to understand current electricity use (kWh) and peak demand (kW);

- a **walkthrough survey** that requires a brief inspection of the facility, all the equipment and methods of operation, plus billing data is also analyzed;
- a **detailed survey** that requires an in-depth inspection and analysis of the facility, including all energy-consuming systems, such as motors, pumps and lighting.

In the case of wastewater treatment plants, the areas that must be most considered are:

- Pumping;
- Aeration (compressors, etc.);
- Sludge handling and disposal (centrifugal thickeners, energy required to heat up the digesters, etc.);
- Lift stations of wastewater;
- Lighting.

The operational requirements for wastewater collection and treatment systems vary directly according to the wastewater load. In the conventional secondary treatment, most of the electricity is used for the biological treatment by either the activated sludge process that requires energy for aeration or trickling filters that require energy for influent pumping and effluent recirculation, pumping systems for the transfer of wastewater, liquid sludge, drying of solids and biosolids. A typical distribution of energy use in a conventional activated sludge treatment plant, the most common type of plant used in wastewater treatment, is illustrated in F**igure 2.15**.

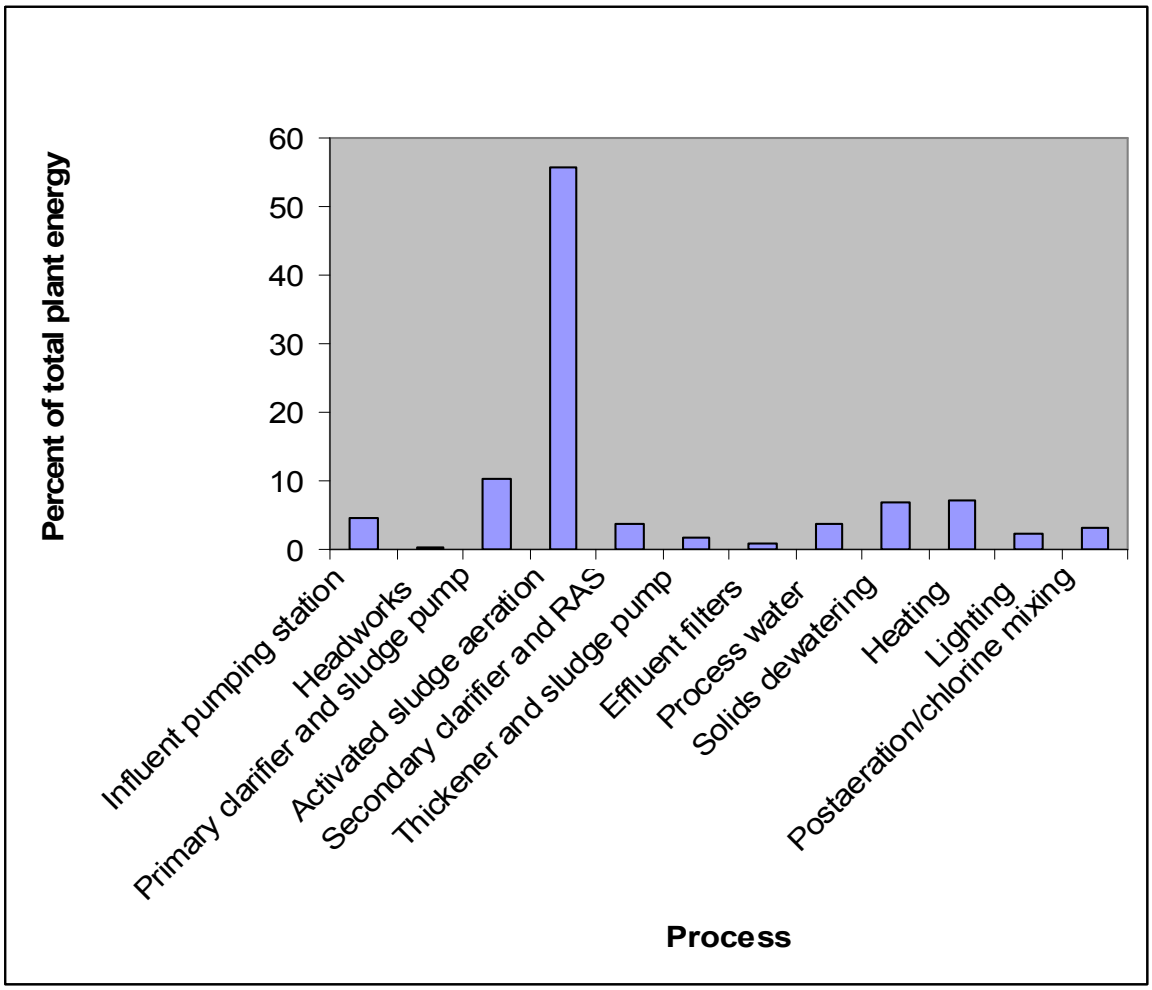


Figure 2.15: Distribution of energy usage in a typical wastewater treatment plant employing the activated sludge process (Metcalf and Eddy, 2003)

About 50% of the energy used at an activated sludge plant is used for aeration (**Figure 2.15)**. For instance, mechanical aeration is an essential process in the majority of wastewater treatment plants and accounts for the largest fraction of plant energy costs, ranging from 45 to 75% of plant energy expenditure (Henze *et al.*, 2008)

Table 2.6: Energy impacts of new technologies on wastewater treatment (Metcalf and Eddy, 2003)

Technology	**Energy impact**
	kWh/1000 m^3
Fine pore diffusers (for aeration)	33 to 39
Ultrafine pore diffusers	47 to 58
Dissolved oxygen control systems (as compared to manual control)	13 to 26
Energy efficient blower control systems, i.e., inlet guide vanes, inlet butterfly valves, or adjustable speed drives	13 to 39
Energy efficient aeration blowers (as compared to blowers with inlet guide vanes)	26 to 39
UV (ultraviolet) disinfection	13 to 53
Membranes	
Microfiltration	53 to 106
Reverse osmosis	264 to 528

In closing this section of wastewater treatment and greenhouse gas emission, it is important to highlight the various aspects of the emissions in the full chain of the sanitation system and that of producing fossil fuel energy as a reference. For every stage (wastewater collection, transport, treatment, reuse or ultimate disposal) in the process the most important areas where possible GHG are emitted (or absorb) are depicted in the **figure 2.16** below.

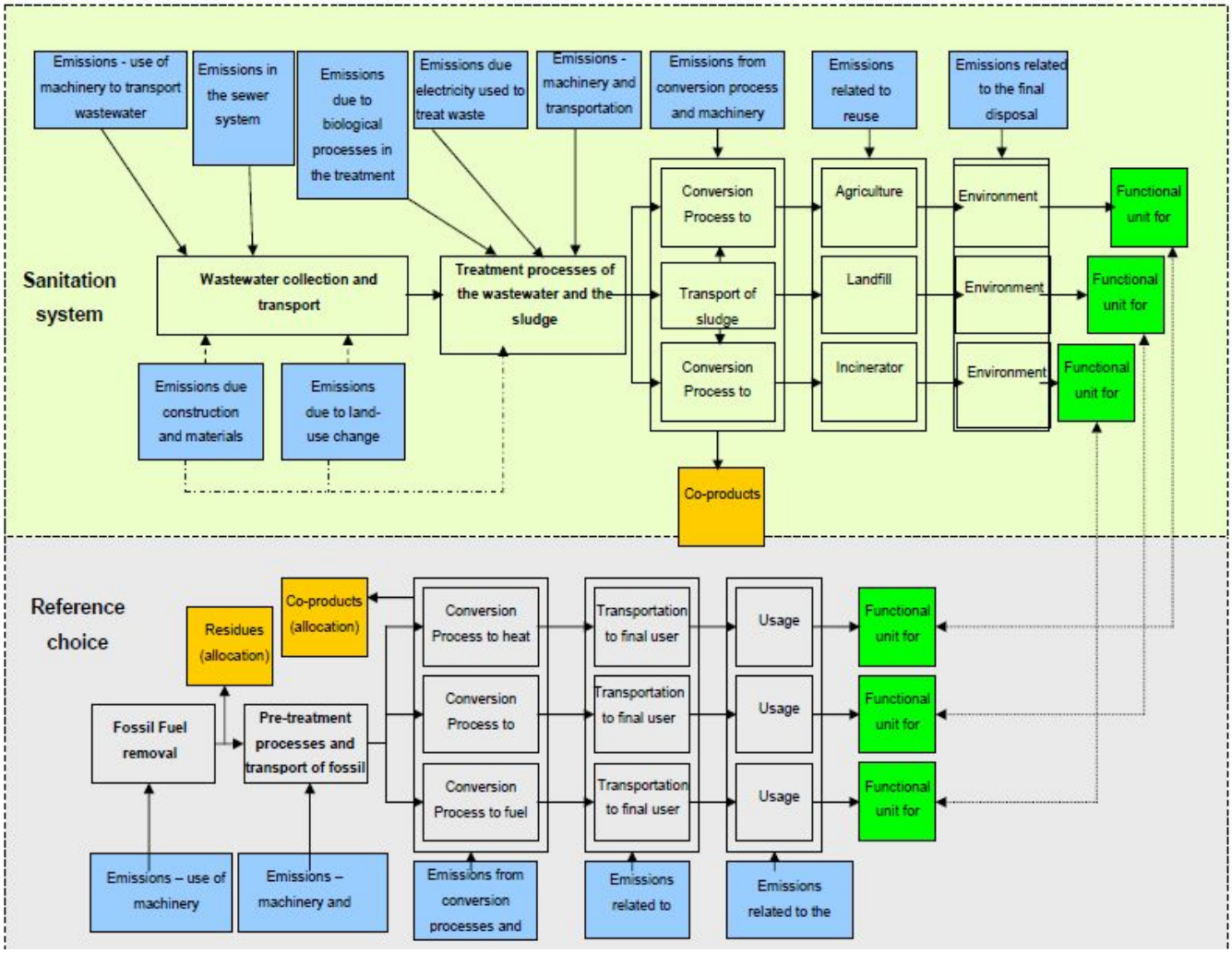


Figure 2.16: Flowchart of emissions in full sanitation chain and fossil fuel energy production as reference

Adapted from (GreenDynamics, 2008)

2.7. Overview of GHG Emission Estimation Methods

There are a number of methods for estimating GHG emissions from wastewater treatment systems. These include mathematical models, mass balances, and experimental monitoring

2.7.1. Experimental Methods for Measuring GHGs

Several types of methods are available for measuring GHG emissions experimentally: static-chamber techniques, dynamic-chamber techniques, and eddy covariance techniques (Yuesi and Yinghong, 2003). However, each method has different advantages, disadvantages, and susceptibility to measurement errors. These devices use special equipment to trap gas samples that are subsequently analyzed by gas chromatography to determine gas concentrations.

- **Dynamic Chamber Techniques**

This device is used to determine the emission rates of the test compound, which is a function of the increase in mass of the sample over time. A pump is used to inject dry clean "sweep" air into a chamber at a fixed rate. The volumetric flow rate of the sweep air through the chamber is recorded and the concentration of the specimen of interest is determined at the chamber outlet. This device is used to quantify a wide range of different gas fluxes including CH_4, CO_2, N_2O and H_2S in addition to NH3 volatilization. One of the advantages of this device is its use in situ to analysis directly collected samples. Nevertheless, the major drawback of this device is incorrect measurements due to pressure surplus (or deficit) and inadequate flow rates (Van der Steen *et al.*, 2004).

- **Static Chamber Techniques**

This device is also used to determine emission rates from wastewater treatment. The static chamber is a rectangular prism opened at the lower end. Walls of the chamber are covered with a Mylar sheeting to avoid any warming effect inside the chamber. A buoyancy collar is fitted around the chamber to ensure an air headspace of 35 L above the wastewater surface. The lower end of the chamber is immersed about 25 cm below the surface and acts as a skirt to reduce the perturbation of the air/water interface (Soumis *et al.*, 2004).

The static method uses a chamber on a fixed base at a point in the wastewater treatment system. This method appears to be the simplest setup in use, because there is neither sweep gas to deal with nor any valves to control flow rate. Nevertheless, to achieve steady state conditions a longer sampling period is required because, the air inside the chamber is not circulating. Static chambers have been widely used in GHG measurements from wastewater in ponds (Stadmark and Leonardson, 2007) and in constructed wetlands (L. Rousseau *et al.*, 2004). However, according to Duchemin et al. (1999), some adjustment may be done on the regular static chamber to adapt it to a free floating static chamber with the added advantage of avoiding sampling artifacts due to long hours of sampling at a single location and disturbance of sediment surface.

♦ **Eddy Covariance Technique**

The Eddy Covariance Technique ascertains the exchange rate of CO_2 across the interface between the atmosphere and a plant canopy by measuring the covariance between fluctuations in vertical wind velocity and $C0_2$ mixing ratio (Yuesi and Yinghong, 2003). The method was employed to study $C0_2$ exchange of agricultural crops under ideal conditions during short field campaigns (Castellví *et al.*, 2008). The atmosphere contains turbulent motions of upward and downward moving air that transport trace gases such as $C0_2$. The Eddy Covariance Technique samples these turbulent motions to determine the net difference of material moving across the canopy-atmosphere interface (Myklebust *et al.*, 2008). Like Static and Dynamic Chamber Techniques, the Eddy Covariance Method also has limitations. This method is most applicable: over flat terrain, when the environmental conditions are steady; and when the underlying vegetation extends upwind for an extended distance. Violation of these assumptions can cause systematic errors in the results.

♦ **Gas Chromatography**

Gas chromatography is the main analytical method for measurement of GHG concentrations. The flame ion detector can be employed for CH_4 chromatography (Picek et al., 2007), while electron capture detector chromatography is used for N_2O. Thermal capturing detector (TCD) can be used to quantify CH_4 and CO_2 concentrations.

2.7.2. IPCC Guidelines 2006

The 2006 IPCC guidelines for estimating GHGs are based on linear equations relating sanitation activities, emission factors and biochemical processes for organic matter decomposition in wastewater, sludge treatment and agricultural application. An emission factor is defined as the average emission value or quantity of a specific pollutant emitted to the atmosphere from a given source, relative to the intensity of a specific activity associated with the emission of that pollutant. These factors are usually expressed as the weight of pollutant divided by a unit weight, volume, distance, or duration of the activity emitting the pollutant. Such factors facilitate estimation of emissions from various sources of air pollution. 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 generates GHGs. Therefore, a simplified general algorithm for estimating GHG is as shown below.

Gas emission (kg/ yr) = AD*Fr*DP*EF*CONVF

Where: AD: Activity data (Population served by the system, Volume of water and wastewater treated, Organic loading (COD, NH3), Nitrogen content etc.)

Fr: The fraction of treated wastewater in the treatment plants (anaerobic or aerobic processes).

DP: Design parameters (treatment efficiencies).

EF: Specific emission factor of each gas (CH_4, CO_2, N_2O ...)

CONVF: Conversion factor to standardize the calculation units for the GHG emissions (Préndez and Lara-González, 2008).

According to the IPCC (2006) guidelines for methane emitted during wastewater treatment, its emission factor is defined by a function of the maximum potential amount of CH_4 emitted from a given quantity of organics expressed in BOD or COD. In the same way, the emission factor for N_2O is expressed as a function of the ratio of kilogram of N_2O per kilogram of N. However, in the case of emissions from centralised wastewater treatment facility that involves nitrification and denitrification steps, the emission factor for N_2O is expressed as grams of N_2O per capita per year.

Though emission factors are generally derived from measurements on a number of sources presumed to be representative of a particular source sector, El-Fadel and Massoud (2002) stressed that there are many uncertainties related to insufficient data about many other factors, including nutrient limitations,

extent of decomposition, biological inhibition, physico-chemical interactions and requirements for bacterial synthesis. In addition, emission factors are applied independently of the type of wastewater treatment and seasonal variations and their impact on wastewater treatment.

2.7.3. Mass Balance

The general concept of the law of conservation of mass takes into account inputs, outputs and transformations of matter based on the application of mass balance. It describes the accumulation of mass in the system as a function of the mass input into the system, mass output from the system and mass transformation in the system as shown in the equation below.

Accumulation = Input – Output + Transformation

Mass balance is also used to estimate GHGs from wastewater treatment within an appropriate system boundary. For instance, each unit operation of the treatment plant can be considered as a system boundary and a mass balance on COD can be analyzed. The mass balance applications make use of both theoretical (stoichiometric) and experimental (in situ measurements) data combined to create representative equations of a system (Ekama, 2008). Though mass balance is a flexible, fairly accurate and reliable methodology in estimating GHGs (Cakir and Strenstrom, 2005), the major limitation is the inadequate boundary definition, use of non-representative stoichiometric coefficients and the fact that data collection problems which may all lead to some inaccuracy in the estimation of GHG emissions.

2.8. Description of the Investigate Scenarios

The four systems that were investigated are depicted below.

2.8.1. Harnaschpolder

The wastewater treatment plant (WWTP) at Harnaschpolder, located in Midden-Delfland, bordering Rijswijk and Delft, was inaugurated in March 2007. The Harnaschpolder WWTP is one of the largest installations in Europe, with a maximum treatment capacity of 35800m^3/h or the equivalent of 1.3 million persons. This flow consists of 75-80% of the effluent from The Hague and the surrounding area (Helga, 2008). The complete view of the treatment facilities is presented on **figure 2.17** and the process flow diagram on **figure 2.18**.

Figure 2.17 Aerial view of Harnaschpolder wastewater treatment plant (Tekalgne, 2009)

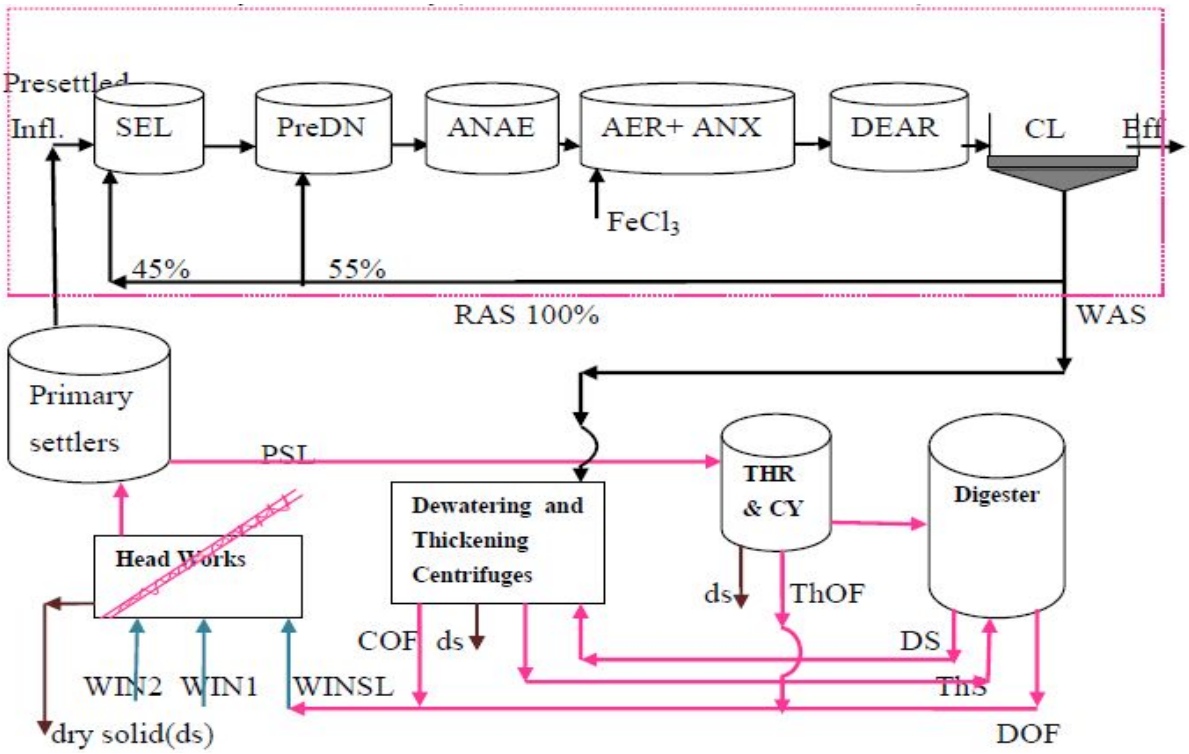


Figure 2.18: Process diagram of Harnaschpolder wastewater treatment plant (Tekalgne, 2009)

- **Description of the Process Units**

Route of the Waterline

- ***Preliminary treatment***

The inlet works consist of seven screens (to remove the coarse materials), septic tank and wastewater pumping station.

- ***Primary settling tank***

Due to the flow rate of 75-80% of the Midden-Delfland wastewater on Harnaschpolder WWTP four primary settlers are used; without adding chemicals; to remove the main part of the pollution that can be settled out.

- ***Aeration tank***

This unit consists of eight biological tanks, where COD, nitrogen and phosphorus removal take place. In the process of these conversions, some GHGs are emitted (CO_2 and N_2O).

- ***Secondary settling tank***

Sixteen final clarifiers are used in Harnaschpolder WWTP to remove the materials that can be settled out.

Route of the Sludge

- ***Primary sludge degritting and thickening***

The primary sludge is pumped in four hydrocyclones (reactors) for degritting; then it flows by gravity in two gravity thickeners, where it is kept for five days to allow for the hydrolysis of the sludge.

- ***Excess biological sludge thickening***

The excess biological sludge from the final clarifiers is thickened by centrifugation. Some polymers are added at the inlet of the three centrifuges to flocculate the excess biological sludge in order to improve the thickening effect.

- ***Mixed sludge anaerobic digestion***

The thickened primary sludge and the thickened excess biological sludge are mixed and pumped to two digesters to be digested. In this unit, biogas (35% of CO_2 and 65% of CH_4) is produced and then used for to generate energy and heat. This biogas composition is same as the one found in literature (Metcalf and Eddy, 2003).

- ***Sludge storage and dewatering***

The digested sludge is dewatered and stored before transporting it to an incinerator plant, located a few kilometres away from the treatment plant.

2.8.2. Sneek

In Sneek, during 2005, 32 houses were built including vacuum toilets and separate collection of black and greywater. The blackwater sewer is connected to the first Decentralized Sanitation and Reuse (DeSaR) pilot plant in Netherlands. The greywater is still transported within the large sewer networks and treated at the conventional wastewater treatment plant of Sneek.

The experience gained from this pilot plant was used for the design of a conceptual decentralized treatment system for 250 houses (the equivalent of 575 persons), which is the focus of our study. In this system, greywater and blackwater are collected and treated separately (**Figure 2.18**).

♦ **Concentrated Blackwater**

Blackwater (collected in vacuum toilets) is obtained from the 250 houses, with ground kitchen waste. Approximately 3.9 m^3 of concentrated blackwater are produced per day. The vacuum toilets of all of the 250 houses will be connected to one vacuum station, where the concentrated blackwater is pumped in batch mode into a storage tank. From the storage tank, the concentrated blackwater is to be pumped to an anaerobic bioreactor of UASB septic tank, where biogas is produced and subsequently converted to heat and electricity.

The effluent from the UASB septic tank undergoes further treatment, where the Anaerobic Ammonium Oxidation System ("Anammox") is applied. This process is an efficient biological alternative to conventional nitrogen removal from wastewaters. Under anaerobic conditions, ammonium is oxidized to nitrogen gas with nitrite as the electron acceptor. Carbon dioxide is only used for growth of the Anammox microorganisms. In comparison to traditional nitrification–denitrification process, this autotrophic process consumes less energy, therefore, a lower CO_2 emission (*Molinuevo et al.*, 2009).

From the Anammox reactor, the effluent is further treated in a struvite reactor, in order to remove remaining COD, nitrogen and phosphate. The struvite reactor consists of two tanks for mixing additives and settling of the formed struvite crystals respectively. Then the effluent from the Struvite settler is pumped to the greywater system.

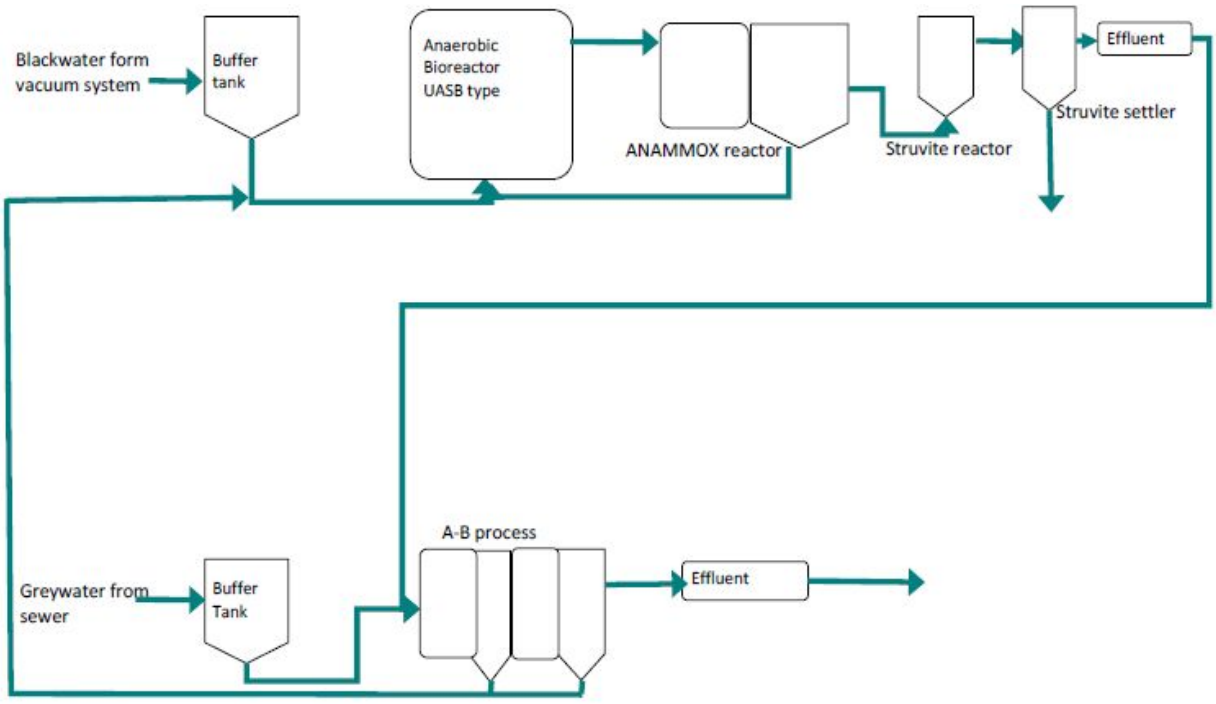


Figure 2.19: Conceptual process flow diagram of Sneek (Meulman *et al*., 2005)

♦ **Greywater Treatment Line at Sneek**

Approximately 51.8 m3 per day is collected using a conventional sewer system and stored in a buffer tank. From this storage, the greywater is pumped to an A-B process where the suspended solids are trapped and settled. The sludge produced from this process is pumped back to the UASB septic tank for further treatment.

2.8.3. EIER-Ouaga

The third system considered for this study is a series of three wastewater stabilization ponds. These ponds are treating the wastewater of the International Institute for water and Environmental Engineering (EIER). This treatment plant is located in Ouagadougou the capital city of Burkina Faso which is a semi-arid tropical zone with an average temperature of 30˚ c. The waste stabilisation pond, which was built in 1989 and rehabilitated in 2004, has a treatment capacity of 55m3/day (varies from 25 to 55 m3/d) or 220 person equivalent.

The improvement of the pilot scale treatment plant in 2004 comprised new treatment options in the

system. The system is composed of five branches (**Figure 2.18**), but only the line including anaerobic pond (BA), facultative pond (BF1), and maturation pond (BM1) is operational. The characteristics of the ponds are depicted in the table 2.7 below.

Although there is a provision for sludge drying, the anaerobic pond has not been desludged in the last years. The effluent water from the maturation pond is used to irrigate the green spaces and the agronomic experimental field of the institute.

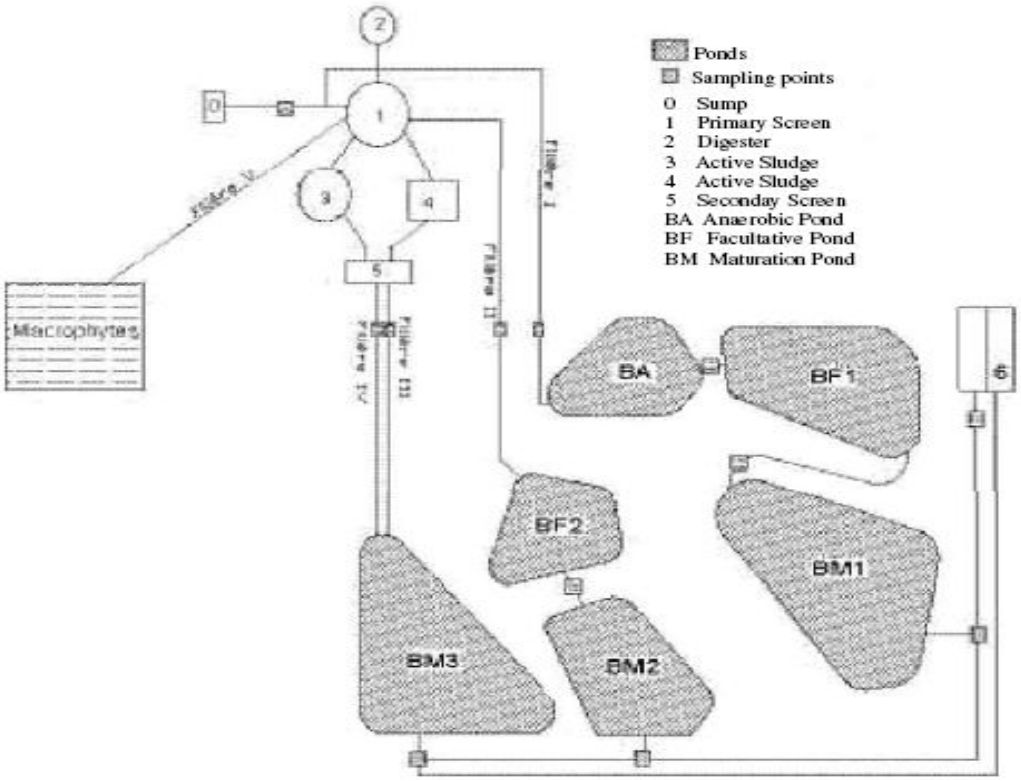


Figure 2. 20: Schematic view the waste stabilization of EIER-Ouaga (Maiga *et al.*, 2006)

Table 2.7: Characteristics of Wastewater Stabilization Ponds (Maiga *et al.*, 2006)

Pond	Depth (m)	Area (m^2)	Volume (m^3)	Hydraulic retention time (days)
Anaerobic	2.6	69.7	181.2	3
Facultative	1.4	415.3	581.4	9.5
Maturation	0.9	336.9	303.2	5.5

2.8.4. Siddhipur

Siddhipur is a farming village located about 10 km south east of the capital city of Kathmandu. Currently there are 100, family-owned Urine-Diverting Dry Toilets, i.e. toilets which collect urine and faeces separately, and in the absence of water (Gantenbein and Khadka, 2009). Siddhipur has a strong Water Supply and Sanitation User Committee (WSSUC) that is already active in the operation and management of the water supply, sanitation and solid waste programs of the community. By working co-operatively with the WSSUC the researchers were able to work within the framework of the existing sanitation plans and understand the immediate needs for, and limitations of a community scale struvite reactor in their community. Therefore, struvite productions are implemented in Siddhipur as shown in the **Figure 2.21** below. The **Figure 2.22** shows a hypothetical greywater treatment with UDD system which is the focus of our study.

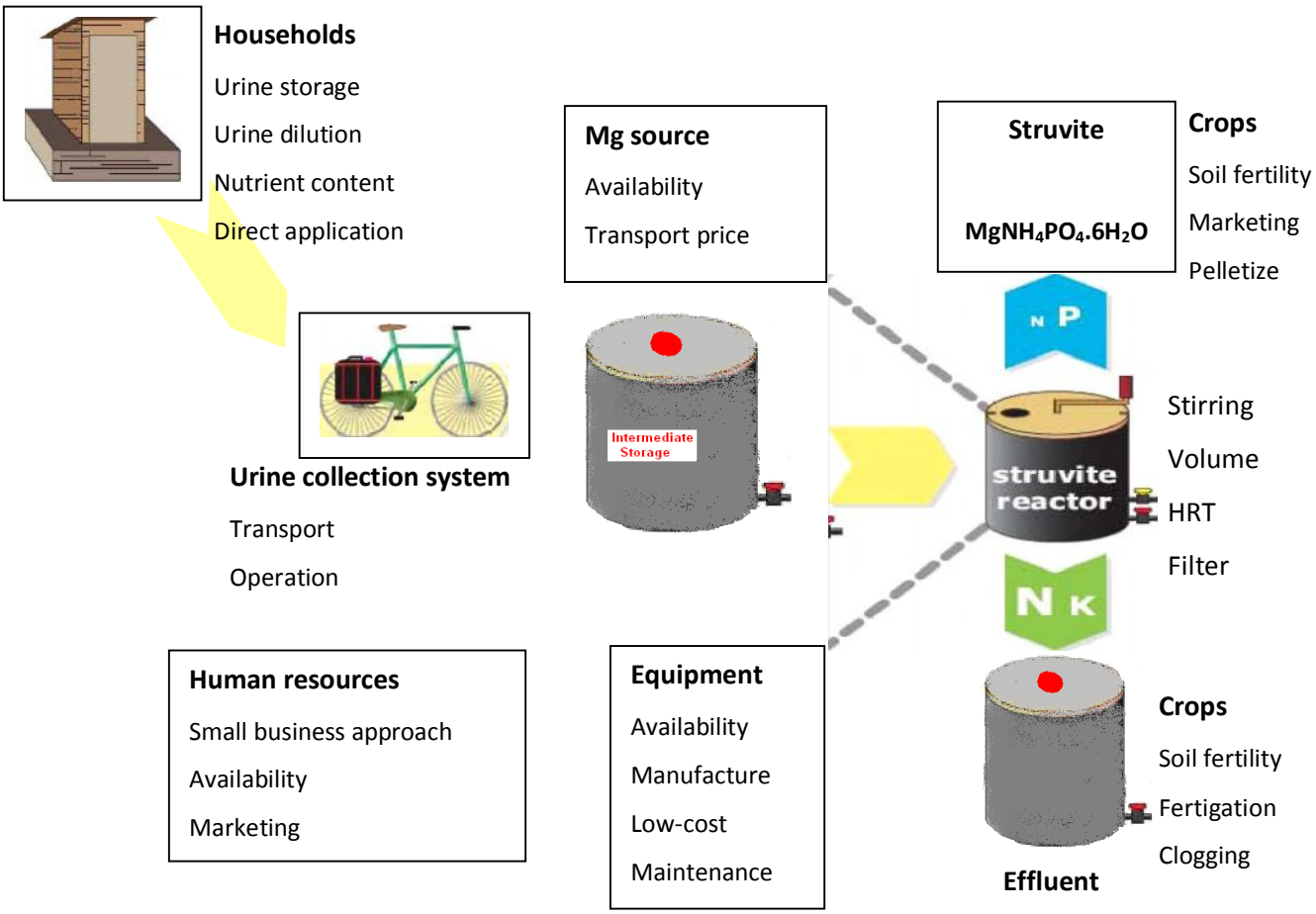


Figure 2.21: Struvite Production Process Implications in Siddhipur (Gantenbein and Khadka, 2009)

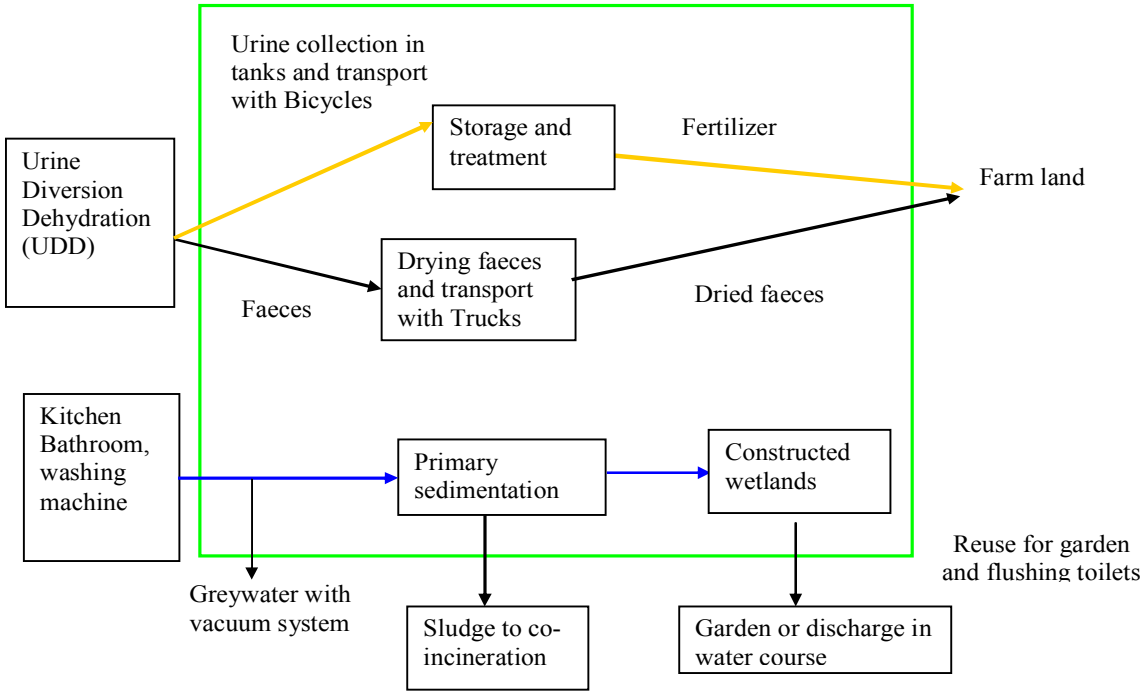


Figure 2.22: Urine diversion dehydration with a hypothetical greywater treatment

With regards to the above description of the four scenarios, it is important to note that the wastewater composition of each system is different from the other (**Table 2.8).**

Table 2.8: Wastewater characteristics of the four scenarios

	Urine	Faeces	Greywater	Kitchen waste	Storm water
Harnaschpolder	+	+	+	-	+
Sneek	+	+	+	+	-
EIER-Ouaga	+	+	+	-	-
Siddhipur	+	+	+	-	-

+ included in wastewater

- not included in the wastewater

In closing, it is important to notice that there are various sources of GHG emissions from wastewater treatment and also number of methods to estimate such emissions. Based on the of the literature review, the appropriate methods and assumptions are identified, are described in the next chapter.

3. RESEARCH APPROACH AND METHODOLOGY

In order to achieve the overall and specific objectives of this research work, the methodology and approaches that were applied are described in **Figure 3.1** below. The research strategy was limited to a desk type study.

In the first place an extensive literature survey was carried out, in order to understand what has been published on this topic. Secondly, four wastewater treatment options were selected for more in-depth analysis. Finally, data were collected and analyzed for the selected systems.

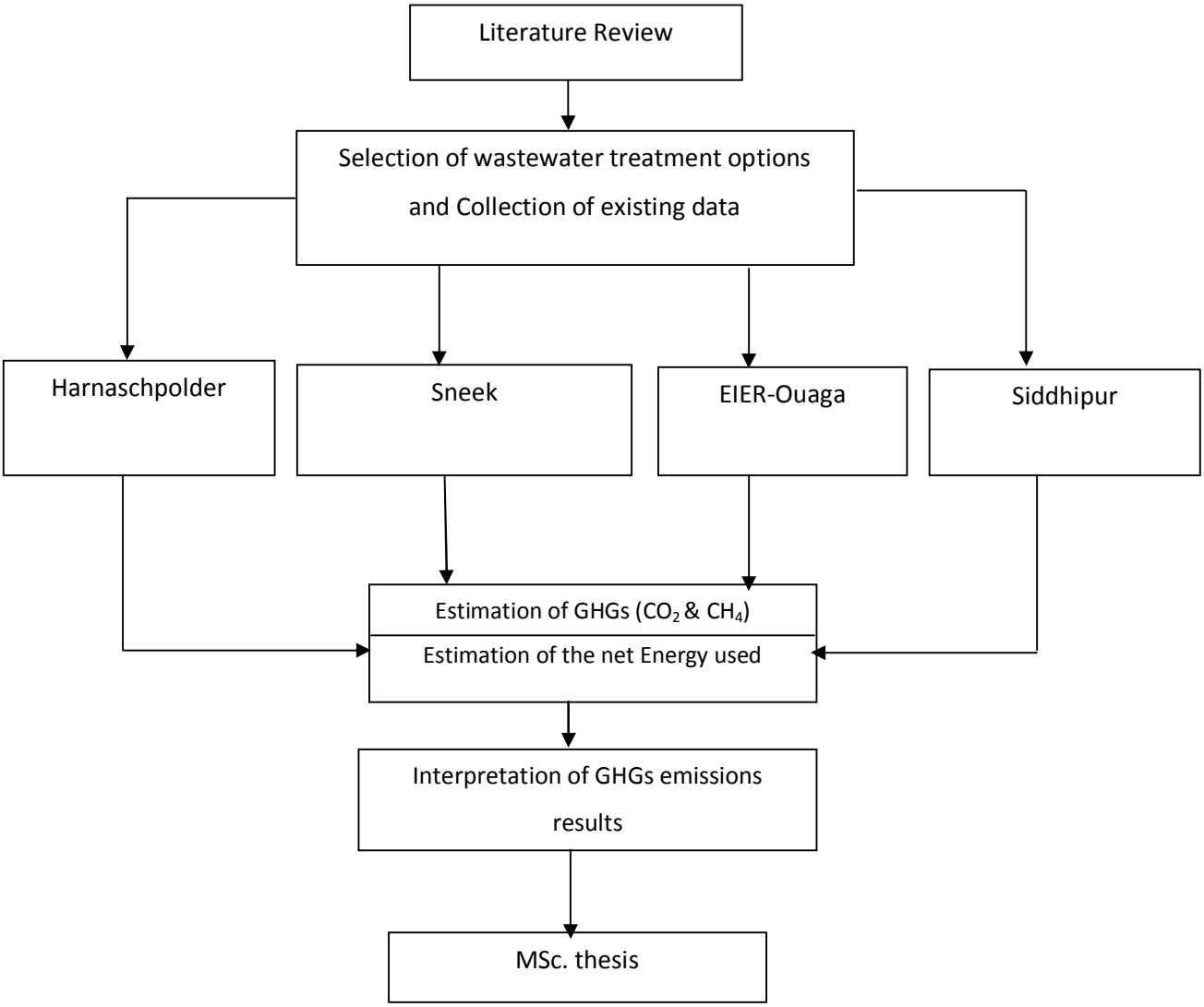


Figure 3.1 Methodology scheme

For selecting the four treatment options, the following criteria were considered:

- The applicability of the system (performance or removal efficiency of organics, coliforms and nutrients) ,
- The availability of data,
- The consideration of future development in terms of sustainability (Socio-cultural, Technical, Economical, Environmental, Health, and Institutional).

After selecting the case studies for this research work, data and information were collected.

- Primary data (plant process scheme, COD, flow rates, energy used, etc) were collected through field visits, and informal interviews conducted with senior officials in two cases. The remaining was done via internet.
- Secondary data (conversion factors) was collected through intensive literature reviews of past studies, reports, publications, and relevant documents from internet.

3.1. Methods for Estimating Carbon Dioxide and Methane

To estimate the amount of CO_2 and CH_4 emitted from the four systems, two methods have been used, namely: COD mass balance, and IPCC guidelines 2006.

3.1.1. COD Mass Balance

The organic material (COD) present in the raw wastewater, after having been exposed to biological treatment, will have one of the following four forms:

(1) sludge COD,
(2) methane COD,
(3) mineralized COD, and
(4) effluent COD.

If a constant flow and load is applied and organic matter does not accumulate in the treatment system (steady state conditions), the daily mass of influent COD is equal to the sum of the daily mass COD leaving the system as methane in excess sludge produced, in the effluent, and the daily amount of COD oxidized.

$$\mathbf{MCOD_{in} = MCOD_{eff} + MCOD_s + MCOD_d + MCOD_o} \qquad \textbf{(equation 3.1)}$$

Where: $\mathbf{MCOD_{in}}$ = daily mass of influent COD
$\mathbf{MCOD_{eff}}$ = daily mass of effluent COD
$\mathbf{MCOD_s}$ = daily mass of COD in the discharged sludge
$\mathbf{MCOD_d}$ = daily mass of digested COD
$\mathbf{MCOD_o}$ = daily mass of oxidized COD

Equation 3.1 was applied on each process unit (from the dominant sources) within the set boundary conditions of the considered treatment system.

3.1.2. IPCC 2006 Guidelines for Estimating GHGs

The 2006 IPCC guidelines for estimating GHGs are based on linear equations relating sanitation activities,

emission factors and biochemical process for organic matter decomposition in wastewater, sludge treatment and agricultural application.

In this research, IPCC 2006 guidelines were used in the estimation of GHGs, in situations where required data were not available. The emission factors are usually expressed as the weight of pollutant divided by a unit weight, volume, distance, or duration of the activity emitting the pollutant. Such factors facilitate estimation of emissions from various sources of air pollution. 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 generates GHGs. Therefore, a simplified general algorithm for estimating GHG is as shown below.

Gas emission (kg/ yr) = AD*Fr*DP*EF*CONVF (Equation 3.2)

Where**: AD**: Activity data (Population served by the system, Volume of water and wastewater treated, Organic loading (COD, NH_3), Nitrogen content etc.)

Fr: The fraction of treated wastewater in the treatment plants (anaerobic or aerobic processes).

DP: Design parameters (treatment efficiencies).

EF: Specific emission factor of each gas (CH_4, CO_2, N_2O ...) see **Annex 7.4** for MCF

CONVF: Conversion factor to standardize the calculation units for the GHG emissions (Préndez and Lara-González, 2008).

3.2. Method for Estimating Energy Used

Energy surveys can vary in complexity, but for the purpose of this study a desktop energy survey level was used. A desktop survey involves an analysis of billing data to understand the current electricity use (kWh) and their peak demand (kW).

In addition to the desktop survey of wastewater treatment plant, below are some general areas that were considered in the assessment of the energy used at the treatment facility:

- Pumping–General;
- Aeration (compressors used);
- Sludge handling and disposal (centrifugal thickeners, energy required to heat up the digesters...);
- Lift stations;
- Lighting.

For estimating the power required to drive a pump the formulae below is used:

Power $N = \frac{\rho * g * h * Q}{\pi}$ **(Watt)** **(Equation 3.3)**

Where**: ρ=** density of water kg/m^3 which is 1000kg/m^3;

g= acceleration of gravity in Western Europe 9.81m^2/s;

h= manometric head in meters water column;

Q= discharge in m^3/s

π = efficiency of the pump

N = the required power to drive the pump in Watt

3.3 Materials

The materials below are the main elements used for this study:

- Excel 2003 software was used as the database administrator and for the computation and estimation of the different GHGs of the four systems considered;
- Different reports and papers from the wastewater treatment plants;
- Internet;
- Library;
- Conversion factors,

Carbon conversion factors are used to calculate the amount of CO_2 emissions resulting from burning fuel for electricity, heating or transport. To calculate the emissions caused by a certain activity, just multiply the amount of it (in the units shown) by the appropriate conversion factor **(Table 3.1).** These factors all provide emissions in units of kg CO_2equiv (carbon dioxide equivalent, used to take into account GHGs other than CO_2).

In order to compare the results with the cases where the wastewater is discharged directly to the immediate environment without treatment an assumption is made that the total COD is completely converted to CO_2 as shown in the equation below.

$$COD + O_2 \rightarrow CO_2$$

Table 3.1: Conversion Factors

Parameters	Typical	Source
Energy used		
Drinking water treatment and distribution	0.47kWh/m^3	(KWR and STOWA, 2008)
Wastewater treatment	26.6kWh/cap.yr	(KWR and STOWA, 2008)
Fossil electricity	0.7737 kg CO2/1000kW	(IPCC, 1996)
	0.59 kg $C0_2$ / kWh	(KWR and STOWA, 2008)
Natural gas	1000 kW for 10.5 ton CO_2/day	(Henze *et al.*, 2008)
	56.8 kg $C0_2$ / $C0_2$ GJ = 1.8 kg / m^3	(KWR and STOWA, 2008)
Coal driven power plant	1000 kW for 21 ton CO_2/day	(Henze *et al.*, 2008)
Global Warming Potential (GWP)		
CO_2	1	(IPCC, 1996)
CH_4	21	(IPCC, 1996)
N_2O	310	(IPCC, 1996)
COD to CO_2	$\frac{44}{32}=1.375$	$C+O_2 \rightarrow CO_2$
CH_4 to CO_2	$\frac{44}{16}=2.750$	$CH_4+O_2 \rightarrow CO_2+2H_2O$
Organic Matters		
COD to TSS	1.42 kg COD/ kg TSS	(Kappeller *et al.*, 1994)
COD to Biogas	1kg COD for 0.35 m^3 of biogas for normal conditions (10 degree at 1atm)	(Marcos and Carlos Augusto, 2005)
% of CO_2 in the biogas formed	35%	(Metcalf and Eddy, 2003)
% of CH_4 in the biogas formed	65%	(Metcalf and Eddy, 2003)

Figure 3.2: Future bright for greenhouse gas tracking

4. RESULTS AND DISCUSSIONS

This chapter presents the results from the analysis of the GHG emissions for each of the four systems. The results were also discussed and compared with other sectors. The details of the methods and materials used to arrive at the results of the GHG emissions were outlined in the previous chapter. More information on the calculations can be found in the appendices. Moreover, this chapter highlights the emissions from the different subsystems of the urban water cycle.

4.1. Results

4.1.1 Harnaschpolder

The Harnaschpolder wastewater treatment plant is the first public-private partnership in the Dutch water board sector. It is one of the largest installations in Europe, with a maximum treatment capacity of 35,800m^3/h or the equivalent of 1.3 million persons. Considerable attention is being paid to sustainability during the design, the construction, the materials used and the operation of this treatment plant.

As a basis of calculations of the GHG emissions from this wastewater treatment plant, design data of 2004, as well as the yearly average operational data of 2008, were used. Single values are obtained after carrying out COD mass balance over the specified boundary conditions. Those results are subjected to variations since the COD load and energy required for daily operations are fluctuating.

4.1.1.1 Overview of Harnaschpolder Wastewater Collection and Transport System

As stated earlier, sanitation in large complex systems is a multi-step process in which wastes are managed from the point of generation to the point of use or ultimate disposal **(Figure 4.1**). Therefore, investigating the environmental performance of such systems requires a great deal of data and time. Considering the difficulty in covering the entire system, it is subdivided into three subsystems, where the second is the focus of this study.

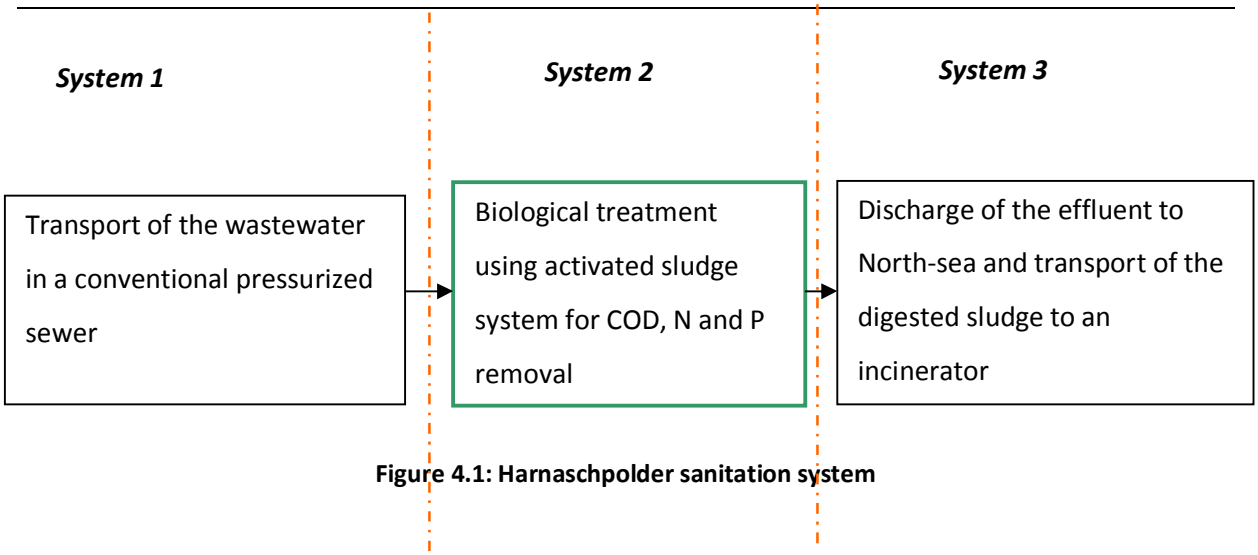


Figure 4.1: Harnaschpolder sanitation system

4.1.1.2 Process Units and Mass Balances

The process flow diagram (**Figure 2.18)** focuses on the second subsystem that was described in the previous section. Two major waste treatment streams are analysed (waterline and sludge line). A COD mass balance is carried out on each process unit and the results are given below.

Route of Waterline

a) Preliminary Treatment

The inlet works consist of seven screens (to remove the coarse materials), sump and wastewater pumping station. This unit is not considered in the estimation of GHGs because of the negligible amount produced.

b) Primary Settling Tank

The inlet wastewater entering the treatment site represents 75% of the maximum flow of the Hague region. For this reason, four primary settlers are used, without adding chemicals, to remove the main part of the pollution that can be settled out. This unit is of less importance to us for this research work since the average retention time is only 2.6 hours and GHG emissions are negligible.

c) Aeration Tank

This unit consists of eight biological tanks, where COD, nitrogen and phosphorus removal take place. In the process of these conversions, some GHGs are emitted (CO_2 and N_2O). To estimate the total amount of CO_2 escaping from the system, a mass balance over the eight biological tanks was carried out with respect to the COD (in, out) and sludge production of the considered system.

It was estimated that 44,776 kg of COD were converted to CO_2 per day which is equivalent to 61,567 kg CO_2 equivalent per day (**Annex 7.3.1 to 7.3.3**)

d) Secondary Settling Tanks

Sixteen final clarifiers are used in Harnaschpolder WWTP. GHG emissions are neglected, because any anaerobic or aerobic process is too short to take place within the short retention time (average retention time of 8.1 hours in the clarifiers).

Route of the Sludge

e) Primary Sludge Degritting and Thickening

The primary sludge is pumped into four hydrocyclones for degritting; then it flows by gravity in two gravity thickeners, where it is kept for five days in order to hydrolysis the sludge. Here we can expect some GHG emissions, due to the long sludge retention time. Nonetheless, this was neglected in this study, because of the lack of necessary data.

f) Excess Biological Sludge Thickening

The excess biological sludge from the final clarifiers is thickened by centrifugation. Some polymers are added at the inlet of the three centrifuges to flocculate the excess biological sludge and improve the thickening effect. GHG emissions are expected to be very low.

g) Mixed Sludge Anaerobic Digestion

The thickened primary sludge and the thickened excess biological sludge are mixed and pumped to two digesters to be digested. In this unit, biogas (35% CO_2, 65% CH_4) is produced. To estimate the total amount of biogas produced, a mass balance over the two digesters was carried out on the incoming and outgoing sludge. Methane emission was computed based on the Intergovernmental Panel on Climate Change (IPCC) proposed model. It was found that 28,573 kg of COD were converted to biogas per day, which translates to 10,001 kg of COD to CO_2 and 18,573 kg of COD to CH_4 per day.

From the digestion processes in the two digesters, 13,728 m^3 per day of biogas is collected. About 0.2% (26m^3/d) is flared, which constitutes the equivalent of 46 kg of CO_2 in GHG emissions per day. The remaining part of the biogas, 13,606 m^3/d, is converted to energy in the Combined Heat and Power (CHP) Plant. This conversion is equivalent to 34,555 Kwh/d and constitutes 43.5% of the energy required for the treatment plant (**Annex 7.3.1 to 7.3.3**).

h) Sludge Storage and Dewatering

For a short sludge retention time, the emission of GHGs is very low and, therefore, neglected in this study.

4.1.1.3 GHG Emission from Biological Processes

In this study, GHG emissions for the Harnaschpolder WWTP due to the biological processes were

estimated considering the aeration tanks and the digesters, using the design data. The methane recovered from these processes is converted to energy which is deducted from the estimated total energy required. The results show emissions of about 47 g CO_2/cap.d or 0.017 t CO_2/cap.yr.

4.1.1.4 Estimation of the Indirect GHGs Emissions

Emissions generated in the production of raw materials, chemicals used and the energy used for the daily operation and maintenance are considered as the indirect emissions.

In this research, the net energy used for the daily operation are used to estimate the GHG emissions.

a) Net Energy Used in the Treatment Process of Harnaschpolder WWTP

Table 4.1 below summarized the energy used and produced from the treatment processes. The results show that 79,469 KWh/d is required for the operation of the treatment plant, but only 57% (44,914 KWh/d) is purchased from the national electricity grid (**Table 4.12**).

Table 4.1: Energy distribution

Parameters	**Bought Energy**	**Production (from CHP or fermentation)**	**Consumption by:**						
			Gas engine/CHP	Direct Power (pumps etc.)	Aeration	Digester	Dewatering	Flared biogas	Others
Hot water/steam (GJ/yr)	0	34,714	0	0	0	33,764	0	0	951
Biogas (m^3/yr)	0	5,010,696	4,966,305	0	0	0	0	9,391	0
Electricity (kWh/yr)	16,393,724	12,612,500	378,375	12,300,000	10,637,424	1,000,000	976,450	0	3,713,975
Natural gas (m^3/yr)	24,714	0	0	0	0	0	0	0	24,714
Total energy consumed KWh/d									79,469
Net energy KWh/d									44,914

b) Emissions from the Net Energy Used

The net energy used is the energy bought from the electricity grid, after deducting the produced energy from the total energy required (**Table 4.2**).

The emissions due to the net energy and the natural gas used were estimated to be 26,621 kg CO_2 per day.

Table 4.2 Emission due to net energy and natural gas

Parameters		Equivalent kg CO_2/d	Total g CO_2/cap.d	Source of energy
Energy purchase KWh/d	44,914	26,499	20.4	Grid electricity (**Table 3.1**)
Natural gas purchase m^3/d	68	122	0.09	Natural Gas (**Table 3.1**)
Total		26,621	**21.3**	

4.1.1.5 Overall GHG Emission of Harnaschpolder WWTP

In this study, the overall GHG emissions for the Harnaschpolder WWTP were estimated considering the direct and indirect (biological processes and energy consumption respectively) emissions of the domestic wastewater treatment; using the design data.

The results show emissions of about 68 g CO_2/cap.d or 0.025 t CO2/cap.yr. If the treatment were not done (discharge of untreated wastewater) the emission would have been 153 g CO_2/cap.d, 46% greater than the actual emission. A summary of the overall emissions from this treatment plant is given below (**Table 4.3**).

Table 4.3: Summary of Harnaschpolder GHG emission

Parameters	Unit	Values
Population equivalent	PE	1,300,000
Design flow	m^3/d	263,862
Influent COD	kg/d	145,062
Biogas production	m^3/d	13,728
Energy production from biogas	KWh/d	34,555
Energy required for the system	KWh/d	79,469
Net energy used	KWh/d	44,914
CO_2 emission due to biological processes	g CO_2 /Cap.d	**47**
	kg CO_2 /Cap.yr	17
CO_2 emission due to net energy used (Table 3.1)	g CO_2 / Cap.d	**21**
	kg CO_2 /Cap.yr	7
Total CO_2 Emission	g CO_2 /Cap.d	**68**
	kg CO_2 /Cap.yr	25
Total COD converted without the WWTP (reduction)	g CO_2 / Cap.d	**86**
	% emission reduction	46

4.1.2 Sneek

The experience gained from the first Decentralized Sanitation and Reuse (DeSar) pilot plant in Sneek (Netherlands) was used to estimate the GHG emission from the conceptual decentralized treatment system of 250 houses (about 575 persons).

As described in Chapter 2 (**Section 2.8.2**), in this system greywater and blackwater are collected and treated separately as illustrated (**Figure 2.19**) in the process flow diagram described earlier.

4.1.2.1 Emissions from the Greywater and Blackwater Biological Processes

a) Buffer Tanks

In the buffer tanks for both greywater and blackwater, GHG emissions are negligible, since the retention time is short, lasting only a few hours.

b) Anaerobic Bioreactor UASB Type

To estimate the total amount of biogas produced and collected, a mass balance over the UASB type reactor was carried out. From this digestion process, about 30 m^3 per day of biogas is collected. It

was assumed that the biogas is composed of 35% CO_2 and 65% CH_4. About 0.2% (0.06m^3/d) is flared, which constitutes 0.11 kg CO_2 equivalent in GHG emissions per day. The remaining part of the biogas, 29 m^3/d, is converted to energy from the Combined Heat and Power (CHP) plant. This conversion is equivalent to 27,269 KWh/d and makes up 35% of the energy required for the treatment plant (**Annex 7.4.1** and **7.4.2**).

c) Anammox Reactor

It was found that 11.73 kg of CO_2 is emitted per day, according to the COD mass balance that was carried out over the Anammox reactor. This emission is due to the biological processes taking place during the nitrification and denitrification processes. There is also potential emission of N_2O, which is another GHG but not our focus in this research.

d) Struvite Reactor

A small amount of CO_2 is emitted during the process of struvite formation. This amount is not taken into consideration, since it is reportedly negligible

e) A-B Process Reactor

The COD mass balance over the A-B reactor showed zero emission of CO_2. This could be explained by the physical nature of this process. Since no biological processes are taken place in the reactor.

4.1.2.2 Emissions due to the Net Energy Used

Table 4.4 illustrates a summary of the energy used and produced in the treatment processes of the plant. The net energy is computed by deduction of the energy produced from the total energy required.

The results show an emission of 10 kg of CO_2 per day (18 g CO_2/capita per day) due to the net energy used by the system.

Table 4.4: Sneek energy balance

Parameters		KWh/yr	KWh/d
Energy requirement		34,080	93
Energy production	Electric :	27,269	75
	Thermal :	50,642	139
Net electric energy consumption		6,811	19

4.1.2.3 Overall GHG Emission of Sneek Conceptual Treatment Plant

The overall GHG emissions for the Sneek Conceptual WWTP were estimated considering the direct and indirect (biological processes and energy consumption respectively) emissions of the domestic wastewater treatment; using the pilot plant data.

The results show emissions of about 38 g CO_2/cap.d or 0.014 t CO_2/cap.yr.

If this treatment were not done (discharge of untreated wastewater) the emission would have been 227 g CO_2/Cap.d, 83% greater than the actual emission. A summary of the overall emissions from this treatment plant is given below (**Table 4.5**).

Table 4.5: Summary of Sneek GHG emission

Parameters	Unit	Value
Population equivalent	PE	575
Design flow	Blackwater m^3/d	3.9
	Grey water m^3/d	51.8
Influent COD	Black water kg/d	72.45
	Grey water kg/d	29.91
Biogas production	m^3/d	29
Energy production from biogas	KWh/d	75
Energy required for the system	KWh/d	93
Net energy used	KWh/d	19
CO_2 emission due biological processes	g CO_2 /Cap.d	**21**
	kg CO_2 /Cap.yr	8
CO_2 emission due net energy used (Table 3.1)	g CO_2 / Cap.d	**18**
	kg CO_2 /Cap.yr	7
Total CO_2 Emission	g CO_2 /Cap.d	**38**
	kg CO_2 /Cap.yr	14
Total COD converted without the WWTP	g CO_2 / Cap.d	188
(reduction)	% emission reduction	**83**

4.1.3 EIER-Ouaga

An analysis of the GHG emissions was conducted on a series of three wastewater stabilisation ponds at the EIER pilot-scale wastewater treatment plant, in the African country of Burkina Faso. The series was composed of one anaerobic pond, one facultative pond, and one maturation pond (**Figure 2.20**).

4.1.3.1 Direct GHG Emissions from EIER WWPT

The data from the performance assessment (October 2004 to July 2005) of the treatment plant was used to carry out a COD mass balance over the three ponds (Anaerobic, Facultative and Maturation). Based on the calculations conducted, it was found that about 15.33 kg of biogas (9.96 kg of CH_4 and 5.37 kg of CO_2 per day) are emitted to the atmosphere per day from the anaerobic pond. Moreover, 2.69 kg of methane is produced from the facultative pond. The emissions of CH_4 and CO_2 are found to be zero in the maturation pond. In summary, 192 kg CO_2 equivalent per day is emitted due to the biological processes (direct emissions).

4.1.3.2 Indirect GHG Emissions from EIER WWPT

The energy in the production of raw materials, chemicals used and the energy used for the daily operation and maintenance are considered indirect emissions. Gravity sewers are used to transport the wastewater to the treatment plant, where no energy is consumed in the treatment processes. The emissions due to the net energy consumed are found to be zero.

4.1.3.3 Overall GHG Emissions from EIER WWPT

The overall GHG emissions for EIER-Ouagadougou anaerobic pond systems were estimated considering the direct and indirect emissions of the domestic wastewater treatment; using the performance assessment data.

The results show emissions of about 192 g CO_2/capita.day or 0.070 t CO2/capita.year.

If the treatment were not done, emissions would have been 224 g CO_2/capita.day, which is 14% greater than the actual emissions. A summary of the overall emissions from this treatment plant is given below (**Table 4.6**).

Table: 4.6 Summary of EIER-Ouaga anaerobic pond systems

Parameters	Unit	Values
Population equivalent	PE	220
Design flow	m^3/d	55
Influent COD	kg/d	36
Biogas production	m^3/d	6
Energy production from biogas	KWh/d	0
Energy required for the system	KWh/d	0
Net energy used	KWh/d	0
CO_2 emission due biological processes	g CO_2 /Cap.d	192
	kg CO_2 /Cap.yr	70
CO_2 emission due net energy used (Table 3.1)	g CO_2 / Cap.d	0
	kg CO_2 /Cap.yr	0
Total CO_2 Emission	g CO_2 /Cap.d	**192**
	kg CO_2 /Cap.yr	70
Total COD converted without the WWTP (reduction)	g CO_2 / Cap.d	32
	% emission reduction	14

4.1.4 Siddhipur

In this alternative system of "UDDTs", the following three waste streams were analysed for GHG emissions (**Figure 2.21** and **2.22**) :

- Urine collection, transport, treatment and reuse as fertilizer;
- Dry faeces collection, transport and reuse as soil conditioner; and
- Greywater collection, transport, treatment and disposal.

In order to assess the GHG emission of these waste steams, data from pilot-scales experiments in Siddhipur, South Africa, India, and many other locations were taken from available literature (**Table 4.7 and 4.8**) and used together with reasonable assumptions.

Table 4.7: Average daily per capita composition of urine, faeces and greywater (Benetto *et al.*, 2009)

	Unit	Urine	Faeces	Greywater
Quantity	kg/cap.d	0.8 - 1.5	0.14 -0.52	80
COD	g/cap.d	15	35	60
N-total	g/cap.d	10	1.5	1.3
P-total	g/cap.d	1	0.5	0.5

Table 4.8: Characterisation of fresh faeces and decomposed faeces after 6 months in UDDT covered in wood ashes (Nwaner *et al.*, 2008)

Property	Unit	Fresh faeces	Decomposed faeces	% reduction
Total COD	mg COD/g	322	123	62
Moisture	g H_2O/g	0.79	0.18	77

4.1.4.1 Direct GHG Emissions from Siddhipur Sanitation System

Based on calculations conducted for the waste stream of Urine, there is expected to be some volatilization of certain nitrogenous elements (NH_3-N, N_2O-N, NO_x-N; **Table 4.9**), although these are not the focus of this research.

Table: 4.9 Expected amount of nitrogen volatilization

Losses	Unit	Piping holding tanks	Storage tanks	Application	Sources
NH3-N	%N urine	<1 (0.01) <0.3	0.003	<10 (6) <1	(Stockholm Vatten 2000; Vinneras et al 1998; Palm *et al.,* 2002)
N2O-N	%N urine			1.25	(Tidaker 2003; EMEP/CORINAIR 2004)
NOx-N	%N urine			0.7	(Tidaker 2003)

For the case of the second stream (Faeces), it is accepted that biological digestion occurring in the urine diversion toilets is mostly anaerobic (Chaggu *et al.*, 2007). This is because as the wastes accumulate at the bottom of the pit or vault, only the thin layer at the surface of the heap is exposed to air. When ash is used as a bulking or conditioning agent, an increase in pH value is observed, resulting in inhibition of biological degradation of the waste.

It was found that 62% and 77% of COD and moisture content reduction, respectively, from fresh faeces to dried ones, which has led to 49 g of CO_2 equivalent emission per person per day.(**Annex 7.6.1** to **7.6.3**).

The third and last waste stream (Greywater) was found not to emit CO_2, since a natural wastewater treatment system (Constructed Wetland) is used.

4.1.4.2 Indirect GHG Emissions from Siddhipur Sanitation System

The energy in the production of raw materials, chemicals used and the energy used for the daily

operation and maintenance are considered indirect emissions (**Table 4.10**). Bicycles are used for the transport of urine to the treatment plant, where 0.06 Kwh/d of electricity is required for pumping and diluting the urine. Gravity-based sewers are used to transport the greywater to the treatment plant, where 0.20 Kwh/d of electricity is consumed in the treatment processes. For the transport of the dried faeces, hand carts are the most common means used here, therefore no fossil fuels are consumed.

The emissions due to the net energy consumed are found to be 0.28 g of CO_2 equivalent emission per person per day, which represent about 0.6% of the total emission.

Table: 4.10 Estimated Energy consumed in Siddhipur Sanitation System

Stream	**Collection and transport**	**Treatment**		**Subtotal energy** (kWh/d)
Urine	0 kw/km (bicycles)	0.08 kWh/m^3 (pumping)	0.1 kWh/m^3 (dilution)	0.06
Faeces	0 kW/km (animals Carts)		0	0
Greywater	0 (gravity sewer)		0.005 kWh/m^3	0.20
Total energy				0.263 kWh/d

4.1.4.3 Overall GHG Emissions from Siddhipur Sanitation System

The overall GHG emissions for Siddhipur Sanitation System were estimated considering the direct and indirect emissions of the system, using data from pilot-scale experiments in Siddhipur, South Africa, India, and many other locations from the literature.

The results show emissions of about 49.4 g CO_2/capita.day or 0.018 t CO2/capita.year.

If the treatment were not done, the emission would have been 138 g CO_2/capita.day, 64% greater than the actual emission. A summary of the overall emissions from this treatment plant is given below (**Table 4.11**).

Table: 4.11 Overall GHG emissions from Siddhipur sanitation system

Parameters	Unit	Value
Population equivalent	PE	510
Design flow	Urine m^3/d	0.33
	Faeces kg/d	127.5
	Greywater m^3/d	41.8
Influent COD	Urine kg/d	3
	Faeces kg/d	17.85
	Greywater kg/d	30.60
Biogas production	m^3/d	3.86
Energy production from biogas	KWh/d	0
Energy required for the system	KWh/d	0.26
Net energy used	KWh/d	0.26
CO_2 emission due to biological processes	g CO_2 /Cap.d	49
	kg CO_2 /Cap.yr	18
CO_2 emission due to net energy used (Table 3.1)	g CO_2 / Cap.d	0.3
	kg CO_2 /Cap.yr	0.1
Total CO_2 Emission	g CO_2 /Cap.d	**49.4**
	kg CO_2 /Cap.yr	18.0
Total COD converted without the WWTP (reduction)	g CO_2 / Cap.d	88
	% emission reduction	64

4.1.5 Summary of the Results

Figure 4.2 summarises the GHG emissions of each scenario with and without the wastewater treatment. Moreover, the gain obtained by implementing each treatment technology is depicted in the figure as a percentage of emission.

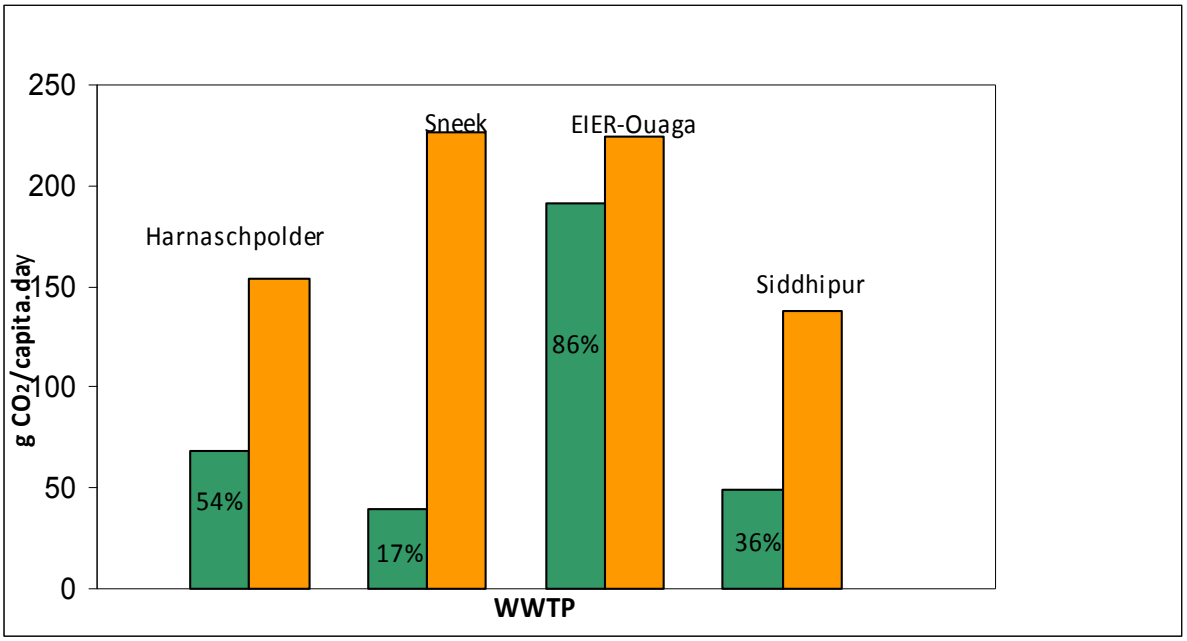


Figure 4.2 Summary of the GHG emission of all four scenarios with ( ) and without ( ) wastewater treatment

It appears from this figure that Sneek and EIER-Ouaga emissions are high when the wastewater is discharged untreated. This can be attributed to their high per capita concentration of the COD content. However, implementing a wastewater treatment plant indicates a lower emission for Sneek, while EIER-Ouaga shows the highest. There are number of factors that can explain these low and high emissions which are discussed in the next section.

Table 4.12: Summary of the Overall Results of the four Scenarios

Parameters	Unit	Name of the wastewater Treatment Plant			
		Harnaschpolder	Sneek	EIER-Ouaga	Siddhipur
Population equivalent	PE	1,300,000	575	220	510
Design flow	Blackwater or mixed m^3/d	263,862	3.9	55	0.33
	Greywater m^3/d		51.8		40.8
Influent COD	Blackwater or mixed kg/d	145,062	72.45	36	127.5
	Greywater kg/d		29.91		30.60
Biogas production	m^3/d	13728	29	6	3.86
Energy production from biogas	kWh/d	34555	75	0	0
Energy required for the system	kWh/d	79469	93		0.26
Net energy used	kWh/d	44914	19		0.26
CO_2 emission due biological processes	g CO_2/cap.d	47	21	192	49
	kg CO_2/cap.yr	17	8	70	18
CO_2 emission due net energy used	g CO_2/cap.d	20	18	0	0.3
	kg CO_2/cap.yr	7	7	0	0.1
Total CO_2 Emission	g CO_2/cap.d	68	38	192	49.4
	kg CO_2/cap.yr	25	14	70	18.0
Total COD converted without the WWTP (reduction)	g CO_2/cap.d	86	188	32	88
	% emission reduction	46	83	14	64
Without treatment		153	227	224	138
% of energy reuse		43	35	0	0

The **Table 4.12** summarises the overall results of the analysis of this research work. It shows that Harnaschpolder and Sneek are reusing almost half of their energy requirement while EIER-Ouaga and Siddhipur has zero reused of energy. Details of the results presented here are discussing in the following section.

4.2. Discussion

4.2.1 Harnaschpolder

The global GHG emission followed by the Harnaschpolder wastewater treatment indicates that 68 g CO_2 per capita per day is 44% greater than the range of values (30-38 g CO_2/c.d) found from the literature (**Table 1.3**) (Hospido *et al.*, 2007, Kärrman and Jőnsson, 2001).

This great difference may in part be explained by the method used in the estimation. Life Cycle Analysis (LCA), SimaPro 5.1 software and the Centre of Environmental Science (CML) of Leiden University methodology were the tools used for the evaluation of the environmental performance of this system, while COD mass balance was the tool considered under this study. In determining the environmental impact (GHG emission) of those systems by using the LCA approach, many assumptions (e.g., the fraction of degradable organic component removed as sludge = 0.63 (Casey, 1997), the fraction of wastewater treated anaerobically = 5-10%, maximum methane yield = 0.25 kg CH_4/kg BOD, no flaring of methane) appears to underestimate the CO_2 emission. For example, the LCA methodology uses the BOD value to represent the amount of organic fraction in a municipal wastewater streams, whereas the COD value was used in the concept of COD mass balance. Many details are not known about the use of others programs (SimaPro 5.1 software and CML), which may also influence the results.

Secondly, the complexity involved in the treatment process could be the reason for this increased emission. Nowadays, the increased demand for the wastewater effluent quality and the handling of sludge have introduced more and more complex processes in the wastewater treatment. For instance, Harnaschpolder WWTP (a modern activated sludge system) includes both biological and chemical phosphorus removal, whereas the other systems are conventional activated sludge where strict effluent standards were not applied.

Lastly, the scale of the treatment plant also could be an important factor that shows this difference. Other WWTP's capacities ranged from 75,000 to 125,000 inhabitants, while Harnaschpolder attends approximately 1.3 million population equivalent. It is not always verified that economy of scale, will minimise the effect of GHG emission, since smaller systems tend to neglect some aspects that are more visible in the larger systems. For example, big wastewater systems require more pumping, more surface for aeration and therefore, more energy consumption and more GHG emission in the

day-to-day operation.

Furthermore, this GHG emission could be increased by certain factors if the collection, transport (pressurised sewer) and the effluent and sludge are included in the estimate. Nevertheless, this emission can be reduced if the energy produced from incineration process of the dewatered sludge or the reuse of the compost sludge as soil conditioner is considered.

On the other hand, about 43.5% of the total energy required for the operation and maintenance of the treatment plant is obtained from the biogas produced from the digestion of the sludge. This management strategy reduces the environmental impact of CO_2 emissions to about 16% (**Annex 7.3.3**). According to KWR and STOWA 2008 report titled "Towards a Climate Neutral Water Netherlands", the use of energy-efficient equipment, and the saving and reuse of energy, water and materials during the Harnaschpolder wastewater treatment is 6.3% lower than the national average. This reduction represents about 2% (**Table 3.1**) of the daily GHG emission due to energy consumption only, which is a considerable amount of CO_2 if all the wastewater treatment plants of Netherlands are considered.

4.2.2 Sneek

In general terms, the Conceptual Wastewater Treatment Plant produced the least amount of GHG emissions (38 g CO_2/ capita per day or 0.014 ton CO_2/capita per year) within the four scenarios analysed. This could be explained by the fact that not only the biogas is reused for the production of electricity and heat, but also the treatment scale (pilot) as discussed in **Section 4.2.1 Paragraph 4.**

This emission could be lowered further, if the struvite produced as fertilizer is deducted from the emissions generated during chemical fertilizer production. This project can be a potentially excellent CDM project, because implementing such project in a place where no wastewater treatment is available could reduce the GHG emission by about 83% (**Figure 4.2**). It should be noted that in Sneek decentralised system, the production of biogas (reused for energy and heat production) is increased by the addition of ground organic kitchen waste which is not considered in the other three systems.

However, increased of GHG emission is expected when the system boundary is expanded to include the collection and transport (vacuum sewers) subsystem. The energy demand for the

vacuum and pressure pumps can vary depending on the layout of the system. **Annex 7.9** lists energy data from several vacuum systems. An average energy demand of 25 kWh/(cap. yr) for the vacuum pumps is generally used, which corresponds to 14.75 kg CO_2 /(cap.yr). In addition, if the sludge handling after the digestion has been considered, the GHG emission from this system will have increased by some factors.

4.2.3 EIER-Ouaga

Despite the fact that no electrical energy is used in the treatment process, the GHG emission from EIER-Ouagadougou anaerobic pond systems is found to be the highest (192 g CO_2/c.d or 0.070 ton CO_2/c.year), compared to the other three scenarios (**Figure 4.2**). It was estimated 80% higher than the cleanest scenario (Sneek). This may be explained by several factors. First, the biogas produced from the anaerobic pond, which represents 82% of the total GHG emission, is not collected. Second, the wastewater characteristics (high biodegradability of the wastewater COD/BOD<2, lower dilution and no mixing of storm water) could also explain this relatively high GHG emission, unlike the Western European wastewater.
And last, climatic conditions (i.e., high temperature, pH) play an important role in the high GHG emission and the efficiency of the treatment plant.

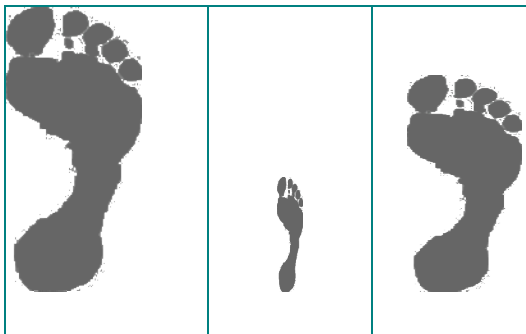
This scenario could be very interesting, if the large amount of biogas that is produced by the anaerobic pond were collected and converted to electricity. An important point is the reuse of wastewater effluent for irrigation, since water scarcity is an important issue in the city of Ouagadougou. Moreover, the reuse of effluent for irrigation will not only reduce the energy demand due to lower water consumption, but also reduce the amount of chemical fertilizer required and therefore other GHG emissions.

However, in spite of this increased emission level of CO_2 (192 g CO_2/c.d or 0.070 t CO_2/c.year) from Ouagadougou's wastewater treatment, it is still very low compared to other sectors, like public transport (**Table 4.13**) and (**Figure 4.4**). It is clearly shown that the average emission from this wastewater treatment presents less than 3% (2.4%) of the average emission (2.956 t CO_2/c.year) from the transport sector.

4.2.4 Siddhipur

The fourth scenario gives also very important results in terms of GHG emission (49.4 g CO_2/c.d or 0.018 ton CO_2/c.year). This result, compared to recent research done by UNICEF India (Winrock, 2008) on three types of sanitation systems (Open defecation 22.68 g CO_2/c.d, Leach pit toilets 9.66 g CO_2/c.d and Toilet-linked biogas plants 3.36 g CO_2/c.d), is relatively high. This can be associated to the fact that only one waste stream (faeces) is considered during the estimation of the GHGs. It is important to point out that, a field experiment was devised by the research group of UNICEF India to collect and measure the gases which are produced from the fresh faeces in open defecation, since no available information is found in the literature. This type of method (field experiment) can be an interesting basis to estimate GHGs from new sanitation systems, such as Ecosan, in order to compare with the theoretical method used in this research.

The total emission could be lowered further if the struvite and dry faeces used as fertilizer is deducted from the emission emitted during chemical fertilizer production. This project can be a potentially excellent CDM project, because implementing such project in a place where no wastewater treatment is available could reduce the GHG emission by about 64% (**Figure 4.2**).
In spite of the low emission levels that would be registered, considering transport of urine and dry faeces by trucks would contribute to more than 3% (Remy and Ruhland, 2006) to the total estimated emission.
In summary, the GHG emission from this treatment plant is still very low, even negligible, compared to other sectors (**Figure 4.3**).



My Footprint	Siddhipur Average	World Target	• My footprint is **3.27 t CO_2/cap.yr** • Siddhipur is **0.018 t CO_2/cap.yr** • World target **2 t CO_2/cap.yr** • average worldwide is about **4 tCO_2/cap.yr** **Source**: carbon footprint website (see ref.)

Figure 4.3: Comparison of different carbon footprint (http://www.carbonfootprint.com/index.html)

The comparison performed showed that the different configurations entail variations on the emission of GHGs. Although higher electricity consumption was reported for the modern activated sludge system of Harnaschpolder, it was found to emit less GHG compared to the natural system (anaerobic pond systems of EIER-Ouaga).

From the above discussions, it may be safely concluded that the systems considered cannot actually be bluntly compared with each other. Because wastewater of different characteristics are treated in the scenarios considered (**Table 2.8**) and the scale of the treatment plants (pilot, conceptual, full-scale) are also another factor that will make unfair comparison of the systems.

As a result, there is evidence to suggest that GHG calculations can help in making a cleaner technology selection, since it is a key parameter (criterion of air contamination) to environmental sustainability.

Lastly, in order to have a better indication of the results obtained in the analysis of the four wastewater treatment scenarios presented in this work, a comparison is made with the public transport sector in the world (**Table 4.13** and **Figure 4.4**).

Table 4.13: Different GHG emission values from wastewater and transport sectors

Sectors	Value (ton CO_2 equiv.* per capita per year)	Sources
Wastewater treatment		
Harnaschpolder	0.025	(Table 4.3)
Sneek	0.014	(Table 4.5)
EIER-Ouaga	0.070	(Table 4.6)
Siddhipur	0.018	(Table 4.11)
Transport sector		
City of Toronto	2.43	(Kennedy, 2002)
United States Average	4.54	(Moomaw and Johnston, 2007)
European Average	1.887	(DEFRA, 2001)

* CO_2 equiv = combination of CO_2 and CH_4 (**Table 3.1**)

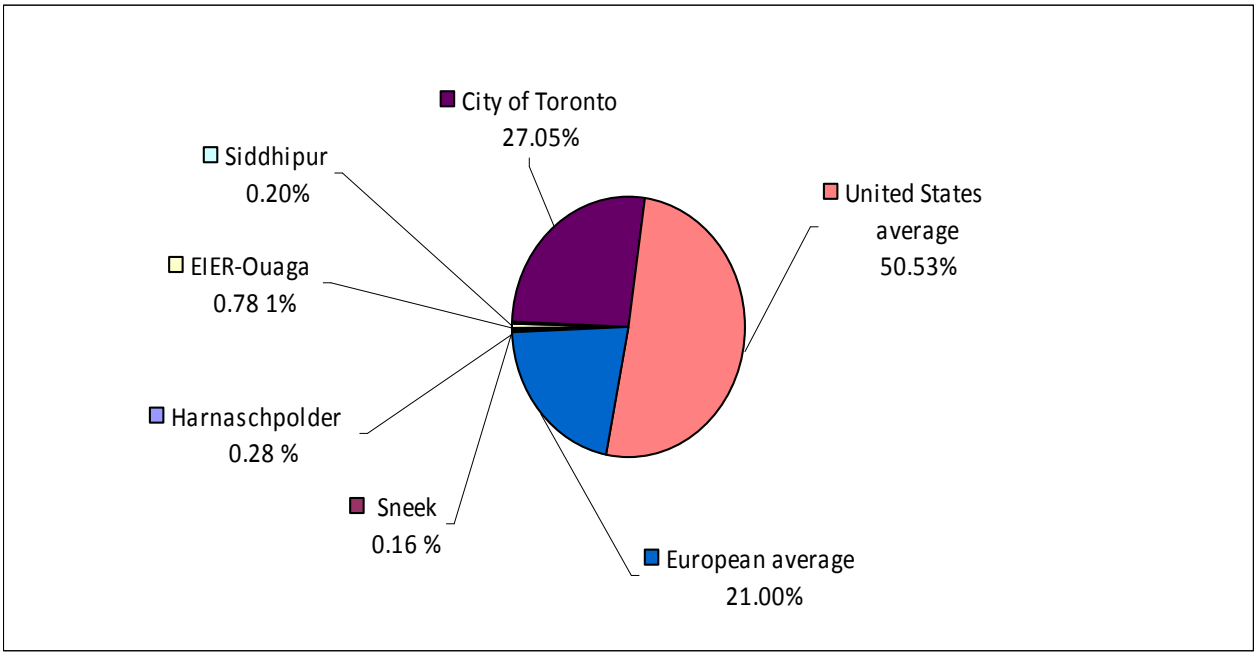


Figure 4.4: Comparison of the GHG emissions of the four scenarios with transport sector in the world

The **Figure 4.4** clearly indicates that the wastewater treatment sector contribution is relatively meaningless compare to the public transport. The United States transport sector contributes more than half in the emissions of GHGs.

Figure 4.5: Demonstration of decentralized waste water purification (vacuum and UASB technology

http://themas.stowa.nl/Themas/Projects.aspx?mID=7216&rID=1006&aID=1639

5 CONCLUSIONS AND RECOMMENDATIONS

5.1. Conclusions

This chapter discusses the conclusions drawn from the results obtained from the estimation of GHG emissions in both conventional and innovative sanitation systems. The research was conducted on four different wastewater treatment configurations: namely: (1) Harnaschpolder, (2) Sneek, (3) EIER-Ouaga and (4) Siddhipur. This analysis was based on the Intergovernmental Panel on Climate Change (IPCC) 2006 guidelines for estimating CO_2 and CH_4, together with Chemical Oxygen Demand (COD) mass balance and literature review.

Acknowledging the limitations encountered in carrying out this research an estimated daily average of 87 g of CO_2 equivalent, ranging between 38 to 192 g was derived to be the per capita CO_2 emission for the four different wastewater treatment scenarios considered. The major conclusion of this study reveals that the GHG emissions results are largely technology-dependent and highly influenced by case-specific boundary conditions.

The analysis of the available information of the selected wastewater treatment technologies discloses that, the GHGs emitted from these systems are much lower compared to other anthropogenic sources like the public transport sector. Despite the fact that the contribution of the GHG produced by wastewater management only reaches about 3% in relation to other anthropogenic sources, the management of this type of information could enable the sanitation company to control their environmental management, thus contributing to the accomplishment of GHG emission reductions objectives at the national and international level.

On the other hand, based on energy production, the modern activated sludge system has proven to be more energy intensive, but due to the fact that the digestion process offers significant energy potentials from the partial conversion of organic material into biogas. The high energetic benefit offsets the considerable energy demand; more than 43.5% of the total energy for the treatment processes, thus tremendously reducing its carbon footprint.

Concerning the innovative sanitation systems, the utilization of human excreta as fertilizer lowers the load of toxic heavy metals to agricultural soil in comparison with conventional chemical fertilizer. Depending on the system configuration, alternative sanitation systems can have a lower energy

demand and subsequently cause fewer emissions of GHGs. Only the increased emission of acidifying gases (mostly NH_3) represents a considerable drawback which can be handled. Furthermore, these innovative sanitation systems can be promoted under CDM projects.

To ensure a positive impact of these treatment systems on the environment, it is recommended to introduce an optimum biogas reuse (for the production of electricity and heat), the source separation of human excreta (to disburden the wastewater treatment processes) and any other wastewater treatment management strategies.

Another vision is greater communication about the carbon footprint of each specific wastewater treatment technology will not only promote it but also will contribute in the achievement of the MDGs (Number 7).

Knowledge gained in this study would add to the better understanding of how much the wastewater treatment sector is contributing to the emissions of GHGs and therefore, how to take the necessary actions by the decisions makers to reduce these emissions

5.2. Recommendations

Based on the results, discussions and conclusions, the following recommendations are proposed.

This study used literature data and assumptions in estimating GHGs. It is recommended in future studies to have more rigorous laboratory experiments and pilot scale plants to enhance the significance of the presented results. An optimum data quality can be only achieved by carrying a direct measurement (on site) of the GHGs on the field. This will enable the improved data quality to play an important role in the next steps for the estimated of GHGs emission on wastewater treatment technologies.

This study used Excel software in computing the data. Carry out further studies on the development of a tool to calculate the GHG benefits of full scale sanitation system, both conventional and innovative sanitation systems will be a great advantage in the estimation process. The tool to develop should consist of cradle to grave sanitation chain, with a user friendly interface that is easy to use for entrepreneur and that gives clear and reliable answers to decision makers on GHG emissions. In addition the tool should be accompanied by a solid database, which will be based on information

gotten from rigorous laboratory experiments (first paragraph).

This study used different types of wastewater treatment plants, therefore the systems fulfil different levels of treatment and thus are not comparable on an equivalent base of reference. In order to establish the same base of reference, the carbon footprint criteria have to be standardizing for comparison and technology selection purposes.

This study has considered only carbon dioxide and methane emissions, but other significant GHGs for instance nitrous oxide have also been shown to be emitted from wastewater treatment. It is recommended to perform additional research on these gases because there is still much uncertainty about the emissions of this GHG from wastewater treatment and also very poor information about the contribution of new treatment technologies emission of GHGs is available in literature.

Figure 5.1: collection and transport of urine

Source of the picture: Bastian Etter, Eawag: Swiss federal institute of aquatic science and technology

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7 ANNEXES

Annex 7.1: Examples of human intervention in the global biogeochemical cycles of carbon, nitrogen, phosphorus, sulfur, water, and sediments. Data are for the mid 1900s.

(Falkowski et al., 2000)

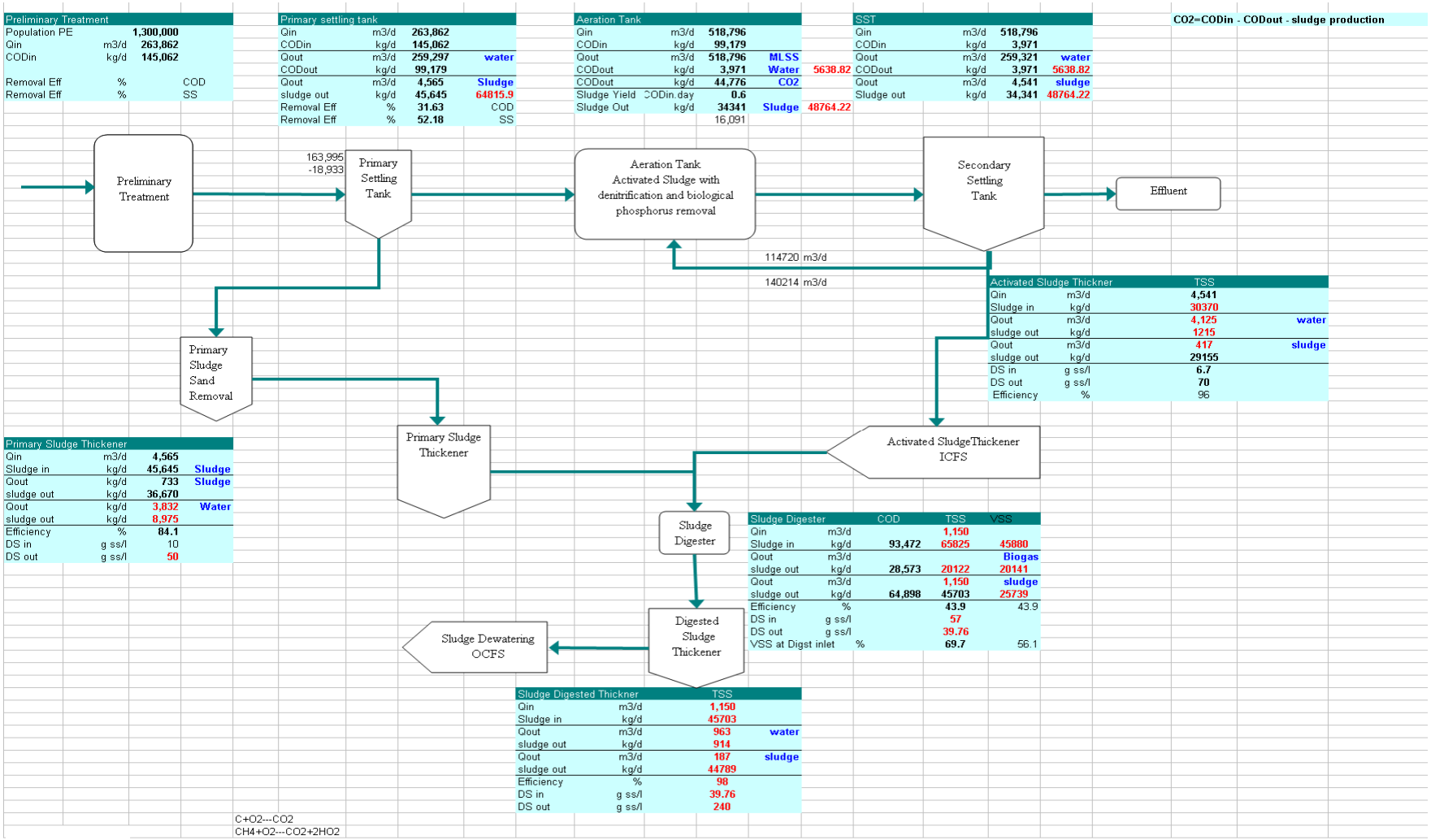
Element	Flux	Magnitude of flux (millions of metric tons per year)		% change due to human activities
		Natural	Anthropogenic	
C	Terrestrial respiration and decay CO_2	61,000		
	Fossil fuel and land use CO_2		8,000	+13
N	Natural biological fixation	130		
	Fixation owing to rice cultivation, combustion of fossil fuels, and production of fertilizer		140	+108
P	Chemical weathering	3		
	Mining		12	+400
S	Natural emissions to atmosphere at Earth's surface	80		
	Fossil fuel and biomass burning emissions		90	+113
O and H	Precipitation over land	111×10^{12}		

Annex 7.2: **Default Methane correction factors values for domestic wastewater** (IPCC, 2006)

DEFAULT MCF VALUES FOR DOMESTIC WASTEWATER			
Type of treatment and discharge pathway or system	**Comments**	**MCF [1]**	**Range**
Untreated system			
Sea, river and lake discharge	Rivers with high organics loadings can turn anaerobic.	0.1	0 – 0.2
Stagnant sewer	Open and warm	0.5	0.4 – 0.8
Flowing sewer (open or closed)	Fast moving, clean. (Insignificant amounts of CH_4 from pump stations, etc)	0	0
Treated system			
Centralized, aerobic treatment plant	Must be well managed. 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 metres, use expert judgment.	0.2	0 – 0.3
Anaerobic deep lagoon	Depth more than 2 metres	0.8	0.8 – 1.0
Septic system	Half of BOD settles in anaerobic tank.	0.5	0.5
Latrine	Dry climate, ground water table lower than latrine, small family (3-5 persons)	0.1	0.05 – 0.15
Latrine	Dry climate, ground water table lower than latrine, communal (many users)	0.5	0.4 – 0.6
Latrine	Wet climate/flush water use, ground water table higher than latrine	0.7	0.7 – 1.0
Latrine	Regular sediment removal for fertilizer	0.1	0.1

[1] Based on expert judgment by lead authors of this section.

Annex 7.3. 1: Calculation Spreadsheet of Harnaschpolder (1)



Annex 7.3.2: Calculation Spreadsheet of Harnaschpolder (2)

Mass balance for Design data				CH4+O2---CO2+2HO2														
Plant Units	**In**					**Out**				**Difference**								
	COD	COD	CO2	CH4		COD	COD	CO2	CH4									
	Dissolved	Sludge				Dissolved	Sludge											
	kg/day	kg/day	kg/day	kg/day		kg/day	kg/day	kg/day	kg/day	kg/day								
PST	**145,062**	**18933**	0	**0**		**99179**	**64816**	**0**	**0**	**0**								
AT	**99179**	**0**	0	**0**		**5639**	**48,764**	**44,776**	**0**	**0**								
Digester	**0**	**93472**	0	**0**			**64898**	**10,001**	**18,573**	**0**								
Total								54,776	18,573		Biological			**Biogas loss**				
CO2 equivalent (COD and CH4) kg/d								75317.66468	51074.6665		61567	kg CO2/d		26	m3/d			
Total due to biological processes CO2 kg/d									126392.33		61613			0.2	%			
			CO2 g/cap/d						**97**		47	g CO2/cap.d		46	**kg CO2/d**			
			kg CO2/year						**35**		17	kg CO2/cap.year						
Total COD converted to CO2 kg/d									199460.25									
			CO2 g/cap/d						**153**					Emission reduction				
Total emission (biological and energy used)									244442.3892		88234	kg CO2/d		difference	**gco2/c.d**	%		
				g CO2/cap/d					**188**		68	g CO2/cap.d			**86**	46		
				kg CO2/year					**69**		25	kg CO2/cap.year						
Energy used																		
			In duty	**Standby**		**operation time**	**operation time**	**Energy consumed**										
						h/d each	**d/week**	**kwh/d**	**Q m3/s**	**Head h m**	**n efficiency**		75708					
Influent pumps						24	7	52.43	183.238	3.5	0.8		149589.041					
Primary sludge pumps			4	2		14.3	7	0.07	0.093	3.2	0.7		79158.6					
Total number of blowers			4	2		11.5 to 24	7	149589.0411	18250	Nm3/h	81186 kgO2/d							
Settled sludge recirculation pumps			16	4		24	7	9.50	0.885	8.2	0.8							
Excess biological sludge pumps			16	4		14.2	7	0.17	0.023	8.2	0.7							
Thickned primary sludge pumps			2	1		12.2	7	0.02	0.041	4.2	0.7							
Thickned primary sludge recirculation pump			2	1		24	7	0.09	0.111	4.2	0.7							
Excess biological sludge pumps at inlet of			3	1		16	7	0.06	0.094	3.2	0.7							
Number of centrifuge for Excess Bio-sludge			3	1		24	7	851.44	4541.000	m3/d	1 to 2 kwh/m3							
Excess biological sludge pumps at outlet o			3	1		16	7	0.005	0.006	4.2	0.7							
Energy needed to keep the digester at 35 c								1808.00										
Number of compressor			2	1					1200	Nm3/h								
Digested sludge pumps			3	1		9.6 to 24	7	0.02	0.019	4.5	0.7							
Number of centrifuge for digested sludge de			3	1		24	7	215.63	1150.000	m3/d	1 to 2 kwh/m3							
Dewatered digested pumps			2	1		7.4 to 24	7	0.61	0.005	4.2	0.7							
Effluent pumps						24	7	51.53	180.084	3.5	0.8							
Chemical dosing pumps																		
efficiency of pumps		screw pumps	60 to 75%					152570.5938										
		centrifugal	70 to 87%															
				ρ= density of water kg/m3														
power	N= ρ * g * h * Q / n		where	g= acceleration of gravity in western Europe 9.81m2/s														
				h= manometric head in meters water column														
				Q= discharge in m3/s														
				n	efficiency of the pump													
				N	the required power to drive the pump in watt													

Annex 7.3.3: Calculation Spreadsheet of Harnaschpolder (3)

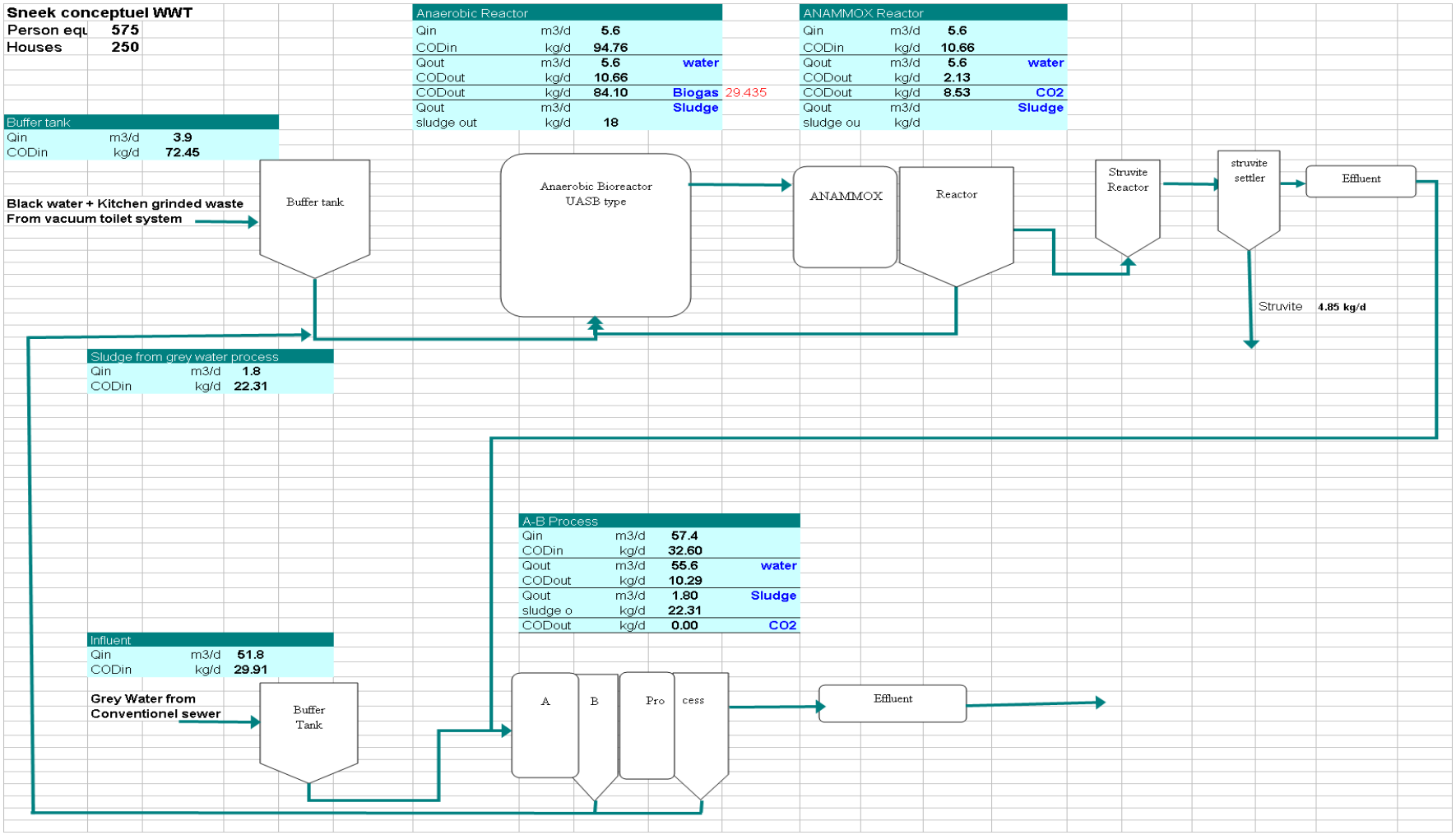
Energy consumption partern

Rwzi-code	15008			Consumption by:								
RWZI name	RWZI HARNA	Bought Energy	Production (from CHP or fermentation)	Gasenginer /	Direct Power (pumps etc.)	Aeration	Digester	Dewatering	Flared biogas	Emission without burning	Others	Delivery to third parties
Hot water / steam (GJ / y)		0	34,714	0	0	0	33,764	0	0	0	951	0
Bio gas (m3/year)		0	5,010,696	4,966,305	0	0	0	0	9,391		0	0
Electricity (kWh/y)		16,393,724	12,612,500	378,375	12,300,000	10,637,424	1,000,000	976,450	0	0	3,713,975	0
Natural gas (m3/y)		24,714	0	0	0	0	0	0	0	0	24,714	0
		44914	77	%								
% reuse	%	57	29,006,224		13,606							
Total used			79469	kwh/d	46886.773							

Energy to CO_2

						kwh/d reduce	kg CO2/d red	gCO2/c.d re	% red
Total Energy required kwh/d			79469			5007	2954	2	2
Energy purchase kwh/d			44914	26499	kg CO2/d	20	g CO2/cap.d		
Natural gas Purchase m3/d			68	122	kg CO2/d	29%	due energy use		
CO2 conversion factors electricity			0.59	kg CO2/kwh		15.59	% of reduction due to biogas reuse		
CO2 conversion factor for gas			1.8	kg CO2/m3					

Annex 7.4.1: Calculation Spreadsheet of Sneek (1)



Annex 7.4.2: Calculation Spreadsheet of Sneek (2)

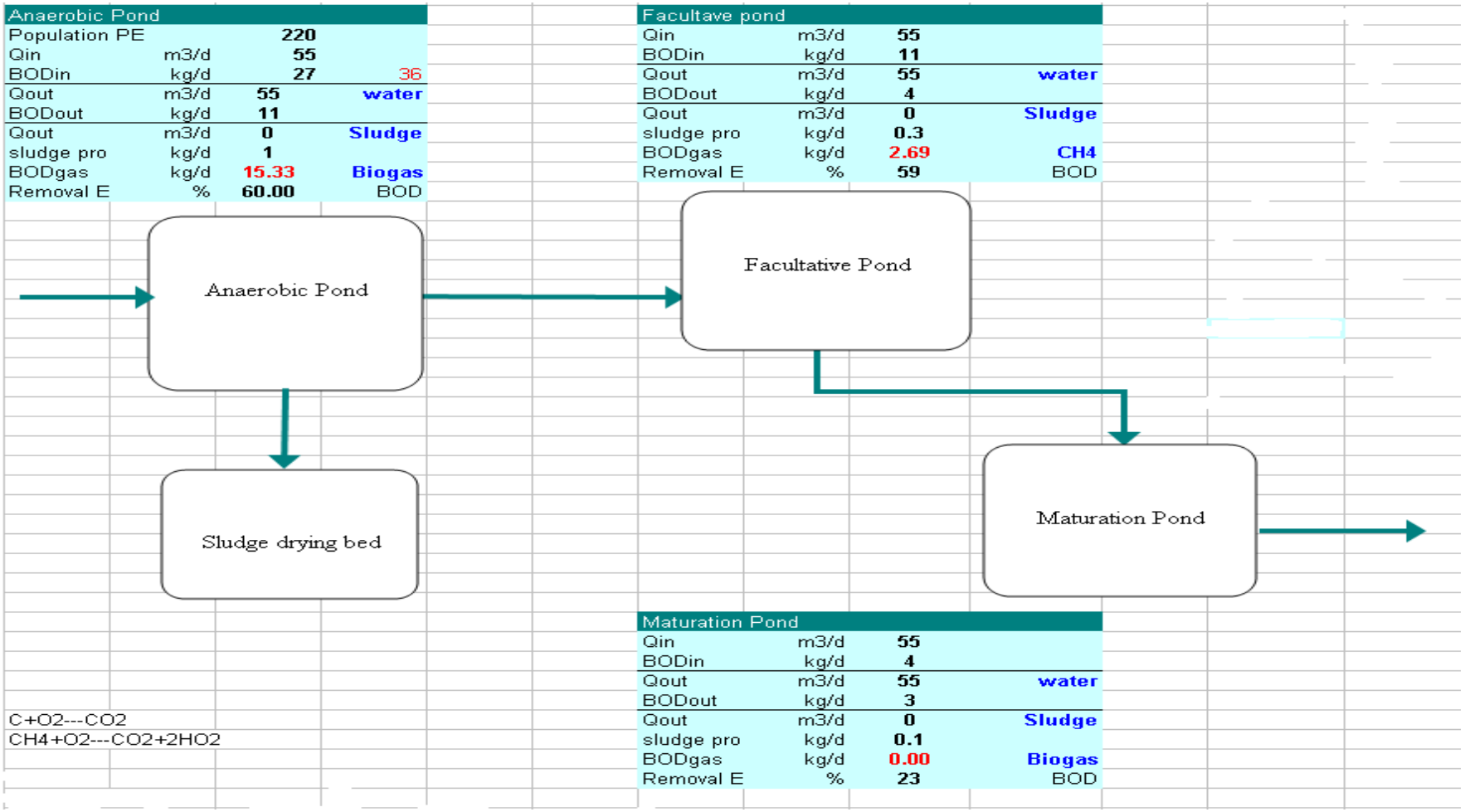
Mass balance of Sneek conceptual WWT															
Plant Units	**In**				**Out**				**Difference**						
	COD	COD	CO2	CH4	COD	COD	CO2	CH4							
	Dissolve	Sludge			Dissolved	Sludge									
	kg/day	kg/day	kg/day	kg/day	kg/day	kg/day	kg/day	kg/day	kg/day						
UASB Type	**0.00**	**94.76**	0.00	**0.00**	**10.66**	**18.00**	**29.44**	**54.67**	**0.00**						
ANAMMOX	**10.66**	**0.00**	0.00	**0.00**	**2.13**	**0.00**	**8.53**	**0.00**	**0.00**						
A-B process	**32.60**	**0.00**	0.00	**0.00**	**10.29**	**22.31**	**0.00**	**0.00**	**0.00**						
Total							37.97	54.67		11.73	kg co2/d				
CO2 equivalent (COD and CH4) kg/d							52.20	150.33							
Total due to biological processes CO2 kg/d								202.53		11.73	Kg CO2/d				
			g CO2 /cap/d					352		21	g CO2/ cap.d				
			kg CO2/cap.year					129		8	kg CO2/cap.y				
Total COD converted to CO2 kg/d								130.30		23					
			CO2 g/cap/d					227							
Total emission (biological and energy used)										23	kg CO2/d				
				g CO2/cap/d						40	g CO2/ cap.d				
				kg CO2/year						14	kg CO2/cap.y				

					Kwh/y	kwh/d	kg co2/	g co2/cap	kg co2/cap.year
energy requirement system:					34080	93			
energy production(combined electric heat production):									
	electric				27269	75			
	thermal				50642	139			
Net electric energy consumption:					6811	19	11	19	7
Co2 conversion factors electri			0.59	kg CO2/kwh					

Biogas loss	
Value	Unit
0.2	%
0.06	m3/d
0.11	kg CO2/d
0.18	g co2/c.d

Emission reduction	
187	g co2/c.d
83	%

Annex 7.5.1: Calculation Spreadsheet of EIER-Ouaga (1)



Anaerobic Pond			
Population PE		220	
Qin	m3/d	55	
BODin	kg/d	27	36
Qout	m3/d	55	water
BODout	kg/d	11	
Qout	m3/d	0	Sludge
sludge pro	kg/d	1	
BODgas	kg/d	15.33	Biogas
Removal E	%	60.00	BOD

Facultave pond			
Qin	m3/d	55	
BODin	kg/d	11	
Qout	m3/d	55	water
BODout	kg/d	4	
Qout	m3/d	0	Sludge
sludge pro	kg/d	0.3	
BODgas	kg/d	2.69	CH4
Removal E	%	59	BOD

Maturation Pond			
Qin	m3/d	55	
BODin	kg/d	4	
Qout	m3/d	55	water
BODout	kg/d	3	
Qout	m3/d	0	Sludge
sludge pro	kg/d	0.1	
BODgas	kg/d	0.00	Biogas
Removal E	%	23	BOD

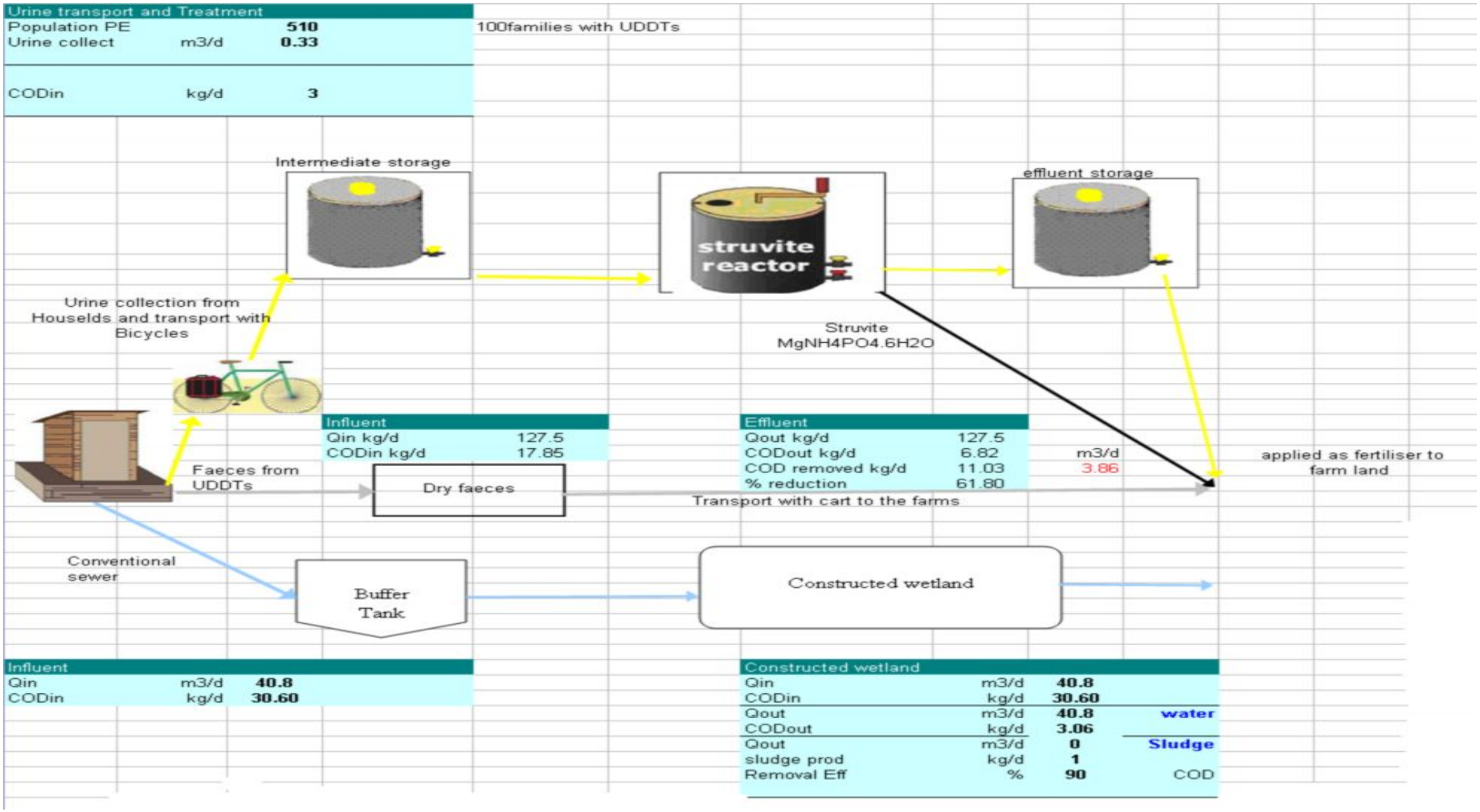
C+O2---CO2

CH4+O2---CO2+2HO2

Annex 7.5.2: Calculation Spreadsheet of EIER-Ouaga (2)

Influent concentrations											
Parameters	**Units**	**Value**	**Efficiency**	**Effluent**							
COD	mg/l	652	81	124							
BOD	mg/l	489	87	64							
TSS	mg/l	320	66	109							
TP	mg/l	15.79									
NTK	mg/l	209.3									
N-NH4+	mg/l	47.3									
N-NO3-	mg/l	4.03									
E-coli	ulog	6.97									
Temperature	*C	29.6									
PH		7.47									
Disolved O2		0.89									
Conductivity	us/cm	655									
Inf	Efficiency	inf Facul	Efficiency	inf Mat	efficiency	effluent Mat					
mg/l	% Anaerobic	mg/l	% Facul	mg/l	% Mat	mg/l					
489	60	196	59	81	23	62					
Ponds	Average BODp mg/	BODp/BODt %	BODt	BODfilter							
Facutative	66	45	147	81							
Maturation	55	47	117	62							
	Assumptions				Reference						
	0.25	25-50% of BODapp to CH4 facul Pond			Siddiqi et al (1972, IN: Arceivala, 1981) in India						
		T>20°C the BOD removal in Anae is 60%			Mara and Pearson, 1986						
	0.05	Biomass yield =0.05 kg VSS/ kg BOD			Henze et al (2009)						
		65% of the biogas is methane									
	Mass balance										
	Unit Plant		CH4	CO2		%					
	Anaerobic Pond		9.96	5.37	kg/d	82					
	Facultative Pond		2.69		kg/d						
	Maturation Pond				kg/d				**Emission reduction**		
	Total		12.65	5.37	kg/d				32	g co2/c.d	
	CO2 equiv		34.80	7.38	kg CO2/d				**14**	%	
				42.18	kg CO2/d						
				192	g CO2/cap.day						
				70	kg CO2/cap.year						
	Total COD			49	kg co2/d						
				224	g CO2/cap.day						

Annex 7.6.1: Calculation Spreadsheet of Siddhipur (1)



Annex 7.6.2: Calculation Spreadsheet of Siddhipur (2)

	Parameter	Unit	Value				
	EcoSan toilets installed in Siddhipur		100				
	Toilets working	[%]	80%				
	Average number of household members		5.1				
	Urine collected per person	[l·y¹]	300				
	Urine collected per household	[l·y¹]	1500				
	Urine collected in Siddhipur	[l·y¹]	122000	334.25	l/d		
	Urine COD	g/c.d	15				
	Faeces COD	g/c.d	35				
Assumptions							
	Faeces	250g/day	Unicef india report(2008)				
	UDDT faeces collection chamber	100l/cap. 6month	Compendium				
0.05	Biomass yield =0.05 kg VSS/ kg BOD						
	The energy demands for pumping and for dilution are estimated to respectively 0.08 and 0.1 kWh/m3 of yellow water (Remy et al., 2006)						
0.25	25-50% of BODapp to CH4 facul Pond						

Mass Balance							
Unit Plant		CH4	CO2				
Urine stream							
Intermediate storage		0	0	kg/d			
Struvite Reactor		0	0	kg/d		**Biogas**	Emission reduction
Effluent storage		0	0	kg/d		3.86	88 g co2/c.d
Faeces stream							**64** %
UDDT vault		7.2	3.9	kg/d			
Greywater stream							
Buffer tank		negligible	negligible	kg/d			
Constructed wetland reactor		0		kg/d			
Total		7.2	3.9	kg/d			
CO2 equiv		19.7	5.3	kg CO2/d			
			25.0	kg CO2/d			
			0.05	kg CO2/ c.d			
			49	g CO2/c.d	49.36		
Total COD of the system			51.01	kg/d			
CO2 equiv			70.13	kg CO2/d			
			138	g CO2/c.d			

Energy consumed		kwh/d	kg CO2/d	g CO2/c.d		%	%
0.55	kg CO2/kwh	0.26	0.15	0.28		99.42	0.58
		Energy Consumsed					
			Collec & transp	Pumping	dilution with water		**subtotal**
		Urine	man power (bycicle)	0.08kwh/m	0.1kwh/m3		0.06
		Faeces	Animal power (Cart)				0
		Greywater	0.005kwh/m3 (source Benetto et al 2009)				0.20
		Total kwh/d					0.26

Annex 7.6.3: Calculation Spreadsheet of Siddhipur (3)

Losses	Unit	Piping holding tanks	Storage tanks	Application	source
NH3-N	%N urine	<1 (0.01) <0.3	0.003	<10 (6) <1	Stockholm Vatten 2000, Vinneras et al, 1998; Palm et al 2002
N2O-N	%N urine			1.25	Tidaker 2003; EMEP/CORINAIR 2004
Nox-N	%N urine			0.7	Tidaker 2003

Greywater	Unit	Palmquist and Jonsson 2003	Koppe and Stozek 1999	Vinneras 2001	Schneidmadl 1999	Lange and Otterpohl 2000	Almeida et al 1999	Bahlo 1999	Butler et al 1995 (US)	Raach et al 1999	Typical
Flow	l/cap.d	110				82.19	70.79	69			80
COD	g/cap.d	47.95	95		62	35	62.76	33	56.83	101.53	60
Dry matter	g/cap.d	0.04							73.71		120
N-total	g/cap.d	1.4	1.3	1.26	0.5	1		1.5		1.4	1.3
P-total	g/cap.d	0.6	0.5	0.3	0.67	0.14		0.15	3.49	0.65	0.5

Assuming that one person generates 250gramme of faeces per day 0.25 kg/c.d

Property	Unit	Fresh faeces	UD waste	% reduction
Total COD	mgCOD/g	322	123	62
Moisture	gH2O/g	0.79	0.18	77
Ash	g/g	0.04	0.7	
Total solids	g/g	0.21	0.82	
Volatile solids	g/g	0.2	0.05	
Amount of BCOD	gCOD/g	112		
Fraction of BCOD	gCOD/gCOD	0.35		

Annex 7.7: Average Composition of Urine, Faeces, and Greywater (per person day) (Benetto et al., 2009)

Quantity	Unit	Urine	Faeces	Greywater
	kg/c.d	1.5	0.14	80
Main constituent				
Dry matter	g/c.d	60	45	120
Organic dry matter	g/c.d	45	42	
COD	g/c.d	15	35	60
TOD	g/c.d	7	21	18
N-total	g/c.d	10	1.5	1.3
P-total	g/c.d	1	0.5	0.5
K	g/c.d	2.6	0.55	2

Annex 7.8: **Energy demand for Vacuum system** (Remy and Ruhland, 2006)

System	Amount of wastewater	Inhab.	Energy demand	Remarks	Source
	[L/(pe*d)]		[kWh/(pe*a)]		
Flintenbreite	5	108	51	Not working to capacity	Otterwasser, 2005
Flintenbreite	5	--	17	Possible	Oldenburg, 2002
Vauban	8.4	40	7	Calculated from operating time	Schneidmadl, 1999
Hannover	9	80	27	Annual period	Herrmann and Hesse, 2002
Hannover	9	80	9	Possible	
ATV	150	--	36		ATV, 1995
SCST	**5.2**	**4891**	**25**	**LCA model**	

Annex 7.9: Transport processes and distances (Remy and Ruhland, 2006)

Load	From	To	Distance
Fertilizers			[km]
Mineral fertilizer	Manufacturer	Farmer	100
Compost	Collection	Compost plant	15
	Compost plant	Farmer	20
Faeces	Separator	Compost plant	15
Digester residue	Biogas plant	Farmer	20
Urine	Holding tanks	Farmer	10
Waste			
Sludge	WWTP	Incineration	30
Biowaste	Household	Collection	(*) 7.5
Biowaste	Collection	Incineration	30
Auxiliary			
Chemicals	Manufacturer	WWTP	300
Zeolithes	Manufacturer	Urine treatment	1000
Construction materials			
Concrete	Manufacturer	Settlement	50
	Settlement	Disposal	50
Others	Manufacturer	Settlement	300
	Settlement	Disposal	100

(*) stop-and-go collection of biowaste from households