CHALMERS

A Commercial Model for Eco-efficient Production of Biogas from Sewage Sludge in China

– Upgrading biogas to vehicle-used bio-methane

Master's Thesis within the Industrial Ecology programme

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CHALMERS UNIVERSITY OF TECHNOLOGY
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Abstract

Producing biogas from sewage sludge has been widely used and shown to be an eco-efficient production in Sweden. On the contrary, it is viewed as an unpromising business in China. Compared to the European sewage sludge, the biogas production rate of Chinese sewage sludge is low. That leads most production of sludge-based biogas to fail in China, because the meager income of the production cannot cover its high cost. On the other side, a great amount of sewage sludge is not treated and disposed of properly, because the lack of knowledge on sewage sludge treatment in the design of wastewater treatment plants. In respect of the environmental degradation caused by the discharge of untreated sewage sludge, China needs to develop a new commercial model to treat and dispose of sewage sludge eco-efficiently.

This thesis aims at proposing a commercial model for the eco-efficient production of biogas from sewage sludge in China. Firstly, through literature review and field investigation of the existing commercial models in the two countries, a tentative idea of the new commercial model for China is identified. In the new commercial model, the sludge-based biogas is upgraded to bio-methane, which can replace natural gas in compressed natural gas (CNG) vehicles. In contrast to the Swedish case, the Chinese wastewater treatment plant that operates the proposed commercial model has to transport its own waste, which can be costly. Besides, the low-gas-produced sewage sludge in China can also affect the economical performance of the mode. To avoid the potential problems, this thesis identifies six business scenarios for the commercial model. The six scenarios are composed of different ways of digestion, the mono-digestion of sewage sludge (MS) or the co-digestion of sewage sludge and food waste (MS&FW), and different ways of waste transport, using bio-methane, CNG, or diesel. Life cycle assessment (LCA) and cost benefit analysis (CBA) are used to analyze the environmental, energy and economical performances of the six business scenarios. Three indicators, the potential global warming effect (GWE), the ratio between energy input and energy output, and the net present value (NPV), are used to assess the eco-efficiency of the scenarios.

The results indicate that the scenario mono-digestion of MS and the use of bio-methane to transport waste is best for implementing the proposed commercial model, as it creates more value with less environmental effects. The scenario co-digestion MS&FW significantly increase the bio-methane yield, but is less profitable and has more GWE than the mono-digestion. Even so, this scenario can be more eco-efficient in the future, when China's electricity system has fewer emissions and the prices of electricity and fuels increase.

Large-scale wastewater treatment plants (>10 [10^4 m^3 wastewater/d]) are suitable to adopt the proposed commercial model. Medium-scale wastewater treatment plants (5~10 [10^4 m^3 wastewater/d]) are capable to carry out the demonstration study of the model, but to be commercialized, they need more supporting policies and collaboration with filling stations. Small-scale wastewater treatment plants (<5 [10^4 m^3 wastewater/d]) are not recommended to use the proposed model.

Keywords: sewage sludge, food waste, biogas, bio-methane, eco-efficient production, commercial model, LCA, CBA

Acknowledgment

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Göteborg August 2012

Zhao Lei

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1 Introduction

1.1 Background

Producing biogas from sewage sludge has been proved to be an eco-efficient waste treatment in Sweden. On the contrary, it is an unpromising treatment in China mainly because the low yield of biogas cannot cover the cost of the treatment. However, under current conditions of market in China, there are possibilities to get an eco-efficient production biogas from sewage sludge.

1.1.1 Eco-efficient production of biogas from sewage sludge in Sweden

Eco-efficiency is a concept proposed by the World Business Council for Sustainable Development (WBCSD) in 1992. It expresses a status that a business creates more goods and services with ever less use of resources, waste and pollution (WBCSD, 2000). The production of biogas from sewage sludge in Sweden is a typical example of eco-efficient production. As municipal organic waste, sewage sludge is treated by anaerobic digestion to produce biogas, which creates both environmental and economical benefits by generating heat, electricity and vehicle-used gas, i.e. bio-methane.

The production of sludge-based biogas has a long history in Sweden, but it wasn't viewed as an eco-efficient business before. In the beginning, the use of anaerobic digestion to treat sewage sludge was mainly to get rid of the waste. Afterwards, the world-wide energy crisis in the 1970s switched the scope of this routine treatment in wastewater treatment plants more to energy business. To pursuit more profits, many plants which composted sewage sludge changed their facilities to produce biogas (Doug Lumley, 2010). The sludge-based biogas takes the largest proportion of the country's annual biogas production. Up to the end of 2008, in the 227 biogas plants in Sweden, there were 138 plants producing biogas from sewage sludge (SBA, SGC, and SGA, 2008).

The technology innovation and the improvement of social consciousness on climate change increase the eco-efficiency of producing sludge-based biogas in Sweden. In the beginning of the 90s, biogas is started to produce bio-methane and use in vehicles. It is more profitable than using biogas to generate heat and electricity (Doug Lumley, 2010). The year 2006 was a milestone in the history of biogas production and use in Sweden, since it was the first year that the sales of bio-methane exceeded the sales of natural gas to vehicles (Eric & Pierre, 2009). Figure 1.1 shows the annual sale of vehicle-use gas in Sweden, from 1995 to 2007. As shown in the figure, approximately 28 million normal cubic meters (Nm^3) of bio-methane was consumed by the transport sector in Sweden. Up to 2009, there were 30 sewage sludge treatment plants building or running biogas upgrading facilities to produce bio-methane. Sweden has become a world leader in using bio-methane in vehicles.

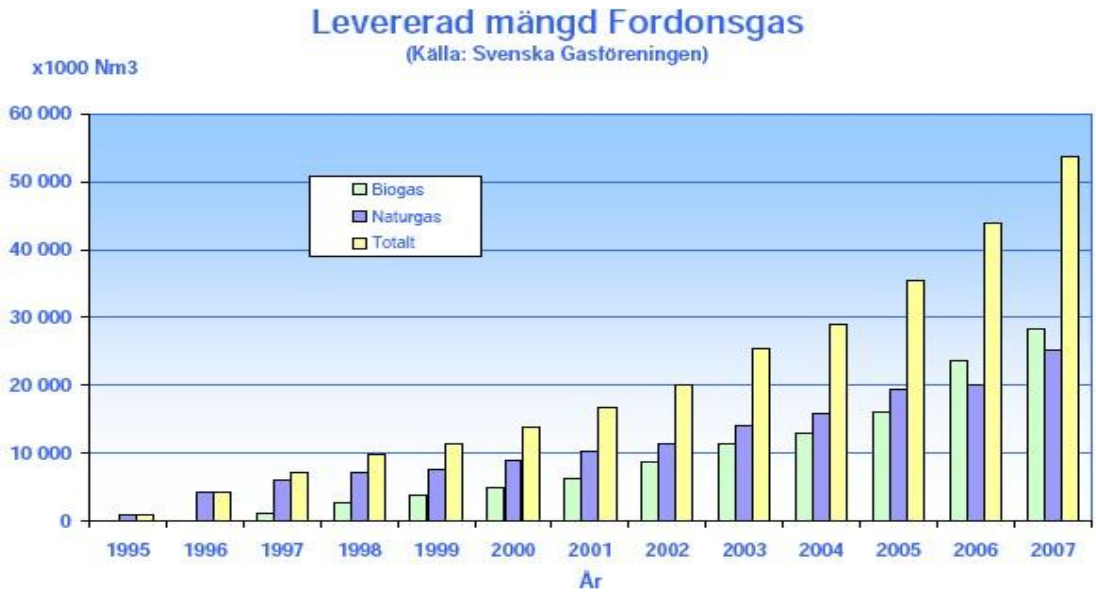

Figure 1.1 Sales of gas for transport sector in Sweden. Data Source: Helena Jansson, 2009.

At present, there are three uses of biogas in sewage sludge treatment plants in Sweden, including heat generation, co-generation of heat and power, and production of bio-methane for vehicle use. Owing to supporting policies and technology improvement, all these three commercial models can earn money. The production of bio-methane is viewed as the most promising commercial model of producing sludge-based biogas in Sweden. The trend of sewage sludge treatment in Sweden is as written by Dalemo et al. (1997) that the objective of handling bioorganic waste has been transformed from hygienic securing to re-use in order to enhance society's ecological sustainability.

1.1.2 Problems and opportunities in the production of biogas from sewage sludge in China

On the contrary to the Swedish case, producing biogas from sewage sludge is viewed as an unpromising business in China. Although China has a long history of using biogas (that could be traced to the early 1950s), the practice are mainly in rural areas for manure treatment and the majority of biogas utilizations in China are for the purposes cooking, lighting and heating (Wang & Wen, 2006). Anaerobic digestion is seldom used in treating sewage sludge in China. Wu et al. (2009) investigated the sludge-based biogas production plants in China in 2005. The result indicated that there were only 46 plants had the anaerobic digestion facilities in the 400 investigated wastewater treatment plants. Much gloomier is that only 25 plants in these 46 plants were in operation.

An essential problem in the production of the sludge-based biogas in China is that the biogas production rate (BPR) of the sewage sludge is so low that the revenue of biogas cannot cover the cost of the sewage sludge treatment. The average biogas yields of sewage sludge in China of 7.5 cubic meters of biogas per cubic meters of sludge (Wu et al., 2009) is far below the Nordic level of 38 cubic meters of biogas per cubic meters of sludge (Christensen, 2010). Affected by wastewater quality, technology of wastewater treatment, scale of sludge treatment and immature management, the biogas yield is even lower in some medium- and small-scale Chinese wastewater treatment plants. That makes many on-site gas boilers unable to save as much energy as expected (Wu et al., 2009). The large-scale wastewater treatment plants encounter hard debates with the electricity grid companies, when they sell their electricity. The unsteady flow of electricity supply and its relatively small amount are the common reasons that the electricity grid companies normally reject the electricity from sludge-based biogas (Liu, 2010). Making profits is vital for the production of sludge-based biogas, since the investment and operation cost are very high and the sewage sludge treatment fee that is compensated by municipal government is not enough and hardly accessible (Wu et al., 2009). As a result, there are quite few decision makers brave enough to invest in the production of sludge-based biogas. However, the low biogas yield doesn’t mean that the production of sludge-based biogas will end in failure in China. The opportunities should be noted as well.

The sewage sludge treatment has become a social concerns and the anaerobic digestion has been recommended by the national government. It is estimated that the amount of sewage sludge produced in 2010 is 3.53 million ton in dry weight. But that sludge wasn’t subject to proper treatment and disposal. A large appearance of wastewater treatment plant started in recent year, 2003. However, most of the wastewater treatment plants do not have proper sludge treatment facilities and dispose of sludge arbitrarily, which leads to environmental degradation (Wu et al., 2009; Yu et al., 2007). In 2009, the Ministry of Environmental Protection published a technology policy on the sewage sludge treatment and disposal, which highlighted anaerobic digestion (MEP, 2009). With great demand and supporting policies, a better development of the production of sludge-based biogas can be expected.

The other opportunity for developing the production of sludge-based biogas comes from the increasing demand of natural gas in China’s transport sector. To reduce emissions, the compress natural gas (CNG) vehicles have been prioritized to promote since 2006. It is estimated that about 110 billion cubic meters of natural gas will be consumed in CNG vehicles in China up to 2015 (Li & Zhou, 2008). In comparison, the total natural gas production was 95 billion cubic meters in 2010 ((NBSC, 2010). So, to fulfill the market demand in future, China has to extract more natural gas or look for other substituted energy. Bio-methane can replace natural gas that is used in vehicles if the methane content is beyond 97%, according to the Swedish biogas standard (Swedish Gas Centre, 2007). Besides, since it is produced from biomass, bio-methane is more environmental friendly than natural gas. Thus, there is hopefully a bright future for bio-methane in China. However, it should be noted that China, at present, has no commercial model for producing bio-methane in sewage sludge treatment plants.

1.2 A new commercial model for production of biogas from sewage sludge in China

China is aware of the eco-efficient production of biogas in Sweden. However, China is unable to use the Swedish models exactly, due to the differences in a series of situations between the two countries.

To achieve an eco-efficient production of sludge-based biogas in China, a new commercial model is proposed. Six business scenarios for the model are designed, considering the possible influences of low biogas production rate and large waste-transport cost.

1.2.1 A new commercial model

In response to the problems and opportunities, two solutions probably can make the production of sludge-based biogas to be eco-efficient.

The first solution is to increase the biogas production rate. In view of the Swedish experience, the co-digestion of food waste and sewage sludge can increase the biogas production rate, owing to the better carbon and nitrogen ration in the mixed feedstock (SBA& SGC&SGA, 2008). Experiments on co-digesting the Chinese sewage sludge and food waste were carried out (FU et al., 2007; Fu et al., 2006) and the results indicated that the Chinese substrate (i.e. the mixture of sewage sludge and food waste) can get larger biogas production rate than the European substrates (Jansen et al., 2004; Sosnowski et al., 2003; Karl et al., 1999; Bolzonella et al., 2006; Gergor et al., 2008.). Figure 1.2 shows the comparisons on the BPR in previous co-digestion studies between China and Europe.

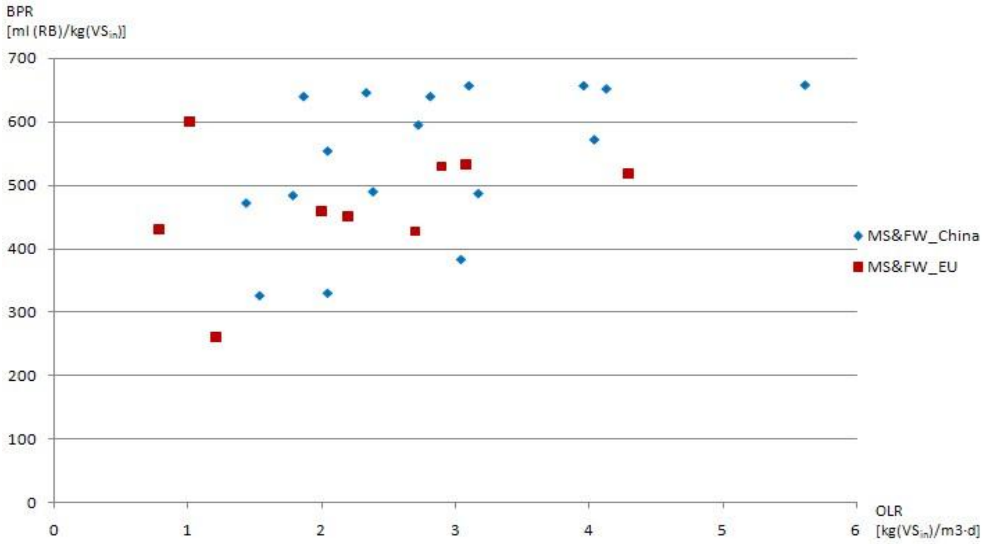

Figure 1.2 Comparison on biogas production rate (BPR) in previous co-digestion studies between China and Europe

Besides, the successful Swedish model of the production of bio-methane and the increasing demand of natural gas in China provide the other solution to increase profits: upgrading biogas and selling bio-methane to filling stations. Compared to the current commercial models of producing electricity and recycling heat, the model of producing bio-methane is not affected by the unstable biogas yield. The more countable and easier transported energy product bio-methane will make the market easier than electricity, thereby, creating more profits. Combining the two solutions above (increasing BPR and upgrading biogas to bio-methane), Figure 1.3 illustrates a new commercial model for production of the sludge-based biogas with upgrading biogas to be the bio-methane for vehicle use.

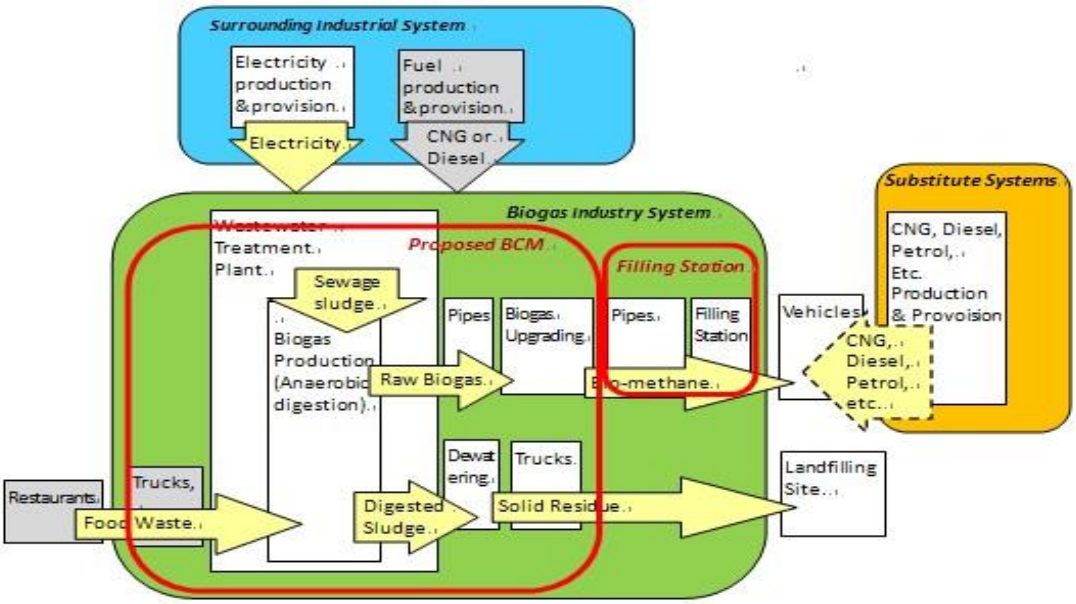

Figure 1.3 A new commercial model for production of sludge-based biogas in China

The operator of this commercial model is assumed to be the wastewater treatment plant, which is in charge of the collection and transportation of food waste from restaurant to the site, producing biogas and bio-methane, dewatering digested sludge and transporting it to the land-filling site, and selling the bio-methane to filling stations.

The sewage sludge is transported to the facilities of sewage sludge treatment through pipes. Unlike in Sweden, the household wastewater and industry wastewater are treated together in the wastewater treatment plant. That makes the quality of sewage sludge volatile and hard to control. The disposal of the digested sludge is through dewatering and filling into land. Adding food waste is considered in this new commercial model in the case that the biogas yield cannot create enough profit even though by producing bio-methane. It should be noted that the food waste used are from restaurants. That is because that the waste separation is hard to realize in China at present and it is relatively easy to get the food waste from restaurants. The technology adopted for the anaerobic digestion (AD) is mesophilic AD (continuous stirred-tank reactor, CSTR). Besides producing bio-methane, some biogas is used to fulfill the heat requirement in digester by burning in a gas boiler. The technology used for biogas upgrading is water wash with regeneration, because it has reliable performance and low operation cost. The bio-methane is injected into the local natural gas grid or is transported to the filling stations by pipes.

The new model differs from the Swedish model in two ways. First, the wastewater treatment plant transports the waste in and out of the plant, rather than other logistic companies. Since the Chinese municipal governments haven't found a proper way to facilitate waste treatment, the potential decision makers of the new model need to do work by themselves. Second, to compete with other food waster collectors, in the new model, no money will be asked from restaurants, meaning no immediate revenue will be made on food waste treatment.

To survive, the new commercial model proposed in this thesis assumes few and independent actors. The main business actors related to this model are wastewater treatment plants, filling stations and land-filling sites. That is unlike the Swedish commercial model, which involves many actors (two Swedish cases of production of sludge-based biogas, i.e. Falköping municipal wastewater treatment plant and Gryaab wastewater treatment plant are in Appendix VIII).

1.2.2 Six business scenarios for the commercial model

Six businesses scenarios are studied in this thesis to find a commercial model for eco-efficient production of the sludge-based biogas. These scenarios are proposed in the consideration of two important factors that would affect the eco-efficiency of the model.

The first factor is the biogas production rate. As discussed above, the Chinese biogas production rate is currently low, but can be improved through co-digestion of sewage sludge and food waste. Hence, there are two cases, the mono-digestion of sewage sludge and the co-digestion of sewage sludge and food waste. The second factor is the cost of transporting waste, which can be as high as one third of the total operation cost (Zhang et al., 2006). It is assumed three scenarios for transporting waste, namely using bio-methane, using natural gas and diesel. Hence, there are six possible business scenarios as follows:

1) MS_BMT: mono-digesting sewage sludge and using BM fueled trucks to transport the solid residues (i.e. dehydrated-digested sludge) to land-filling site.
2) MS_CNGT: mono-digesting sewage sludge and using CNG fueled trucks to transport the solid residues to land-filling site.
3) MS_DT: mono-digesting sewage sludge and using diesel fueled trucks to transport the solid residues to land-filling site.
4) MS&FW_BMT: co-digesting sewage sludge and food waste and using BM fueled trucks to transport the solid residues to land-filling site
5) MS&FW_CNGT: co-digesting sewage sludge and food waste and using CNG fueled trucks to transport the solid residues to land-filling site
6) MS&FW_DT: co-digesting sewage sludge and food waste and using diesel fueled trucks to transport the solid residues to land-filling site

1.3 Aim of this thesis

This thesis is to identify a commercial model for eco-efficient production of biogas from sewage sludge. The model is aimed to be suitable for the conditions in China.

1.4 Working procedures and methods of this thesis

This thesis is based on a literature review and interviews to identify the similarities and differences in the production of sludge-based biogas between Sweden and China. Afterwards, a tentative idea on the new commercial model for eco-efficient production is proposed with six business scenarios, which are introduced in section 1.2. To assess the eco-efficiency of the tentative model, the potential global warming effect (GWE), the ratio between energy input and energy output, and net present value (NPV) are used as three indicators, which represents the environmental performance, energy performance and economical performance of the model, respectively. Chapter 2 and Chapter 3 study environmental and energy performances of the model from a perspective of life cycle assessment (LCA). Chapter 4 analyzes the economical performance of the model by using cost benefit analysis (CBA). Chapter 5 compares the eco-efficiency of the six business scenarios by use of the selected indicators, and Chapter 6 presents the conclusions drawn.

1.5 Interested parties of this thesis

The expected readers of this thesis include both academics interested in the production of sludge-based biogas in China, and decision makers either in municipal governments (e.g. planners and politicians in waste and energy sectors) or in the companies involved in waste management and energy production.

2 Environmental analysis

2.1 Potential global warming effect

The potential global warming effect (GWE) is used as an indicator to evaluate the environmental performance of the model. There are many environmental impacts that can be studied, but this thesis merely studies the GWE due to the inaccessibility of the data used for assessing other environmental impacts. More discussion on this issue is written in the section of limitations in this thesis. In addition, the GWE is important to be studied in this thesis for two reasons as follows:

Firstly, the GWE is a distinct feature of the anaerobic digestion that differs from other waste treatments in environmental impacts. It has been found by previous studies (Hwang & Hanaki, 2000; Suh & Roisseaux, 2001; Lundin, et al., 2004; Houillo & Jolliet, 2005; Hospido, et al., 2005; Murray, et al., 2008; Pasqualino, et al., 2009; Hospido, et al., 2010) that anaerobic digestion has significantly lower GWE than other sewage sludge treatments. The Intergovernmental Panel on Climate Change (IPCC) also recognized that waste management industry plays an increasingly important role in climate change mitigation (IPCC, 2006).

Secondly, the Chinese decision makers pay increasing attention to climate change now. The comparatively low GWE of anaerobic digestion, as compared to other waste treatments, was something that the interviewed decision makers found interesting in the proposed commercial model. More support for implementing the proposed commercial model is hopefully to get if the model's GWE is small or negative.

2.2 Life cycle assessment and GHGs accounting framework

2.2.1 Life cycle assessment

In 2000, WBCSD released a new state-of-art declaration on eco-efficiency, which expanded the system boundary of eco-efficiency to the entire life-cycle of a product (WBCSD, 2000). Life cycle assessment (LCA) is defined in ISO 14040 as a tool for the analysis of the environmental burden of products at all stage in their life cycle, from the cradle to the grave. It has been widely used to study the environmental impacts, including the GWE, on the sewage sludge treatment (Hwang & Hanaki (2000); Suh & Roussseaux (2001); Lundin et al. (2004), Houillion & Jolliet (2005); Hospido et al. (2005) ; Murray et al. (2008), Pasqualino et al. (2009); Hospido et al. (2010)). So, this thesis uses LCA to evaluate the GWE of the six business scenarios for the proposed commercial model.

Figure 2.1 and 2.2 show the system boundaries of each business scenarios. The functional unite is defined as one wet ton of mixed sewage sludge [tww (MS)].

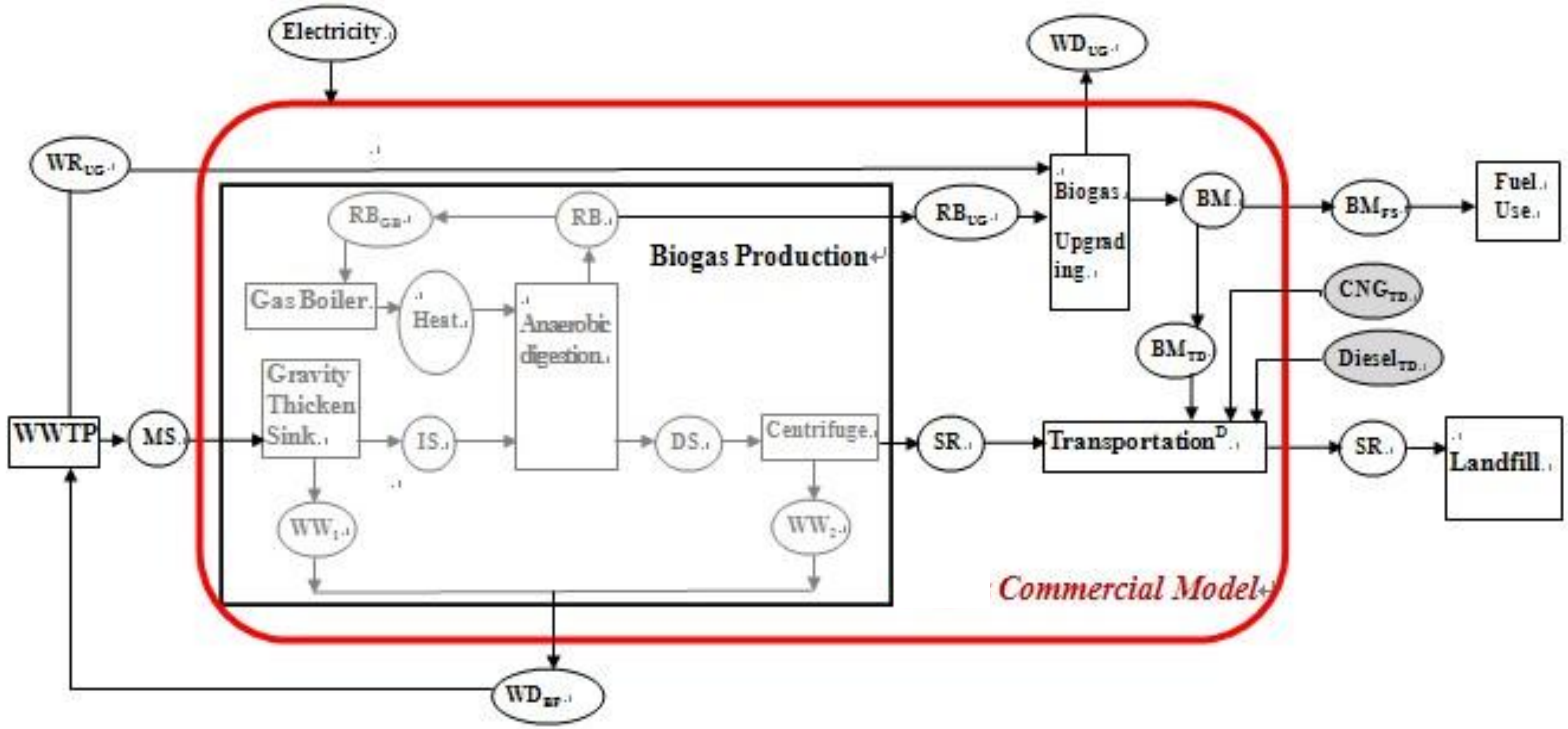

Figure 2.1 Diagrammatical frameworks of GHG emissions accounting for the proposed BCM: MS_BMT, MS_CNGT, and MS_DT

Nomenclature

MS: Mixed sewage sludge; IS: Influent Sludge; DS: Discharged Sludge; SR: Solid Residue; RB: Raw Biogas; RB_{GB}: Raw Biogas consumed in Gas Boiler; RB_{UG}: Raw Biogas sent to upgrading facilities; BM: Bio-methane; BM_{TD}: BM_{FS}: Bio-methane sent to filling station; WW_1: Wastewater discharged from gravity thicken sink; WW_2: Wastewater discharged from centrifuge; WD_{BP}: Wastewater discharged from biogas production; WR_{UG}: Fresh water required by biogas upgrading facilities (i.e. water wash with regeneration); WD_{UG}: Wastewater discharged from biogas upgrading facilities; Bio-methane consumed in transportation solid residue to dispose site (i.e. the variable factor used in the business scenario MS_BMT); CNG_{TD}: Compressed natural gas consumed in transportation solid residue to dispose site (i.e. the variable factor used in the business scenario MS_CNGT); Diesel $_{TD}$: Diesel consumed in transportation solid residue to dispose site (i.e. the variable factor used in the business scenario MS_DT).

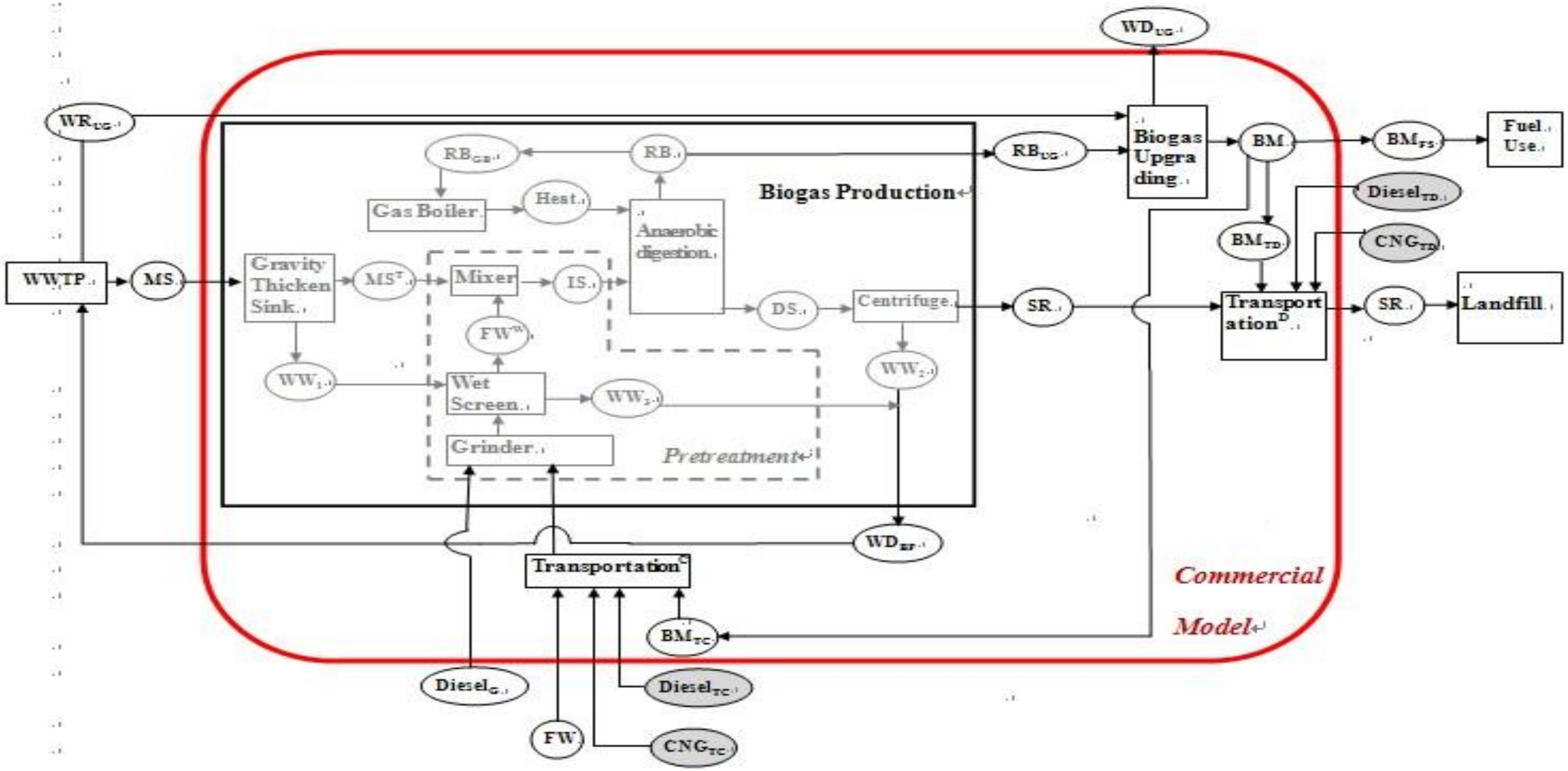

Figure 2.2 Diagrammatical frameworks of GHG emissions accounting for the proposed BCM: MS&FW_BMT, MS&FW_CNGT, and MS&FW_DT

Nomenclature

FW: Food waste; MS^T: Thickened mixed sewage sludge; FWW: Food waste sludge from the wet screen; $Diesel_G$: Diesel consumed in the Grinder; BM_{TC}: Bio-methane consumed in collection the food waste (i.e. the variable factor used in the business scenario MS&FW_BMT); CNG_{TC}: Compressed natural gas consumed in collection the food waste (i.e. the variable factor used in the business scenario MS&FW_CNGT); Diesel $_{TC}$: Diesel consumed in collection the food waste (i.e. the variable factor used in the business scenario MS&FW_DT).

2.2.2 GHGs accounting framework

To make a LCA on the GWE means to count the greenhouse gases (GHGs) relevant flows. Herein, the GHGs accounting is required in this thesis.

However, there is no uniform standard on the GHG accounting for the production of biogas from sewage sludge, although many studies have been done (see Table 2.1). The lack of a uniform standard results the mistakes and losing transparency. By reviewing previous LCA studies regarding the production of sludge-based biogas, it is found that the global warming potential (GWP) of three gases were obscured, namely, biogenic CO_2, the CO_2 from the bond biogenic C in land, and the leakage of CH_4 during the anaerobic digestion. Table 2.1 summarizes the different three GWPs used in the previous studies.

Table 2.1 Differences on the GWPs used in previous LCA studies

LCA on sewage sludge	GWP_{CO2bio}	$GWP_{CO2seq.}$	CH4 leakage during AD
Hwang & Hanaki (2000)	Not defined	Not applicable	Disregard
Suh & Rousseaux (2001)	Not defined	Disregard	Disregard
Lundin, et al., (2004)	Not applicable	Disregard	Not applicable (Exclude AD)
Houillo & Jolliet (2005)	Yes (0)	Disregard	Not applicable (Exclude AD)
Hospido, et al., (2005)	Yes (0)	Disregard	Disregard
Murray, et al., (2008)	Yes (0)	Disregard	Yes (0 & 10% of CH4)
Pasqualino, et al., (2009)	Not defined	Disregard	Obscure, since lack of inventory data
Hospido, et al., (2010)	Yes (0)	Disregard	Yes. But CH4 was assumed from leakage during biogas incineration.

•*Biogenic CO2*

The carbon contained in biogenic CO_2 is converted from the carbon contained in biomass (IPCC, 2006). There is a common consensus that GWP of biogenic CO_2 ($GWP_{CO2\ bio.}$) is zero. However some of the previous LCA studies (Hwang & Hanaki, 2000; Suh & Rousseaus, 2001; Lundin, et al., 2004; Pasqualino, et al., 2009) did not mention the issue of $GWP_{CO2\ bio}$ or used it in a wrong way, and set the $GWP_{CO2\ bio.} = 1$. The wrong use of $GWP_{CO2\ bio}$ can make a significant difference on the GWE of anaerobic digestion of sewage sludge. As was pointed by Hospido et al. (2005), the GWE from a wrong calculation can be three times larger than the GWE from a right calculation. Therefore, it is important to introduce the GWP of biogenic CO_2 used and the processes that generated biogenic CO_2 in a LCA study. In the production of sludge-based biogas, biogenic CO_2 can be generated from the digestion tank, biogas using devices (normally, biogenic CO_2 takes 55% in the volume of the sludge-based biogas), and the landfill site, where the digested sludge is disposed of. The GWP of biogenic CO_2 is counted as zero in this thesis.

•*Sequestration of biogenic carbon*

After filling the digested sludge into land, part of the carbon content in the sludge is bound to soil. This procedure is called the sequestration of biogenic carbon. The GWP of the bound biogenic carbon should not be neglected and should be counted as a saving in GWP, because it is a premise for GWP $CO_{2biogenic}$ being to set to zero (Gentil et al., 2009). It is not right that the previous LCA studies disregarded the GWP of the bound carbon when the GWP of biogenic CO_2 was counted to be zero. In this thesis, the GWP of the biogenic CO_2 saved in the soil bound carbon (GWP $_{CO2\ seq.}$) equals -44/12 $CO_{2\ eq}$. In the GWP $_{CO2\ seq}$, the denominator (i.e.12) is the molecular weight of the biogenic carbon bounded in soil. The molecule (i.e. -44) denotes the molecular of biogenic CO_2 avoided.

•*CH4 leakage during the AD*

Another issue that should be highlighted is that the GWP of the CH_4 in biogas should be counted. The section on biological treatment of waste management in IPCC (2006) emphasizes that the GWP of the CH_4 leakage can be excluded in the GHGs report only under the conditions that there are facilities to ensure that any leaking CH_4 is torched or used for energy production. Otherwise, the GWP of CH_4 leakage should be counted as 21 $CO_{2\ eq}$. Murray et al. (2008) indicated that the GWE of anaerobic digestion of sewage sludge is very sensitive to the amount of CH_4 leakage (i.e. if 10% of the methane leaks, the GWE will increase from -283 to 64 kg/t DM (MS) for anaerobic digestion without lime). However, the CH_4 leakage was neglected in some of the previous LCA, leading to lack of transparency and reliability. In this thesis, the data collected on CH_4 leakage is in Appendix V, and the GWP $_{CH4}$ =21 $CO_{2\ eq}$.

In order to improve the accuracy and transparency, a GHGs accounting framework (shown in the Table 2.2) is used in this thesis.

Table 2.2 GHG emissions accounting framework Upstream-Operation-Downstream-Substitution (UODS)

Additional Background Information	
Waste Characteristics	Energy Production Systems

GHG Accounting Framework UODS				
	Indirect Emission		Direct Emission: operation	Substituted Emission
	Upstream	Downstream		
GWE[kgCO_{2e}/tww]	Sum of all upstream GWF^N	Sum of all downstream GWF^N	Sum of all direct GWF^N	Sum of all substituted GWF^N
GWE_N	GWF^N [kgCO_{2e}/tww]= EF_N*GWP			
GWP	GWP $CO_{2fossil}$=1; GWP $CO_{2biogenic}$=0; GWP $CO_{2biogenic}$ sequestration = (-44/12); GWP CH_4= 21; GWP N_2O=310.			
EF_N[kg GHG^A/tww]	EF_N=A_N*GWF_N			
GWF_N	GWF_A [kg GHG/unit N]; and data source			
Accounted (A_N) [Unit/tww]	Production & provision of (have been subtracted the on-site consumptions savings and should be specified) : • Electricity • Fuel • Heat • Ancillary materials	1)Treatment & disposal of: • Wastewater • End-sludge • End-products transport (e.g. electricity grid, district heating networks, NG grid) 2)Direct Emissions from end-products disposal: • N2O emissions • Carbon sequestration	1)Emissions from the waste 2)Combustion of fuel on site • For heat provide • For facilities operation • For collection & transport	1)On-site consumptions savings (upstream): • Electricity • Fuel • Heat • Materials 2)End-products (downstream): • Electricity • Heat • Fuel • Materials (e.g. fertilizers, etc.)
Not accounted & reasons	• Unaccounted GHGs • Construction • Maintenance • Decommissioning • Embedded energy in waste	• Unaccounted GHGs • Decommissioning	• Unaccounted GHG • Unaccounted waste stream • Staff commuting • Business travel	• Unaccounted GHG

GWE=Global Warming Effect; EF=Emission Factor; GWF=Global Warming Factor; A_N= the amount of accounted flux N. The GWF_N is the defined as that the GHG released from per unit of the consumed physical flux N. And the data collection of GWF_N should be in the context of the studied scope. Owing to the important impacts on the result of GWE, information of both the waste characteristics and energy production systems in the studied or reported context should be uploaded as additional background information.

2.3 Interpretation and analysis

2.3.1 Interpretation and analysis on Life cycle inventory of GWE

Table 2.3 presents life cycle inventory of GWE for the six business scenarios studied for the model. Data collection and the calculation procedures are recorded in Appendix V. Figure 3.3 illustrates the GWE of every processes in the commercial model and compares the total GWEs between the six business scenarios.

Table 2.3 Life cycle inventory of GWE for the six business scenarios

	Indirect Emission: Upstream		Indirect Emission: Downstream		Direct Emission		Substituted Emission (-)		
	IEU	Percentage of Total	IED	Percentage of Total	DE	Percentage of Total	SE	Percentage of Total	Total Emission
MS_BMT	39.663	68.1%	7.102	18.1%	1.868	3.2%	-6.151	10.6%	42.483
MS&FW_BMT	51.005	51.6%	10.262	13.6%	8.049	8.1%	-26.393	26.7%	42.923
MS_CNGT	39.697	67.7%	7.102	18%	2.070	3.5%	-6.358	10.8%	42.511
MS&FW_CNGT	51.062	51.2%	10.262	13.5%	8.380	8.4%	-26.734	26.8%	42.970
MS_DT	39.730	67.7%	7.102	18%	2.045	3.5%	-6.358	10.8%	42.519
MS&FW_DT	51.115	51.3%	10.262	13.5%	8.339	8.4%	-26.734	26.8%	42.982

GWE_N [kg($CO_{2,e}$)/tww]

Upstream	MS	MS&FW	Downstream	MS	MS&FW	Direct Emission	MS	MS&FW	Substituted Emission (-)	MS	MS&FW
Production & provision of electricity: GWE_{EI} b)	39.648	50.832	Wastewater treatment GWE_{WD}	0.138	0.095	CH4 fugitive emission GWE_{CH4FE} f)	1.868	7.749	Substituted CNG from production to combustion GWE_{CNGFS}	-6.358 (-6.151)	-26.734 (-26.393)
Clean water provision: GWE_{WR}	0.015	0.060	N2O from solid residue filled in land GWE_{N2O} c)	8.68	11.78	Biogenic CO2 from raw biogas combustion in boiler GWE_{RBGB}	0	0			
Diesel for grinding (production& provision) $GWE_{DGP\&P}$	__	0.113	C sequestered in solid residue filled in land $GWE_{Seq.C}$ d)	-1.716	-1.613	Diesel for grinding (combustion) GWE_{DGCom}	__	0.300			
Fuel for transportation (production & provision)			Biogenic CO2 from solid residue filled in land GWE^{C}_{O2bio} e)	0	0	Fuel for transportation (combustion)					
BMT	0	0				GWE_{BMTCom} (Biogenic)	0	0			
$GWE_{GTP\&P}$	0.035	0.057				$GWE_{CNGTCom}$	0.201	0.331			
$GWE_{DTP\&P}$	0.067	0.110				GWE_{DTCom}	0.177	0.291			

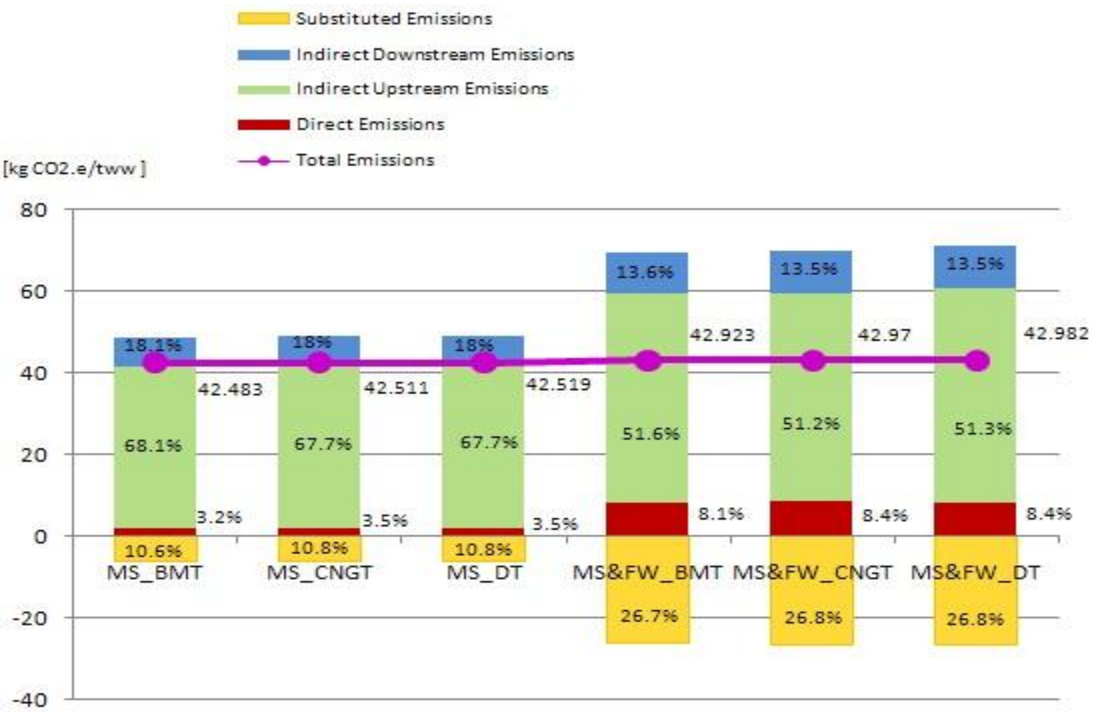

Figure2.3 GWE of the six business scenarios for the proposed commercial model

Firstly, the total GWE in Figure 2.3 indicates that with regard to GWE there is no big difference between the business scenarios of the commercial model. In comparison, the mono-digestion of sewage sludge has less GWE than co-digestion of sewage sludge and food waste from a life cycle perspective. Using bio-methane for transport also is better than the other two scenarios of transport in respect of environmental performance. The scenario with mono-digestion of sewage sludge and use of the bio-methane-fueled trucks for transporting (MS_BMT) is indicated to have the lowest GWE in the six possible business scenarios. But, it should be noted that the difference between the business scenarios is actually not significant, about 0.5 [kg $CO_{2.e}$ / tww]. .

Secondly, Figure 2.3 indicates that the proposed commercial model for production of sludge-based biogas has positive GWE under Chinese conditions. Actually, the production of sludge-based biogas, or anaerobic digestion of sewage sludge can have positive GWE, although it can offset GHGs emission to some extent (Hwang & Hanaki, 2000; Suh & Roisseaux, 2001; Houillo & Jolliet, 2005; Hospido, et al., 2005; Pasqualino, et al., 2009; Hospido, et al., 2010). A summary on GWE from previous LCA studies of production of sludge-based biogas and the system boundaries are in Appendix VI. . Most system boundaries of these LCA studies are similar to the system boundary set in this thesis, i.e. focusing the operation phase. Sewage sludge treatment processes, including anaerobic digestion, the use of biogas and the disposal of digested sludge, are taken into account. The technologies, however, differ. Most previous studies used biogas in combined heat and power plant (CHP), while the proposed commercial model uses biogas to produce bio-methane. Besides, the disposals of the digested sludge are different, as filling into land or using on agricultural land. Because of these differences, the GWE from this thesis cannot be directly compared with previous studies.

What is interesting to see is that the direct emission of the production of sludge-based biogas in the model takes the smallest proportion of the total emissions (3~8%). And the reduction of emission owing to the model counts about 10% or 26% of the total emissions. In comparison, the dominant part of GWE (51~68% of the total emissions) comes from the upstream of the model, which is the indirect GWE of the model. The electricity provision is a main emission source (i.e. 99% of the indirect upstream emission). So, it should be noted that the proposed commercial model can alleviate the climate change, as long as the electricity provision in China is more ‘clean’.

2.3.2 Sensitivity analysis on the electricity system

The energy system plays an essential role in accounting of GHG emissions from waste management systems and waste technologies (Fruergaard & Astrup, 2009). Life cycle inventory of GWE in this thesis also shows that a large proportion of GWE comes from the electricity production and provision. Herein, a sensitivity analysis on different electricity systems is carried out.

Apart from the production and provision of electricity, the production and provision of CNG and diesel influence the GWE of the model as well. However, they are not taken into the sensitivity analysis. This is because the indirect emissions from the production and provision of diesel and CNG (less than 1% of the total indirect upstream emissions) are insignificant compared to the emissions from the production and provision of electricity (i.e. about 99% of the total indirect upstream emissions).

The Chinese electricity production is highly reliant on coal (78.97% coal-based electricity is reported by the Chinese Electricity Association in 2009). In comparison, Europe is more independent of the coal-based electricity. . Figure 2.4 shows the GHG emissions of production and provision of electricity in different countries.

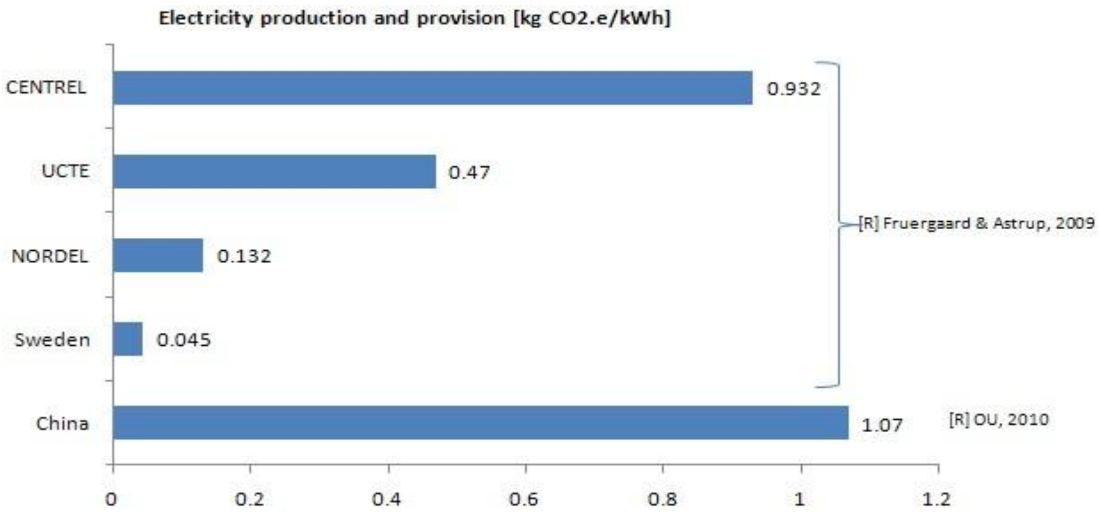

Figure2.4 Comparisons of the GHG emissions of electricity production and provision between China and Europe

The European power associations CENTREL, UCTE, and NORDEL represent the average low, medium and high levels of ‘clean’ electricity in Europe. The electricity generated in Sweden has fewer GWE than electricity of the European power associations. In this thesis, the four European global warming factor of the production and provision of electricity (GWF_{El}) are used in the sensitivity analysis of the GWE of the proposed commercial model in the business scenario MS_BMT.

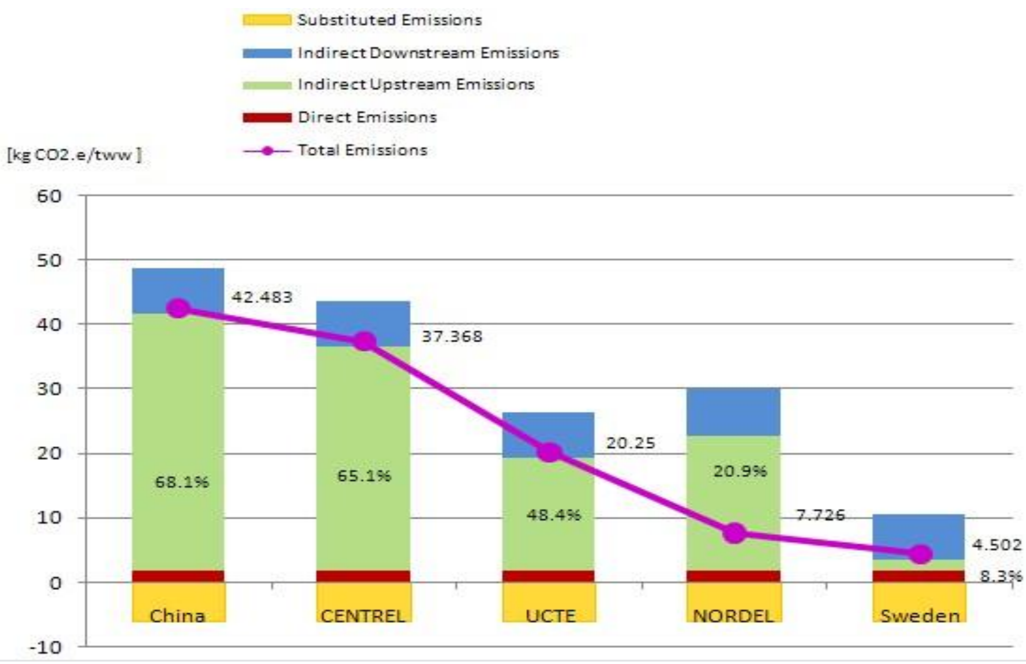

Figure2.5 GWE of the proposed commercial model in different electricity production & provision systems

The six business scenarios:
MS_BMT= mono-digestion MS and using BM fueled trucks to transport the waste on site; MS_CNGT= mono-digestion MS and using CNG fueled trucks to transport the waste on site; MS_DT= mono-digestion MS and using diesel trucks to transport the waste on site; MS&FW_BMT= co-digestion of MS& FW, and using fueled trucks to transport the waste on site; MS&FW_CNGT= co-digestion of MS& FW, and using CNG fueled trucks to transport the waste on site; MS&FW_DT= co-digestion of MS& FW, and using diesel trucks to transport the waste on site.

Figure 2.5 presents the GWE of MS_BMT in respect of different GWF_{El}. As the reduction of emissions from electricity production and provision, the reduction of the GWE of the proposed commercial model is extremely significant (i.e. from 42.483 to 4.502 [kg $CO_{2.e}$/tww]). That indicates that the GWE of the same model can be 10 times lower in Sweden than that is in China, due to different electricity systems. China has put many efforts in reducing the GHG emission of its electricity production system. If China can reduce its emissions to the medium level of GWF_{El} in Europe (i.e. UCTE), the GWE of the proposed model is reduced by half. That will makes the proposed model more attractive from the environmental perspective. It is important for decision makers to know that the GWE of the model is highly sensitive to the electricity production and provision system.

3 Energy analysis

3.1 Ratio between energy input and energy output

Although LCA has its own method to assess the energy impacts, this method is not adapted for assessing the energy performances of the proposed commercial model. The common way of energy analysis is done on an inventory of energy performances, which includes both the consumed energy and produced energy. Similarly, the energy indicator should also embody these two energy performances. However, in a LCA study on waste management, the energy impacts of the proposed commercial model is expresses as: the energy impacts caused by treating per ton of waste [MJ/tww] = the energy consumed by treating per ton of waste – the energy produced by treating per ton of waste. Such an aggregation of consumed energy and produced energy cannot reflect the relation between the energy input and energy output of the proposed commercial model. Hence, the energy impact in the LCA studies on waste management cannot be used as an indicator of energy performances in this thesis.

Compared to the energy impact in waste management LCA, the energy impact in energy product LCA is more sensible for illustrating the energy performances, as the energy impact is expressed by the energy consumed by producing per MJ of energy product (i.e. the energy impact [MJ/MJ] = consumed energy ÷ produced energy). Such energy impact is widely used for comparing the energy efficiency in the production of energy products, for example, electricity and fuels, in previous LCA studies on energy products (OU, 2010; Fruergaard & Astrup, 2009).

The proposed commercial model can be viewed as not only waste management, but also energy production, because it produces bio-methane, which is an energy product. Therefore, this thesis uses the ratio (θ) between energy input (consumed energy) and energy output (produced energy) as an indicator of energy performance. θ is calculated by using the energy flows, which were got from the inventory analysis in Chapter 2.

$$\underset{[MJ\,(EI)/\,MJ\,(EO)]}{\theta} = \underset{[MJ\,(EI)/tww]}{\sum \text{Energy Input (EI)}} \div \underset{[MJ\,(EO)/tww]}{\sum \text{Energy Output (EO)}}.$$

Regarding the six business scenarios, the lower θ is, the better the energy performance of the scenario.

3.2 Inventory analysis on energy flows

The data collection and calculation of the energy flows are in Appendix V.

3.2.1 Electricity consumptions

Table 3.1 presents the summary of electricity consumptions, respectively for scenarios mono-digestion of sewage sludge (MS), and the co-digestion of sewage sludge and food waste (MS&FW). In the scenarios MS, the total electricity consumed by treating one wet ton of sewage sludge is 37.054 kWh, which is equivalent to 133.394 MJ. The electricity consumption of the anaerobic digestion constitutes the main part (94.5%) of the total electricity consumption. In comparison, the gravity thickening, centrifuge and biogas upgrading consume small amounts of electricity, namely, 0.6%, 2.9% and 1.9%. It should be specified that the electricity consumed by anaerobic digestion includes the consumptions of stirring and the pumping systems.

The total electricity consumption in MS&FW is 47.507 [kWh/tww], which is equivalent to 171.025 [MJ/tww]. The amount of electricity consumed by the pretreatment of food waste takes 11.3% of the total electricity consumption. The co-digestion consumes more electricity than the mono-digestion, because the food waste adds more work in every process. As a result, co-digestion consumes about 10 [MJ / tww] more than mono-digestion does.

Table 3.1 Summary of electricity consumptions

The summary of electricity consumptions [kWh/tww] and percentages		
Business Scenarios	MS	MS&FW
Pretreatment of FW	___ (___)	5.385 (11.3%)
Gravity thickening sink	0.24 (0.6 %)	0.24 (0.5%)
Anaerobic digestion	35 (94.5 %)	37.696 (79.3%)
Centrifuge	1.083 (2.9 %)	1.113 (2.3%)
Biogas upgrading	0.731 (1.9 %)	3.072 (6.5%)
Total electricity consumption (equivalent to [MJ/tww])	**37.054** Equivalent 133.394	**47.507** Equivalent 171.025

3.2.2 Fuel consumptions

The heat required by the anaerobic digestion is provided by a fraction of produced biogas. Herein, there are two technical processes, namely, food grinding and transport needed to consume fuel.

Table 3.2 Summary of fuel consumptions for transport on site

The summary of fuel consumptions for transport		
Business Scenarios	MS	MS&FW
Food waste collection and transportation		
T_{BM}^{C}[Nm^3 (BM)/tww]	____	-0.049
T_{CNG}^{C}[Nm3(CNG)/tww]		0.049
T_{D}^{C}[Nm3 (D)/tww]		0.042
Soild residues transportation		
T_{BM}^{D}[Nm^3(BM)/tww]	-0.079	-0.082
T_{CNG}^{D}[Nm3(CNG)/tww]	0.079	0.082
T_{D}^{D}[Nm3 (D)/tww]	0.067	0.069
Total consumptions [MJ/tww]		
BMT	0	0
CNG	0.079*39.6[MJ/Nm3]=3.128	0.131*39.6[MJ/Nm3]=5.188
DT	0.067*35.28[MJ/L]=2.364	0.111*35.28[MJ/L]=3.916

In the co-digestion of MS&FW, the diesel consumed for grinding the food waste is 0.114 [L/tww], which is equal to 4.036 [MJ/tww] (i.e. 0.114*35.28 [MJ/L (diesel)]). There is no such consumption in the mono-digestion.

The co-digestion of MS&FW consumes more fuel than the mono-digestion, because it has more transports for collecting food waste. It is assumed that no fuel is consumed for transport in the business scenario, in which bio-methane is used for transport and hence there is no need to import fuel. As shown in Table 3.2, the fuel consumption for the transport on site ranges from 0 to 5.188 [MJ/tww] in the six business scenarios.

3.2.3 Energy output

Bio-methane is the energy output of the proposed commercial model. In the applied system perspective, only the bio-methane sent to filling stations or the natural gas grid (shown in Figure 2.1 and 2.2) is counted as energy output.

Table 3.3 presents the energy output of the different business scenarios. The co-digestion of MS&FW produces three times more energy than the mono-digestion of MS.

Table 3.3 Summary of energy output

Summary of energy output [MJ/tww]						
Business Scenarios	MS_BMT	MS_CNGT	MS_DT	MS&FW_BMT	MS&FW_CNGT	MS&FW_DT
Energy output	82.011	84.776	84.776	351.907	356.454	356.454

3.3 Analysis of the ratio between energy input and energy output

Figure 3.1 presents the energy performance indicator θ and the energy inputs and outputs in the six possible business scenarios.

In respect of the two digestion ways, the co-digestion of MS&FW is much better than the mono-digestion of sewage sludge. The ratios θ of the co-digestion scenarios are half of those in the mono-digestion scenarios. Besides, the ratios θ of the mono-digestion scenarios are all around 1.6, which means the energy consumed by the proposed commercial model almost equals the energy produced by the model. It indicates that when the model only treats sewage sludge, it should be viewed as a commercial model of the waste treatment, not the energy production. On the contrary, the merit of producing energy actually shows when the food waste is added, which makes the proposed commercial model produce two times the energy it consumes in the production.

Figure 3.1 indicates that the way of transport does not affect the energy performance of the model very much. There is no significant difference on the energy performances among the different transport scenarios, BMT, CNGT and DT. The reason for that is that the energy consumption for transport takes an extremely small proportion of the total energy consumption of the model. The main energy consumption of the model is the electricity.

Finally, Figure 3.1 shows that the proposed commercial model can achieve a relatively large amount of energy, when it co-digests sewage sludge and food waste, and uses bio-methane for transporting the waste.

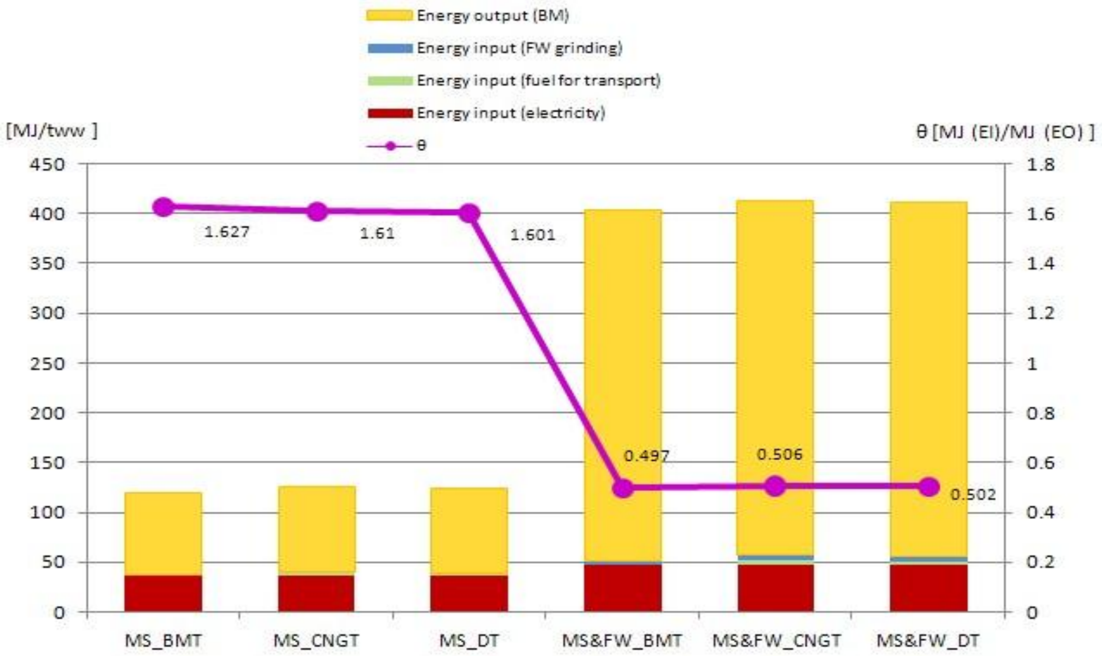

Figure 3.1 Energy performances of the six business scenarios

3.4 Sensitivity analysis on distance of waste transport

The distance of waste transport is an important assumption made in studies of waste management (Houillon & Jolliet, 2005). Therefore, a sensitivity analysis has been carried out to study the influence of the distance on the energy performances.

In this thesis, the distances of transporting a truck of food waste and the distances of transporting a truck of digested sludge are assumed to be 30 km and 50 km, according to the land scale of Beijing. In comparison, the transporting distance assumed in the previous LCA studies of sewage sludge treatment ranges from 10 km to 75 km (Suh & Rousseaux, 2001; Lundin, et al., 2004; Houillon & Jolliet, 2005; Murray, et al, 2008; Møller et al., 2009.). To assess the sensitivity of the energy performances on the transporting distance, the transporting distances used in the energy analysis are reduced by half, i.e.15 km for transporting food waste and 25 km for transporting the digested sludge, respectively. The business scenarios with mono-digestion of MS are used for the sensitivity analysis.

Figure 3.2 compares the energy performances of three business scenarios, MS_BMT, MS_CNGT, and MS_DT at different transporting distances. It indicates that the energy performance of the proposed commercial model is not sensitive to the changes of transporting distance. The total energy consumption in all studied business scenarios were reduced, after shortening the distances. But, the reduction is very small.

About 1% change on the ratio θ is led by the 50% change on the distances. That indicates that the energy performance of the proposed commercial model is very robust with regard to the transporting distance assumptions. Therefore, there are not likely to be different energy performances of the model, when it is built for cities of different scales.

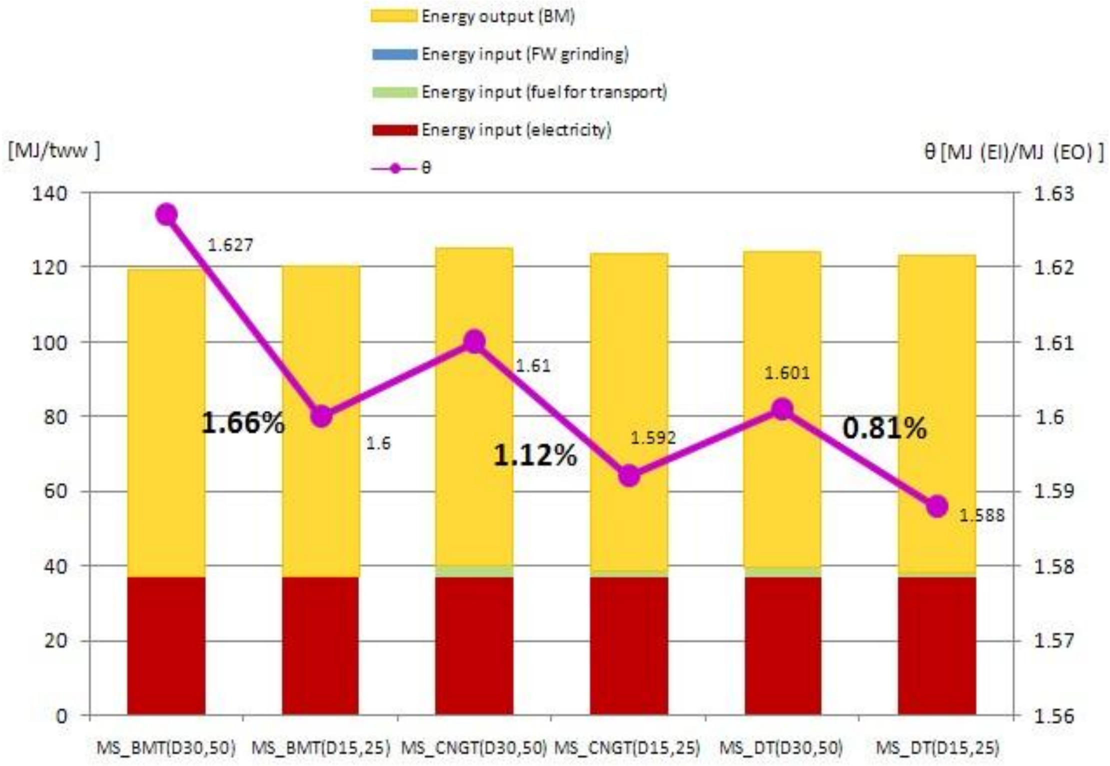

Figure 3.2 Energy performances at different transporting distances

4 Economic analysis

4.1 Net present value

The failure of the current commercial models for the production of sludge-based biogas is that they cannot make money. The proposed commercial model in this thesis is aimed to make an eco-efficient production, which has less environmental impacts and creates more values than current models. To see which business scenario can create most values for the proposed model in China, the net present value (NPV) is used as an economic indicator in this thesis.

The reason for adopting NPV is that it reflects the allocation of a project's economic values in its life time (Hanley & Barbier, 2009). NPV is the sum of Present Value (PV) during the life time of the studied projects. PV is the differences between the sum of discounted revenues and the sum of discounted costs (i.e. $PV= (R-C)*(1-r)^{-t}$). Consequently, $NPV= \sum PV= \sum(R-C)*(1-r)^{-t}$, where t denotes the year. In another words, the NPV represents the sum of all discount cash flows during the life time of a project. Therefore, the project can be acceptable (or profitable) if the NPV>0. So, in the comparison of the economic performance of the six business scenarios, the larger the NPV is, the better the scenario.

4.2 Cost benefit analysis

Cost-Benefit Analysis (CBA) is a tool for decision makers to determine the feasibility to obtain profit to implement a project or a management system. The CBA has been shown to be an effective tool for implementation of environmental management systems (Hanley & Barbier, 2009). Besides, NPV, the CBA can be used on payback time (PBT), which is the year when the investors can get their input money back from the market (i.e. the PBT=t, when $NPV^{t}= \sum_{t} PV= \sum(R-C)*(1-r)^{-t}=0$). The CBA is used to evaluate the economic performances of the proposed model, and to acquire NPV and PBT of the six business scenarios.

It should be noted that CBA studies use a functional unit based on the scale of a project, rather than the function used in LCA studies. Besides, the Ministry of Environmental Protection in China recommends using anaerobic digestion on the municipal wastewater treatment plant, which is larger than 100,000 cubic meters wastewater per day. Hence, it assumes that the proposed commercial model will treat the sewage sludge produced from a large wastewater treatment plant with a capacity at 100,000 [m^3 wastewater /day]). So, the sludge treatment capacity of the proposed model is 583 [tww (MS) /day] (see calculations in Appendix VII).

The life time of the model is assumed to be 15 years and it assumes that the plant operates all year. The discounting rate is assumed to be 6%, which is the discounting rate of the investments announced by the People's Bank of China. To achieve a reliable study, the monetary flows of the model include the investment cost, monetary flows of the counted physical flows, maintenance cost for facilities and equipments, labor cost and revenues. The cost on the buildings and other administration fees are excluded in the study. The data collection and calculations are in Appendix VII.

4.3 Interpretation and analysis

4.3.1 Inventory of cash flows

The cash flows analyzed in this section is to understand the economic impacts from different counted physical flows. Table 4.1 is the inventory of cash flow. In order to illustrate more clearly, Figure 4.1 visualizes Table 4.1.

Table 4.1 Inventory of cash flows of the six business scenarios

Summary of cash flows (Investments, Costs, and Revenues) of the BCM in its six business scenarios						
	MS_BMT	MS_CNGT	MS_DT	MS&FW_BMT	MS&FE_CNGT	MS&FW_DT
Investment [MSEK]:	**265.963**	**265.963**	**265.683**	**346.604**	**346.604**	**346.315**
Biogas production a)	260.823	260.823	260.823	329.303	329.303	329.303
Biogas upgrading	4.017	4.017	4.017	16.146	16.146	16.146
Hybrid CNG and BM trucks	1.123	1.123	0	1.123	1.123	0
Diesel trucks	0	0	0.842	0	0	0.842
Costs [MSEK/yr]:	**11.642**	**11.71**	**11.736**	**13.168**	**13.281**	**13.328**
Consumption Costs:	5.533	5.601	5.632	7.059	7.172	7.224
Electricity	4.734	4.734	4.734	6.069	6.069	6.069
SR deposit	0.799	0.799	0.799	0.822	0.822	0.822
Diesel for FW grinding	0	0	0	0.168	0.168	0.168
Transport fuel	0	0.068	0.099	0	0.113	0.165
Maintenance Costs	0.53	0.53	0.525	0.53	0.53	0.525
Biogas production	0.3	0.3	0.3	0.3	0.3	0.3
Biogas upgrading	0.2	0.2	0.2	0.2	0.2	0.2
Hybrid CNG and BM trucks	0.03	0.03	0	0.03	0.03	0
Diesel trucks	0	0	0.025	0	0	0.025
Labor Costs	5.579	5.579	5.579	5.579	5.579	5.579
Revenues [MSEK/yr]:	**44.590**	**44.657**	**44.657**	**51.193**	**51.304**	**51.304**
MS treatment	42.583	42.583	42.583	42.583	42.583	42.583
BM selling	2.006	2.074	2.074	8.609	8.721	8.721

As shown in Figure 4.1, the dominant operation costs of the proposed model are those for labor and electricity. In contrast, the transport cost takes the smallest proportion (0~1.2%) of the total operation cost. So, changing the fuel used for transporting waste does not change the operation cost significantly. Similarly, there is no obvious difference in the total operation cost between the scenarios mono-digestion of sewage sludge (MS) and co-digestion of sewage sludge and food waste (MS&FW). The extra money spent on transporting food waste and pre-treating food waste is not much. But, in respect of the revenue, the co-digestion of MS&FW creates four times more money than the mono-digestion of MS in selling bio-methane. Overall, the sum of revenues exceeds the sum of operation cost in all the business scenarios assessed.

However, it should be specified that the analysis of cash flows in this thesis is not a dynamic assessment. To see if the proposed commercial model can be profitable or not, it needs to do the study from a life time perspective. This requires analyzing the NPV and the PBT of the model.

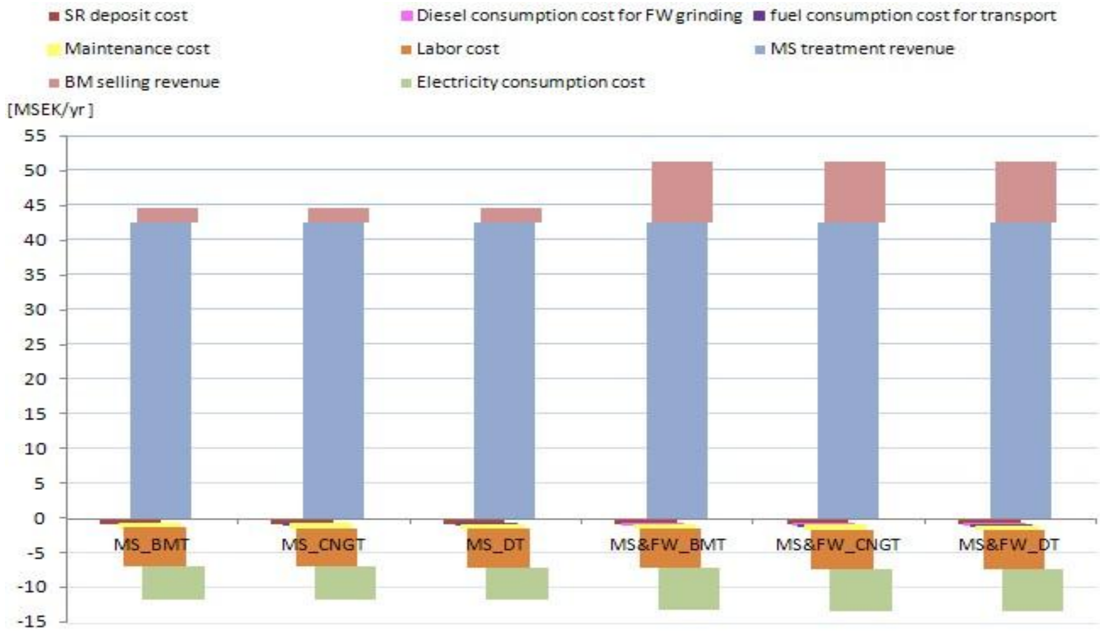

Figure 4.1 Cash flows of the six business scenarios. The investment is not shown in this figure. The capacity of treating sewage sludge is 583 [tww (MS) /day].

4.3.2 Analysis of net present value and payback time

In this thesis, the life time (t) of the proposed BCM is assumed to be 15 years, and the discounting rate (r) is 6%. The PV, NPV and PBT of the six business scenarios are calculated by using the inventory of cash flows (Table 4.1). Figure 4.2 presents the results.

Firstly, the NPV of all the business scenarios are larger than zero, which means that the proposed model (583 [tww (MS) /d]) is profitable, and hence is acceptable.

Secondly, it indicates that the mono-digestion scenario is more profitable than the co-digestion scenario, as there is a sharp decrease of NPV when the model changes to the co-digestion of MS&FW. The PBT of the mono-digestion of MS is 12 years, and the PBT of the co-digestion of MS&FW is 14 years. This indicates that the investors of the mono-digestion MS can get their money back two years earlier than the investors of the co-digestion MS&FW. The analysis of cash flows identified the great advantage of the co-digestion scenarios in creating values of bio-methane. This does not conflict with the result that the mono-digestion scenarios are more profitable. It is because the investment of mono-digestion scenarios is lower than the investment of co-digestion scenarios.

Thirdly, there is no obvious difference in the economic performances between different transport scenarios (BMT, CNGT, and DT). That means that the mode of transport does not affect the economic performance of the proposed model very much. Although this result is not in agreement with what was estimated in Chapter 1, it is reasonable, because the transport cost takes merely a small proportion of the total operation cost (i.e. 0 to 1.2%).

Finally, in comparison, the mono-digestion of MS and using diesel fueled trucks for transporting waste is best from an economic perspective.

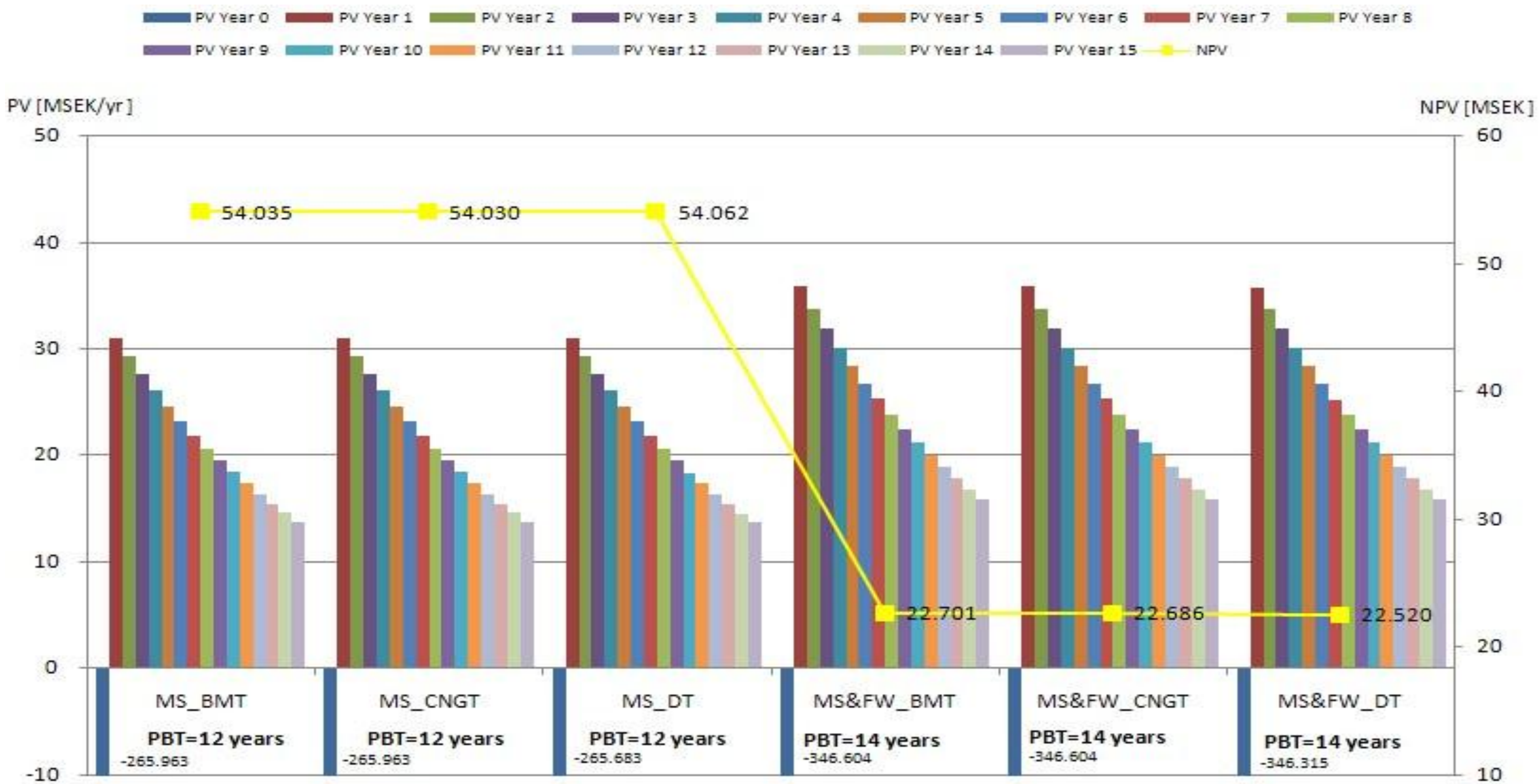

Figure 4.2 NPV, PV and PBT of the six business scenarios for the proposed model at a capacity treating 583 [tww (MS) /d]

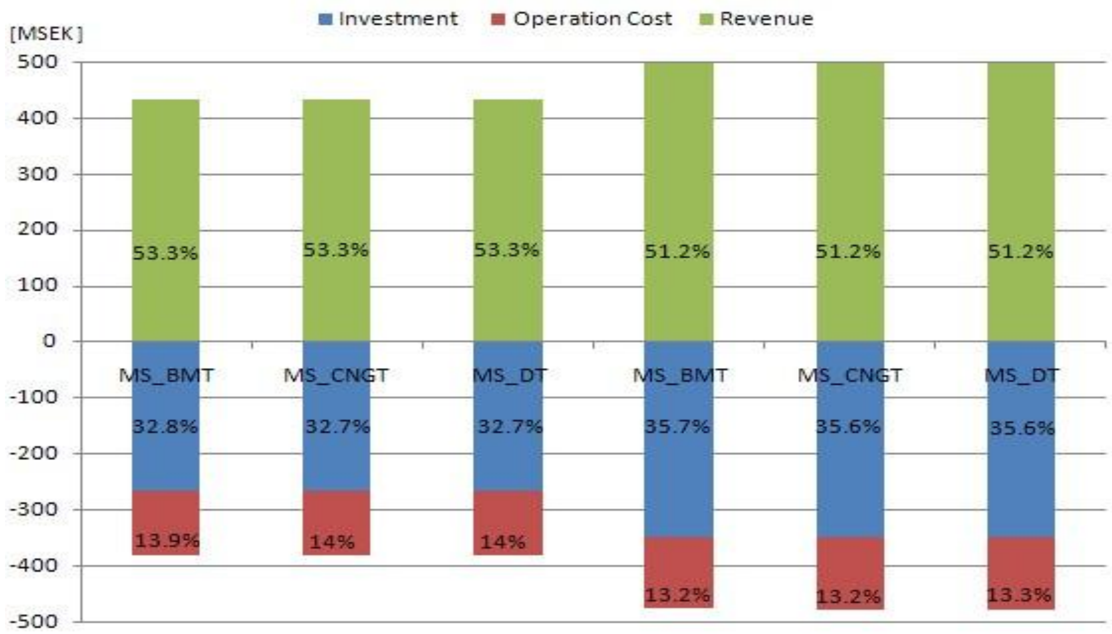

Figure 4.3 Proportions distribution of investment, operation cost and revenue during the life time (15 years) of the proposed commercial model in a capacity treating 583 [tww (MS) /d]

Figure 4.3 shows the distribution of investment, operation cost and revenue during the life time (15 years) of the proposed model. Overall, the revenue takes about half of the total cash flows. In the cost category, the investment is larger than the operation cost.

4.3.3 Sensitivity analysis on the prices of electricity and fuels

The prices of electricity and fuels are the two important data used in the CBA in this thesis. The collection of these data is aimed to reflect the current situation of the market in China. However, these prices are most likely to change in the future, because of the limited energy resources. Therefore, the sensitivity analysis is carried out on the prices of electricity and fuels.

In this thesis, the annual price growth of electricity, diesel, CNG and bio-methane is assumed to be 3%, 5%, 10%, and 10%. These assumptions are made according to industrial reports and the trend of price growth in the past few years.

Firstly, the assumption on the price growth of electricity is made according to the *Report of the Electricity Industry Planning in the Twelfth-Five Years*, which predicts that the annual increasing rate of electricity price will keep at 3% in the next ten years (Chinese Electricity Association, 2010).

Secondly, the assumption on the price growth of diesel is made by reviewing its changes. As shown in Figure 4.4, the average annual price growth of diesel was about 3% in the past two years in China. Considering the increasing space of diesel price, the annual price growth of diesel price in China is estimated to be 5% in the future.

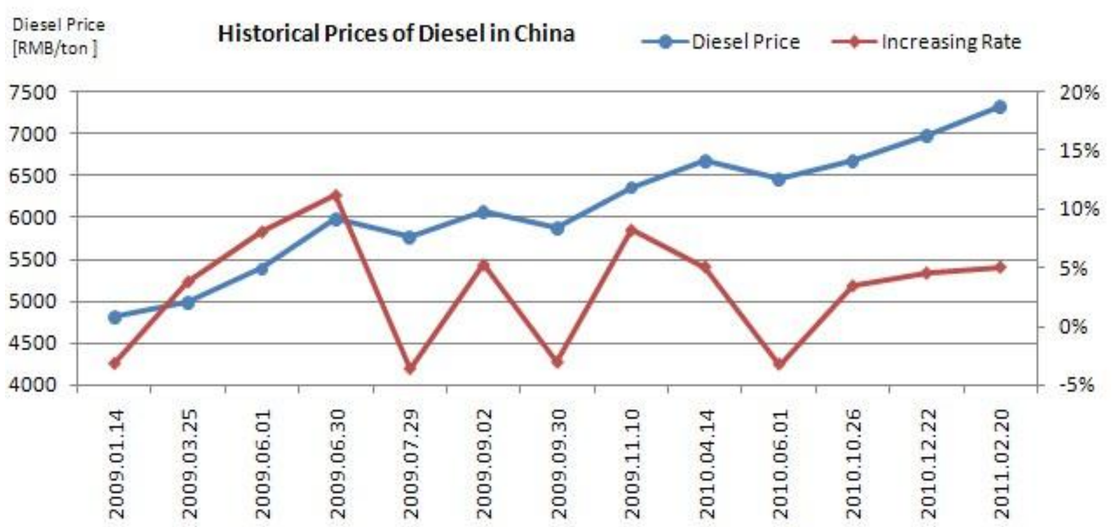

Figure 4.4 Historical Prices of Diesel in China since the year 2009
Data Source: Historical Fuel Price Adjustments (EZJSR website, 2011)

Thirdly, the price growth of CNG and bio-methane also depends on the natural gas market in China. China is deficient in natural gas (NG) resources. The NG resource per capital share in China is not more than 10% of the average international level. As the demand of NG has been increasing in recent years, a trend of importing has been enlarged (e.g. more than 8% of NG consumption is imported). On the other side, the price of the national produced NG is far lower than the other energy prices. Usually, the price of NG equals to 60% of the crude oil price in equivalent energy content in the international market. In contrast, the current Chinese land NG price merely equals to about 25% of the international crude oil price. To enable efficient resource use and sustainable development, the National Development and Reform Commission (NDRC) has implemented a new management policy on the NG pricing (NDRC, 2010), since the 1st, June in 2010. According to this management policy, the NG factory pricing in the year 2010 was increased, and the increasing rate was increased to 24.9%. Moreover, it was announced that the NG factory price in China will be increased by steps during the next following years (NDRC, 2010).

In 2010, the NDRC made an important adjustment on the prices of NG and 93# gasoline. As regulated, the price of NG should be no less than three quarters price of the 93# gasoline. This price adjustment was regulated to be achieved price in two years.

Fuel prices in the Sichuan province can be used as an example. The current gasoline price is 6.5 RMB (almost equivalent to 6.5 SEK) per liter, and the vehicle using NG is sold at 4 RMB per Nm^3, after the price increase. Compared to the 75% of the gasoline price, the increasing rate of vehicle using NG price in the next two years is at least 20%. Taking into account the probable increasing rate of gasoline in the future (i.e. 5% annually), the increasing space of vehicle using NG price is extremely huge with 100% increasing rate. In this thesis, a conservative estimate of the annual price growth of the CNG price is 10%. In addition, it is assumed that the price of bio-methane keeps equivalent with the CNG prices.

Figure 4.5 presents the results of sensitivity analysis on the prices of electricity and fuels.

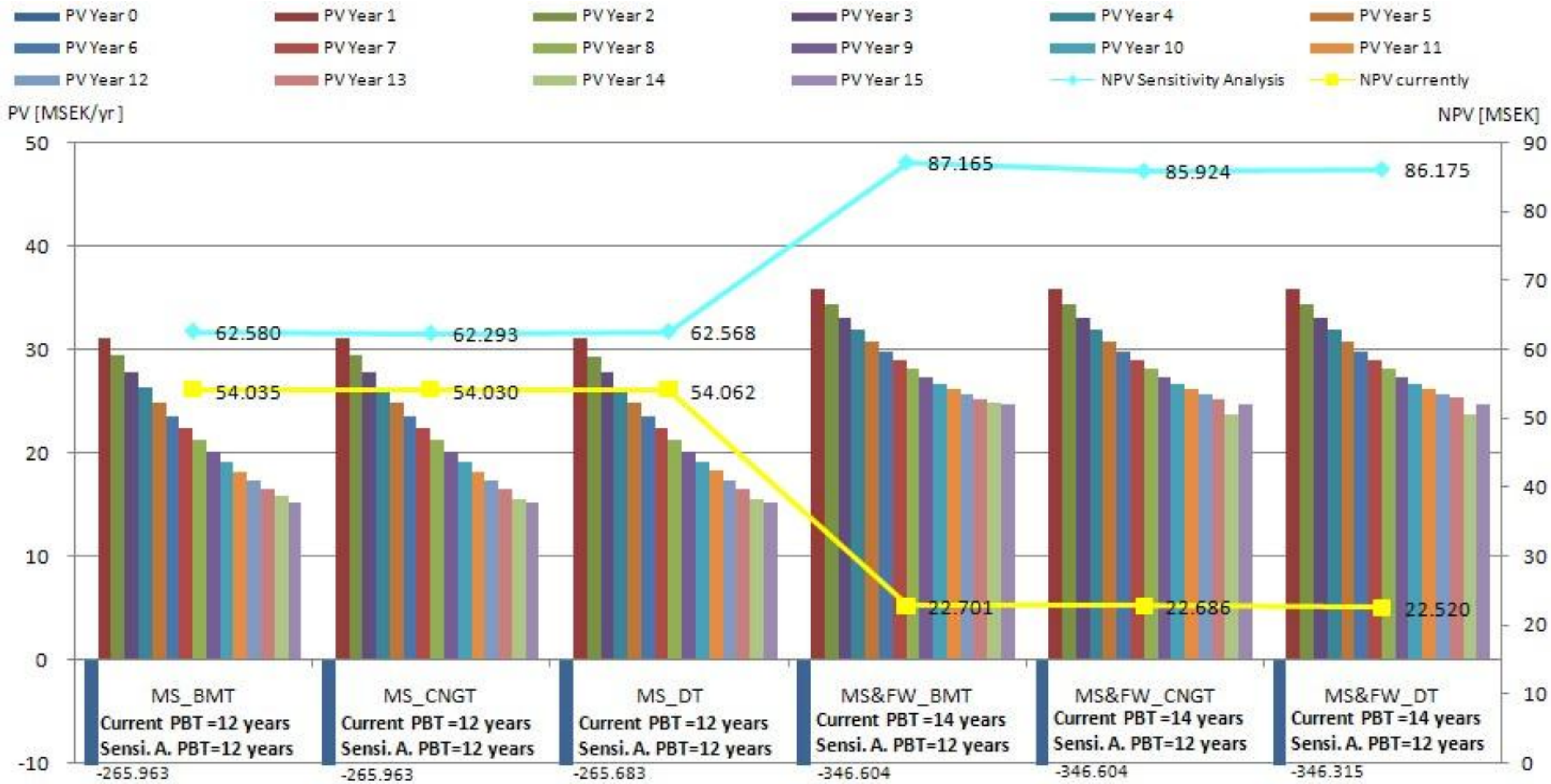

Figure 4.5 Sensitivity analyses on prices of electricity and fuels

It indicates that the scenario with co-digestion of MS&FW is very sensitive to the prices of electricity and fuels. The NPV of this scenario increases almost three times by small rate of increase on the prices of electricity and fuels (i.e. electricity 3%, diesel 5%, CNG and bio-methane 10%). In comparison, the scenario with mono-digestion of MS is somehow less sensitive to the prices of electricity and fuels, as it increases about 14%, and the PBT is the same as before. It can be explained by the fact that the economic performance of co-digestion of MS&FW is more dependent on the selling of bio-methane. In result, the co-digestion of MS&FW is more profitable than the mono-digestion of MS. The co-digestion of MS&FW and using bio-methane for transporting waste (MS&FW_BMT) has the best economic performances.

Nowadays, the government in China is committed to promoting natural gas use. CNG vehicles are given priorities for use in the public transport sector. Supporting policies also make the price of natural gas more competitive than gasoline. Therefore, it should be noted that the business scenario MS&FW_BMT can be expected to create more economic value for the proposed model in the future. Meanwhile, the potential decision makers for the proposed model should be aware that the business scenario mono-digestion of sewage sludge and using diesel for transport is more profitable for the model, if it is carried out now.

5 Assessment of eco-efficiency

5.1 Method for assessing the eco-efficiency

According to the concept of eco-efficiency proposed by the World Business Council for Sustainable Development, a commercial model for eco-efficient production of sludge-based biogas is to create more energy, to treat more waste and to make more money with less environmental impacts. Hence, to assess the eco-efficiency of the proposed commercial model is to make an aggregated assessment of its environmental, energy and economic performance..

It should be noted that the assessment of the eco-efficiency of the production of sludge-based biogas cannot use the typical formula of eco-efficiency exactly. The typical formula of eco-efficiency is:

$$\text{Eco} - \text{efficiency} = \frac{\text{Product or service value}}{\text{Environmental influence}}$$

$$= \frac{\text{Product or service value}}{\text{Quantity of product or service produced or sold}} \times \frac{\text{Quantity of product or service produced or sold}}{\text{Environmental influence}}.$$

It is hard to use this formula to assess the eco-efficiency of the production of sludge-based biogas. An essential reason for this is that it is hard to define the production of sludge-based biogas as a waste treatment or energy production business. Actually, the production of sludge-based biogas plays both of these two roles. That implies that there are two numerators in the formula, i.e. the energy production and the monetary value. The environmental influence is the denominator and the 'quantity of product or service produced or sold' is used with one ton of sludge. But, the energy production cannot be calculated with the monetary value because they have different units. On the other side, it cannot exclude the monetary value in the formula, because producing more energy does not necessarily mean that it is more profitable. As indicated by the economical analysis, although the co-digestion of MS&FW can produce more bio-methane than the mono-digestion of MS, the co-digestion is less profitable than the mono-digestion in its life time, because it has a higher investment and operation cost. Therefore, to assess the eco-efficiency of the production of sludge-based biogas, there is a need for other methods.

This thesis uses three indicators to assess the eco-efficiency of the proposed commercial model for the production of sludge-based biogas. These three indicators are the potential global warming effect (GWE), the ratio between the energy input and energy output (θ), and the net present value (NPV). They respectively represent the environmental, energy and economic performances of the model. Figure 5.1 illustrates the assessment of eco-efficiency by the three indicators.

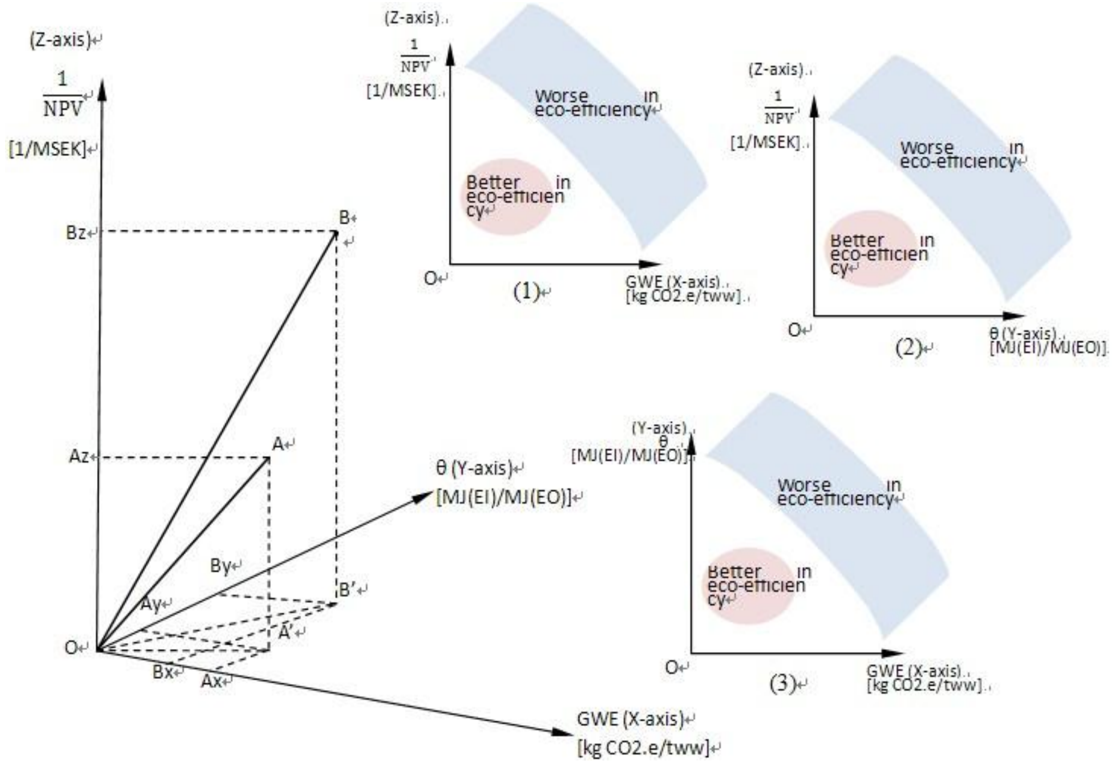

Figure 5.1 Method for assessing the eco-efficiency of the proposed commercial model θ represents the ration between the energy input and energy output

As shown in Figure 5.1, the indicators GWE, θ and NPV are allocated at the three-dimensional axis, X-Axis, Y-Axis and Z-Axis, respectively. Please note the Z-Axis represents the inverse of NPV. Thus, the smaller data at the Z-Axis means the larger profits got in the studied business scenario. The sub-figure (1), (2), and (3) in Figure 5.1 are the two-dimensional axis of every two indicators, respectively. They describe the relation between these two indicators and the eco-efficiency. The idea of the concept eco-efficiency is to create more profits with less environmental impacts. So, in the sub-figures, the point, which is closer to the origin (O) of a polar coordinate system, has better performances in term of eco-efficiency. Therefore, in the three-dimensional space, the eco-efficiency is measured by the distance from the point (that synthesized the three performances of this scenario) in space to O. In results, to compare the eco-efficiency between two business scenarios is to compare their distances: the shorter the better.

Take the instance shown in Figure 6.1:

$$OA = \sqrt{OA_x^2 + OA_Y^2 + AA'^2} \; ; \quad OB = \sqrt{OB_x^2 + OB_Y^2 + BB'^2}$$

where OA_x, OB_x denote the GWE with the unit [kg $CO_{2.e}$/tww]; OA_y, OB_y denote the θ (ratio between energy input and energy output) with the unit [MJ (EI)/MJ (EO)]; AA’, BB’ denote the inverse of NPV with the unit [1/MSEK]. The result OA<OB means the scenario A is better than the scenario B in term of eco-efficiency.

5.2 The most eco-efficient business scenario

By using the method for assessing the eco-efficiency, Table 5.1 shows the distances from the point of the six business scenarios in space to O. In comparison, the business scenario with mono-digestion of sewage sludge and using bio-methane to transport waste is currently the most eco-efficient scenario for the proposed commercial model in China.

Table 5.1 Summary of the environmental, energetic and economical performances and the sustainability measurement

		Z-Axis	X-Axis	Y-Axis	O-BS
Business Scenarios (BS)	Economical Performance		Environmental Performance	Energy Performance	Sustainability measurement
	NPV [MSKE]	1/NPV [1/MSEK]	GWE [kg$CO_{2,e}$/tww]	θ [MJ(EI)/MJ(EO)]	Distance
MS_BMT	54.035	0.019	42.483	1.627	42.514
MS_CNGT	54.030	0.019	42.511	1.610	42.541
MS_DT	54.062	0.018	42.519	1.601	42.549
MS&FW_BMT	22.701	0.044	42.923	0.497	42.926
MS&FW_CNGT	22.686	0.044	42.970	0.506	42.973
MS&FW_DT	22.520	0.044	42.982	0.502	42.985

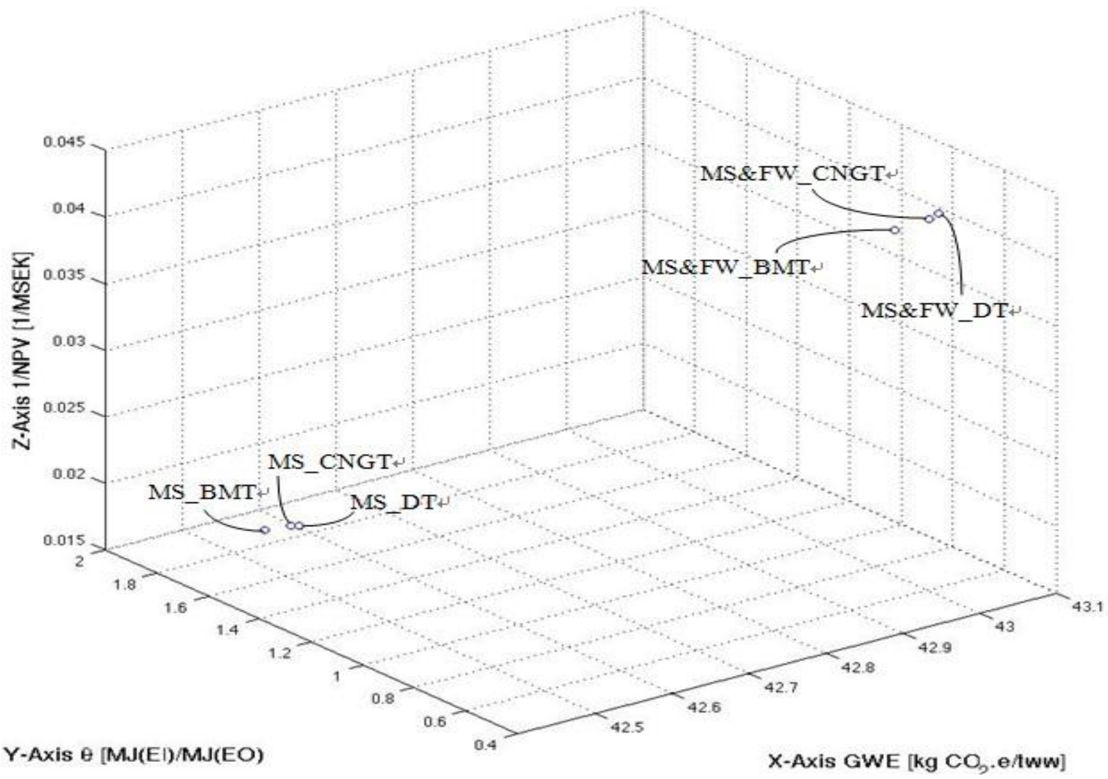

Figure 5.2 Scatter plots of the six business scenarios in respect of the environmental, energetic and economic performances. θ represents the energy intensity: Energy consumption/ Energy production. NPV reflects the value of the proposed commercial model with a capacity of 583 tww (MS) treated per day. And such amount of sewage sludge is produced by a wastewater treatment plant in the scale of 10 [104 m3 wastewater/d].

Figure 5.2 elaborates the scatter of the three-performance-aggregated points of the six business scenarios in space. Overall, there is small difference in the eco-efficiency of different transport ways. On the contrary, there are big differences in the eco-efficiency of different digestion ways. That means that the digestion way has great impact on the eco-efficiency of the proposed commercial model.

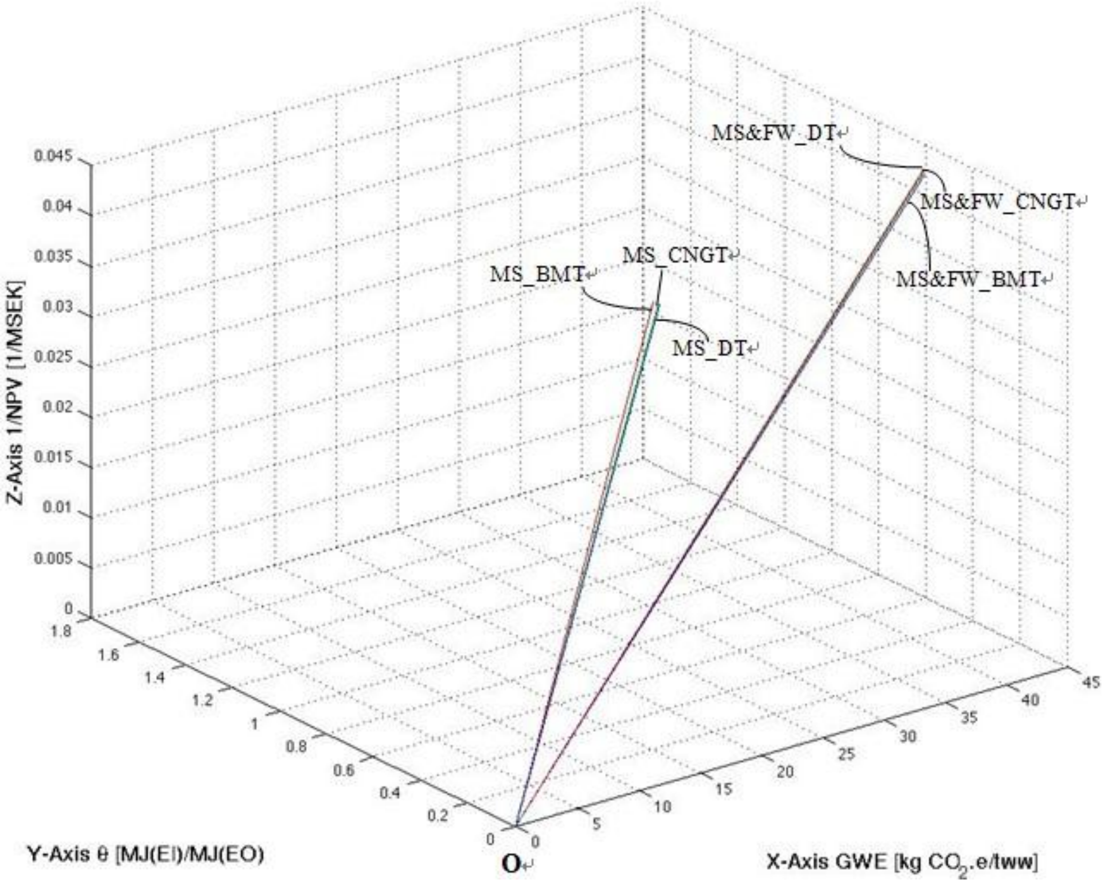

Figure 5.3 Eco-efficiency of the six business scenarios. θ represents the energy intensity: Energy consumption/ Energy production. NPV reflects the value of the proposed commercial model with a capacity of 583 tww (MS) treated per day. And such amount of sewage sludge is produced by a wastewater treatment plant in the scale of 10 [10^4 m^3 wastewater/d].

Figure 5.3 illustrates the eco-efficiency of the six business scenarios. It indicates that the scenario with mono-digestion of sewage sludge and using bio-methane to transport waste (MS_BMT) is the best for the proposed commercial model. Compared to other scenarios, the MS_BMT is more profitable and causes less global warming. Although the MS_BMT does not produce energy as much as the scenarios of co-digestion do, it is the optimal scenario from the perspective of eco-efficiency.

Figure 5.3 also shows that the scenario, co-digesting of sewage sludge and food waste and using bio-methane to transport waste (MS&FW_BMT) is actually less eco-efficient than the scenario MS_BMT. It shows the MS&FW_BMT emits more green house gas emissions and is less profitable than the scenario MS_BMT.

For the decision makers who would like to adopt the proposed commercial model for the production of sludge-based biogas in China, the MS_BMT scenario can be implemented under the current conditions in China.

6 Discussion

6.1 Issues more than CBA

The CBA in this thesis is limited to unfolding the implementation and financing way of the proposed commercial model. Therefore, two issues that are relevant to the economic performance beyond the cost benefit are discussed in this section.

6.1.1 Suitable scale of wastewater treatment plant for adopting the proposed commercial model

One of the advantages of the proposed commercial model is that it can create more profit by producing bio-methane. However, if the production of bio-methane is too small, it cannot be accepted by filling stations. If wastewater treatment plants cannot get money from bio-methane, they won’t adopt the proposed commercial model. As known, the bio-methane production depends on the amount of treated sewage sludge; and the amount of treated sewage sludge depends on the scale of the wastewater treatment plant. Hence, to facilitate the implementation of the proposed commercial model, it is necessary to identify the suitable scales of wastewater treatment plant.

Two criteria are chosen to identify the suitable scales of wastewater treatment plant: the daily bio-methane production and the net present value (NPV) of the proposed commercial model. A daily bio-methane production of 0.7 [10^3 Nm^3/d] is used as a criterion to discuss if the studied scale of wastewater treatment plant is worth to make a demonstration study of the proposed commercial model. The reason for setting a criterion on a demonstration scale, rather than an industrialized scale, is because demonstration projects are widely used to test new technologies before implementation at an industrial scale. The purposes of carrying out a demonstration project are not only to study the technical performance, but also marketing and operation. Some municipal government officers who were interviewed for this thesis and have potential power to influence the approval of such a demonstration project imply that a demonstration project of the proposed commercial model can be authorized as long as its daily bio-methane production can fulfill the daily fuel demand of one public transport line in the city. Liu & Hou (2009) concluded that the daily CNG demand of one transport public line ranges from 700 to 14,000 cubic meters. Therefore, a daily bio-methane production of 0.7 [10^3 Nm^3/d] is used as a lower limit for wastewater treatment plants to implement the proposed commercial model.

Besides the daily bio-methane production, the NPV of the proposed commercial model is used to identify if the studied scale of wastewater treatment plant can afford the implementation of the proposed commercial model. As it was introduced at page 24, NPV is a value that is widely used to select project. If NPV>0, it means the project can be accepted from an economic perspective. Otherwise, the project cannot be accepted. In this thesis, the NPVs of the proposed commercial models of different scales are calculated by using the method of CBA.

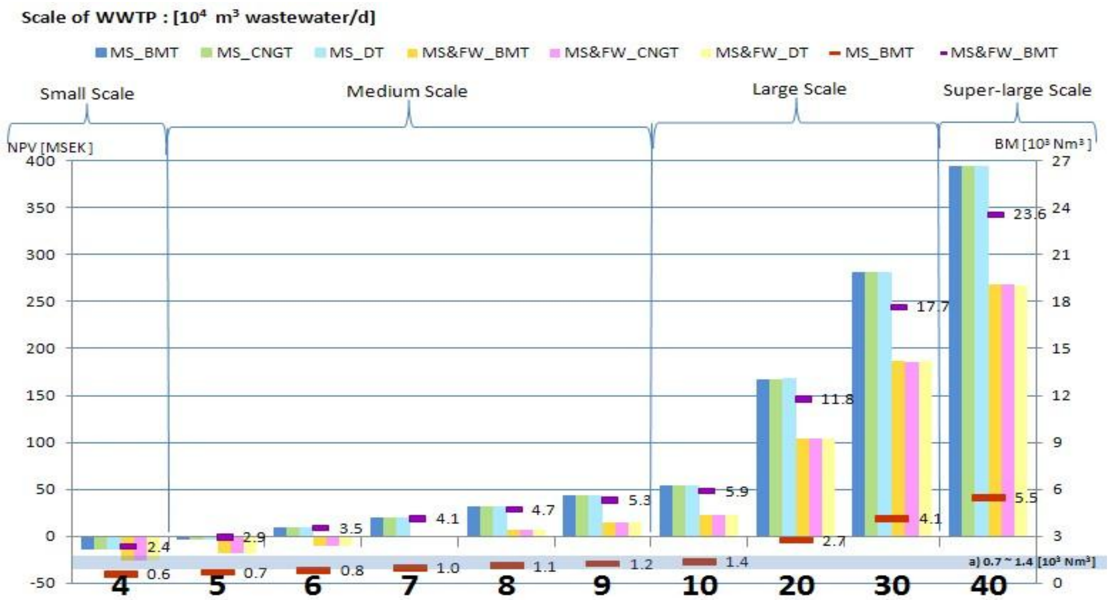

Figure 6.1 Feasibility of the proposed commercial model with respect to the scale of WWTP The light blue bar represents the daily CNG demand of one public transport line.

Figure 6.1 presents the NPV and daily bio-methane production of proposed commercial models that are built on different-scale wastewater treatment plants. It shows that the daily bio-methane production of small-scale wastewater treatment plants (<5 [10^4 m^3 wastewater/d]) is less than 0.7 [10^3 Nm^3/d] when the small scale wastewater treatment plant merely digest sewage sludge. In the case of co-digestion of sewage sludge and food waste, small-scale wastewater treatment plants can produce bio-methane of an amount more than 0.7 [10^3 Nm^3/d]. However, the NPVs of the proposed commercial models built on small-scale wastewater treatment plants are less than zero, meaning unprofitable, in both the mono-digestion and the co-digestion scenarios. That implies small-scale wastewater treatment plants are not suitable to use the proposed commercial model.

For medium-scale wastewater treatment plants (5~10 [10^4 m^3 wastewater/d]), the daily bio-methane production is enough for use by one line of public transport (i.e. 0.7 [10^3 Nm^3/d]), in any way of digestion. The NPV of the wastewater treatment plant whose capacity is lower than 7 [10^4 m^3 wastewater/d] is less than zero. So, the medium scale wastewater treatment plant is capable to carry out the demonstration of the proposed commercial model, when it is given preferential supports on policies and finance. But in a real market, the low production of bio-methane (0.7~5.3[10^3 Nm^3/d]) may make it hard to motivate filling stations to buy the bio-methane.

At present, there are 29 CNG filling stations owned by the company Beijing Public Transport (BPT, 2010). It is assumed that these filling stations are responsible for providing the CNG consumed by the public transport in Beijing (216 [10^3 Nm^3/d]). The average gas supply for one filling station is about 7.4 [10^3 Nm^3/d]. By comparison, the daily bio-methane production of the medium-scale wastewater treatment plants, i.e. 0.7~5.3 [$10^3$$Nm^3$/d], is very small. This indicates the difficulty in trading bio-methane out to filling stations. Depending on the digestion scenarios, the income of selling bio-methane takes about 4% or 16% of the total revenues of the proposed commercial model. So, if the bio-methane cannot be sold out, the proposed commercial model will take a big risk of getting the investment back. To avoid that, this thesis suggests medium-scale wastewater treatment plants to build collaboration with filling stations before running the proposed commercial model.

Large-scale wastewater treatment plants (>10 [10^4 m^3 wastewater/d]) are suitable for adopting the proposed commercial model. Figure.6.1 indicates that both of the NPV and daily bio-methane production of the large-scale wastewater treatment plants are desirable. Until the year 2006, the proportion of large-scale wastewater treatment plants is more than 27% of the total wastewater treatment plants in China. The total wastewater treated by these large-scale wastewater treatment plants is 0.34 billion tons (wastewater) per day (Wu et al. 2009). There is big potential of using the proposed commercial model is China.

6.1.2 CDM and the proposed commercial model

To reduce the global GHG emissions in a cost effective way, the clean development mechanism (CDM) under the Kyoto Protocol allows the industrialized countries to invest in emission-reduction projects conducted in developing countries in return of certified emission reduction (CER) credits (each equivalent to one ton of CO_2). For decision makers in China, the approximate 11.5 Euro per CER credit (J. P. Morgan, 2009) is a potentially strong incentive for emission-reduction projects. According to the United Nations Framework Convention on Climate Change (UNFCCC), there were 999 projects registered by China, 40.73% of the total registered projects in the world, up to October 2010 (shown in Figure 6.2). The Chinese decision makers are very fervent about CDM projects. Until March 2011, the number of registered projects in China has increased from 999 to 1283 (UNFCCC, 2011).

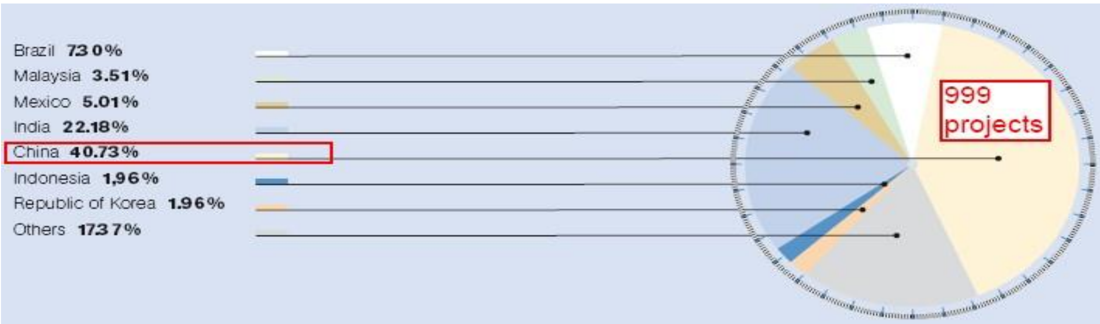

Figure 6.2 Registered project activities by host party. Total: 2,453 Data Source: UNFCCC, 2010.

The high investment of the proposed commercial model makes Chinese decision makers interviewed for this thesis look for financial support. Herein, CDM sounds very prospective. To support information for decision makers, issues related to CDM and the proposed commercial model are discussed in this section. Moreover, this discussion also aims to find a method for quantifying the GWE into monetary flow (i.e. external cost).

Figure 6.3 illustrates the distribution of current Chinese registered CDM projects into different scopes. Currently, the dominant emission-reduction projects in China are in the scope of energy industries (83.80%). In contrast, the registered projects related to waste handling and disposal takes merely 3.35% of the total amount of registered projects. Regarding alternative solid waste treatment, the registered projects (5 projects) can be divided into two kinds: composting of municipal organic solid waste (MOSW), and incineration of municipal solid waste (MSW). No large-scale anaerobic digestion project is registered by China in this field; while 9 projects are registered in the field of small-scale activities related to the anaerobic digestion applied in wastewater and sludge treatment. The treated wastewater and sludge in these projects are however from industrial processes, such as alcohol brewing, or manure management, not wastewater treatment plants. No registered project is aimed at the anaerobic treatment of municipal sewage sludge. In the energy industry, 80 projects related to methane recovery and utilization were registered up to 2011 (CCNDRC, 2011). However, the main utilizations are the electricity generation, and co-generation of electricity and heat. There has been no project on the injection of bio-methane into the natural gas grid until now.

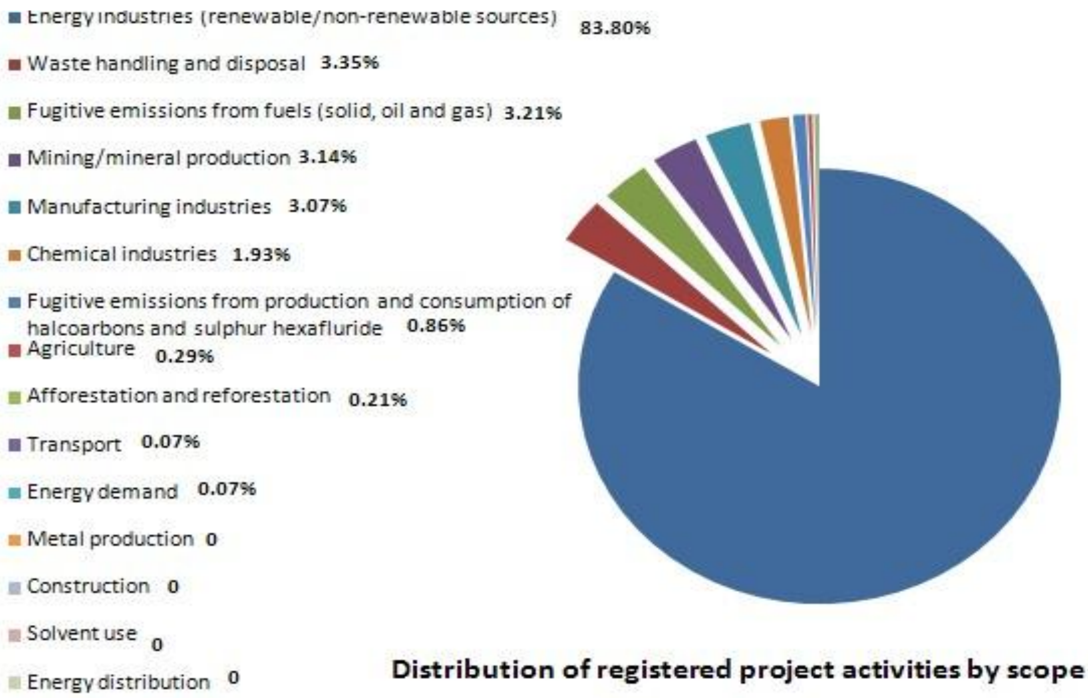

Figure 6.3 Distribution of registered CDM project activities in China by scope UNFCCC, March, 2011

Although there is no registered project on the production and use of biogas from sewage sludge, there are validated methodologies for assessing and monitoring emissions of a project that implements the proposed commercial model. This means that the proposed commercial model can be registered as a CDM project, and consequently obtain money for rewarding its contribution on the GHG abatement in forms of carbon emission reduction (CER) credits.

However, the register of a CDM project should not be taken as a determinant factor in financing the proposed commercial model, because it has many difficulties and risks. One of the difficulties is to identify adaptable methodologies, because the proposed commercial model is related to many scopes in the guidance of CDM methodologies. Besides, by applying different comparative cases, the proposed commercial model could result in different GHG abatement. This will significantly affect amount of CER credit acquired by wastewater treatment plants who apply the CDM project on the proposed commercial model. The potential GWE studied in this thesis focused on GHG emissions related to the proposed commercial model. Thus, comparative case, in which the proposed commercial are not used to treat sewage sludge and food waste were exclude. However, regarding of CDM, GHG emissions from comparative case should be studied. At present, most sewage sludge is simply limed and dewatered before filling into land. A major part of the food waste from restaurants is used to feed pigs at peasants' back yards. Neither of these two waste treatments emits much GHG emissions. On the other side, the production and use of natural gas is the current situation when the proposed commercial model is not implemented. Both production and use of natural gas emit a great amount of GHG emissions. However, in the proposed commercial model, the GHG abatement for avoiding production and use of natural gas is not big, because the amount of produced bio-methane is not big. As indicated in Table 2.3, the proposed commercial model can avoid about 6.3 or 26.7 kg CO_2 equivalent emissions by treating one ton of sewage sludge. This emission takes about 10.8% or 26.8% of the total emission from the proposed commercial model. Therefore, use of the proposed commercial model can lead to more GWE than the current situation of sewage sludge treatment, food waste treatment, production and use of natural gas. If so, the proposed commercial model cannot be financed by CDM, because it does not reduce GHG emissions compared to the comparative case. However, if it is not compared with the current sewage sludge and food waste treatments, the proposed commercial model can come out more effective in reducing GHG emissions by replacing the production and use of natural gas. Therefore, it is very tricky to set the comparative case of the proposed commercial model. This should be noted by decision makers. Furthermore, it is suggested the academicians who make CDM methodologies or study the GWE of waste management to discuss how the setting of system boundaries can affect the results of GWE in the future.

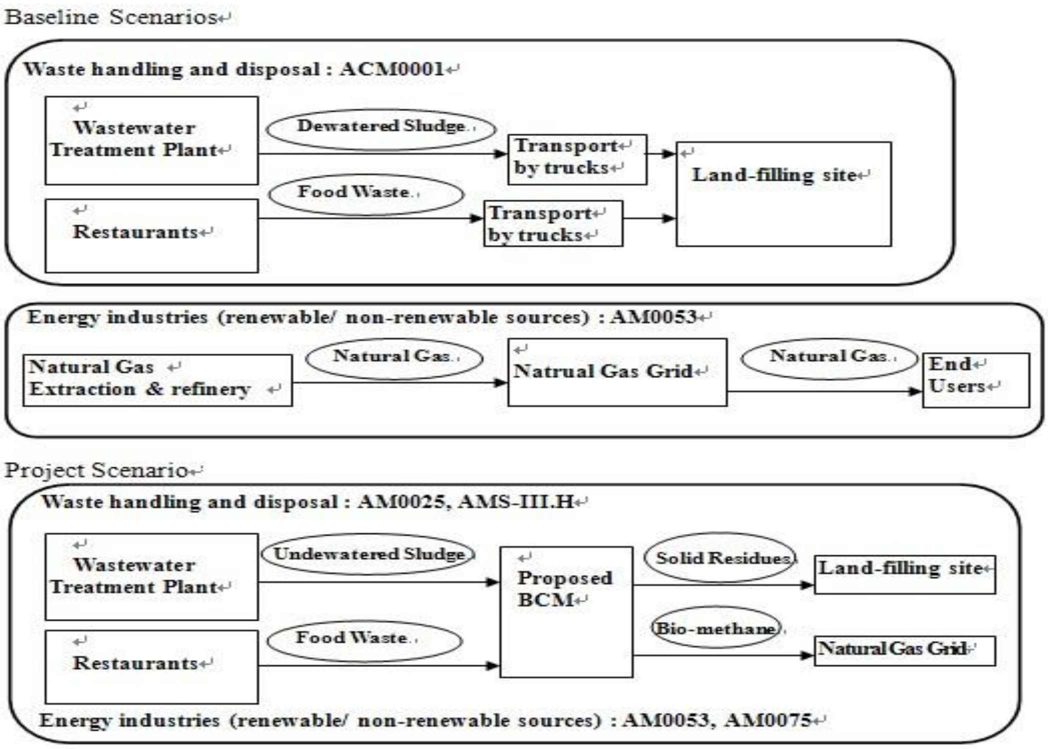

Figure 6.4 Methodologies used for the proposed commercial model to be a CDM project

Figure 6.4 presents a preview of the CDM methodologies relevant to the proposed commercial model. Decision makers and academicians who are interested in the GHG abatement of the proposed commercial model can use these methodologies for further studies.

Moreover, CDM has many challenges in the implementation, for example the high transaction costs. Statistically, the transaction costs for small and medium-sized projects range from ＄50000 to＄225000 (Rose Mero-EPMS, 2008). Furthermore, the price of CER credits changes depends on demand and supply in the carbon market. That leads to a high risk for the management and operation of the proposed commercial model. Therefore, to facilitate the development of the proposed commercial model, it may be more helpful to look for supporting policies and business collaboration, than to register a CDM project.

6.2 Limitations and further studies

A commercial model for eco-efficient production of biogas from sewage sludge in China is identified in this thesis. But, due to the limitations of time, data accessibility and methodology, some important aspects of the proposed commercial model are not investigated: the environmental impacts except potential GWE, the GHGs abatement and external cost. The discussions below are about these three questions and their possible further studies.

6.2.1 The environmental impacts except GWE

This thesis focused on assessing the potential GWE of the proposed commercial model. Other environmental impacts, such as eutrophication and acidification were not studied because the data are unavailable. Regarding of the anaerobic digestion of sewage sludge in China, most studies aim to report the experimental result of biogas production ability. The characteristics of digested liquid and digested sludge are seldom mentioned in these studies, because they are excluded in their study objectives. The reports on the few current running sewage sludge treatment plants do not pay attention to the data report of digested liquid and digested sludge. Therefore, the environmental impacts except GWE cannot be assessed in this thesis. However, it is interesting and important to study all the environmental impacts of the proposed commercial model, especially the eutrophication and acidification, because the disposal of digested sludge can significantly affect the soil and water environment. The assessment should be done by using real Chinese data, not world-wide default value, because there are many differences on the characteristics between the Chinese sewage sludge and European sewage sludge. Therefore, this thesis suggests further studies on the environmental impacts of the proposed commercial model, or other models for the production of sludge-based biogas to collaborate with the experimental study group for collecting data.

6.2.2 GHGs abatement

The assessment of the eco-efficiency of the proposed commercial model requires the environmental analysis in this thesis to illustrate the potential GWE of the proposed commercial model, but, the GHGs avoided by adopting the proposed commercial model are excluded in the system boundary of this thesis.

It would be interesting to study the GHGs abatement of the proposed commercial model in the future, because the GHGs abatement can be used for making carbon trading price, which has been used to facilitate the development of clean technologies in Sweden, but not in China yet. However, the study of GHGs abatement has challenges in lacking methodology and data now.

As what was discussed in the section 6.1.2, whether the proposed commercial model results in GHGs abatement much depends on comparing with which case. Regarding of CDM methodologies, a comparison between the proposed commercial model and a case including the current sewage sludge treatment, food waste treatment, production and use of natural gas can result in that the proposed commercial model leading to more GHG emissions, rather than GHGs abatement. However, a comparison between the proposed commercial model and other sewage sludge treatments, such as composting, drying and combustion would most likely result in the proposed commercial model generating less GWE than other sewage sludge treatments. Similar conclusions were indicated in previous comparative LCA studies, which compared anaerobic digestion of sewage sludge with other sludge treatments in a European context.

It is important to interpret analytic results into sensible suggestions. It is tricky and not right to manipulate methodologies for getting expected result. Moreover, the adopting the proposed commercial model should not only take into account GWE, but also other environmental problems, which would occur without using the proposed commercial model. Therefore, it is suggested that academics do more studies on the GHGs abatement of the proposed commercial model by using different methodologies. Besides, it is suggested to further study the GHGs abatement doing more investigation about the waste management situation in China before data collecting and assessment. For decision makers, it is important to know that any analytic assessment has its perspective and limitations.

6.2.3 External cost

The economic analysis in this thesis did not take into account the external costs of GHGs in the proposed commercial model, due to the lack of data and proper methods.

There are two common methods used for quantifying GHGs into monetary flows. One is the economic input output analysis-based life cycle analysis (EIO-LCA), and the other equals the world-wide price of carbon trading to the external costs of the avoided GHG emissions.

In a previous study (Murray et al., 2008), EIO-LCA is used to study the environmental and cost inventory of sewage sludge treatment and end-use scenarios. The external costs of six different air pollutants included in Murray et al. (2008) were referred to the external costs declared by Matthews & Lave (2000). But, those external costs are not adaptable to this thesis, because those costs were U.S costs, not the Chinese costs. The available estimates of Chinese costs were not enough for doing the EIO-LCA study (Murray et al., 2008).

Other studies on the subsidy policy to manure biogas projects in China used the price of carbon trading to estimate the external costs of avoided GHGs in their proposed projects (Peng Xin yu, 2009). The price of carbon trading is usually used to estimate the external environmental value on GHGs abatement. However, the GHGs abatement of the proposed commercial model was not studied in this thesis. Therefore, further studies on GHG abatement of the proposed commercial model, as well as on methods of external cost are suggested.

7 Conclusions

Through investigation and analyses, the commercial model that produce bio-methane by digesting the sewage sludge produced from wastewater treatment plant is shown to be an eco-efficient production of biogas in China. In a wastewater treatment plant with a capacity of 10 [10^4 m^3 wastewater/d], the commercial model can treat 583 tons of wet weight sewage sludge, produce 1374 cubic meters of bio-methane. Under the current market conditions in China, a net profit can be made at the 12^{th} year since operation. From a life-time perspective (i.e. 15 years), the proposed commercial model is profitable. Although it reduces sewage sludge, the commercial model has a global warming effect of 42.483 kg CO_2 of per treated ton of sewage sludge (wet weight). But, it should be noted that most emissions of the model comes from the production and provision of electricity, which is decided by the electricity system in China, not the proposed model. And the commercial model can produce bio-methane, which is a ‘clean’ fuel and can replace natural gas.

The co-digestion of sewage sludge and food waste is feasible and is demonstrated to be able to significantly increase the bio-methane production in the proposed commercial model. However, the co-digestion is less eco-efficient than the mono-digestion of sewage sludge, because the co-digestion has a higher global warming effect and is less profitable. Also, co-digestion is shown to be of advantage in creating profits when the prices of energy increase in future. Besides, this thesis shows that even without the payment on food waste treatment, the proposed commercial model can give all investment and operation costs back in 14 years. Considering the 15-years life time of the model, government officers should think about providing more incentives to motivate the adoption of the commercial model. Regarding the different ways of transporting the digested sludge to landfill, there is no significant difference in using bio-methane fueled trucks, CNG-fueled trucks and diesel-fueled trucks.

It is found that large-scale wastewater treatment plants (i.e. which is larger than10 [10^4 m^3 wastewater /day]) are more suitable to adopt the proposed commercial model. Medium-scale wastewater treatment plants (i.e. 5~10 [10^4 m^3 wastewater /day]) are capable to carry out the demonstration study of the proposed commercial model, because its daily production of bio-methane is enough to be used by one line of the public transport. However, this production is not enough to motivate filling stations to buy the bio-methane. Thus, it requires both the efforts of government and the medium-scale wastewater treatment plants in the implementation of the proposed commercial model. Besides more policy supports, this thesis suggests to build collaboration with filling stations before running the proposed commercial model. It is not recommended to build the proposed commercial model for small scale wastewater treatment plants (< 5 [10^4 m^3 wastewater /day]).

By studying the methodologies of CDM projects, it is found that the proposed commercial model can be registered as a CDM project and get more financial supports depending on its GHG abatement. However, decision makers should be cautious when registering the project. There is no project registered related to sewage sludge treatment and bio-methane so far. The methodologies are complicate, and the GHG abatement of the proposed commercial can be highly depended on the setting of comparative case. Besides, CDM has risk on the carbon trading price. So, to facilitate the development of the proposed commercial model, it is suggested to primarily look for supporting policies and business collaboration.

Finally, due to limitations of this thesis, it is suggested to do further studies on the environmental impacts except GWE, GHG abatement and external cost of the proposed commercial model.

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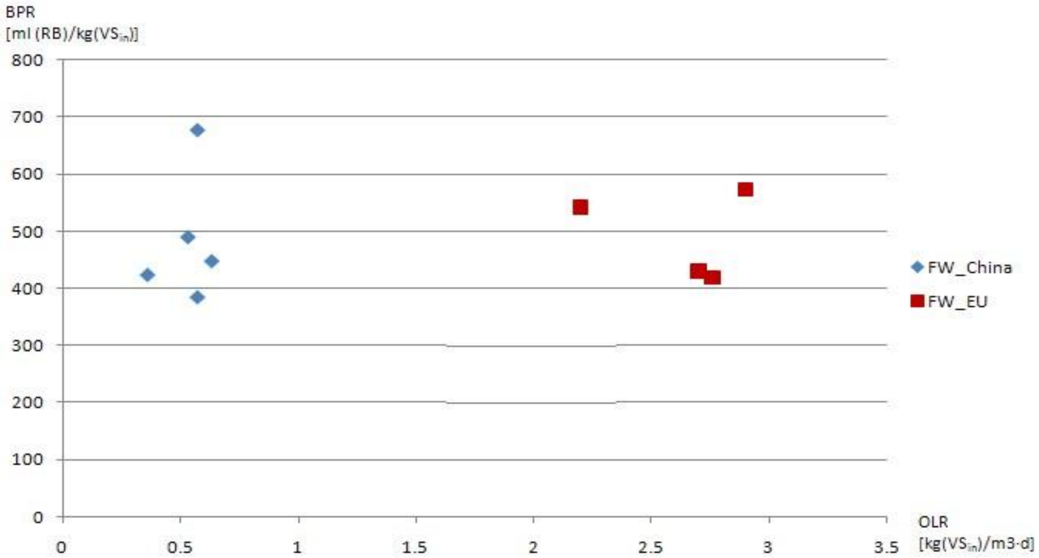
Appendix I

Comparison on the characteristics and biogas production abilities between the food waste in China and the sorted municipal solid waste in Europe

Waste composition	Scale	TS [% of ww]	VS [% of TS]	TC [% of TS]	TN [% of TS]	C/N	Temp [°C]	HRT [d]	SMP [ml(CH$_4$)/g(VS$_{in}$)]	CH4 content [% vol]	BPR [ml(RB)/g(VS$_{in}$)]	OLR [kg(VS$_{in}$)/m^3·d]	Country	[R]
Food waste	Lab	24	96.7	54	2.4	22.5	35	16	331.6	74	448a	0.63g	China	Li et al.,2010
		21.9	82.6	52.2	2.7	19.3	35	19	362.4	74	490a	0.53g		
Food waste	Lab	n.d	n.d	n.d	n.d	n.d	35	35	210	54.51	385a	0.57g	China	Liu et al., 2009
									369	54.51	677a	0.57g		
Food waste	Lab	24.6	94.3	n.d	n.d	n.d	35	28	313.4	a.74%	424a	0.36g	China	Li et al., 2009
Food waste	Pilot	4	92	58	4.6	12.6	34.5	15(SRT)	395	69	572a	2.9	Sweden	Jansen et al., 2004
S-MSW	Pilot	32	87	48	3.1	15.5	34.8	15(SRT)	271	63	430a	2.7	Sweden	Jansen et al., 2004
OFMSW[1)]	Pilot	n.d	n.d	45	1.8	24.5	56+35 2)	30	251.4b	60	419	2.76	Poland	Sosnowski et al., 2003
S-MSW	Pilot	21.3	82.3	n.d	n.d	n.d	37	25	n.d	n.d	543	2.2	German	Karl et al., 1999

1) OFMSW: organic fraction of municipal solid waste is composed of potato 55%, bread 5%, paper2%, fruit & vegetables 28%, rice & spaghetti 10%.
2) It was conducted in the two stage anaerobic digestion.

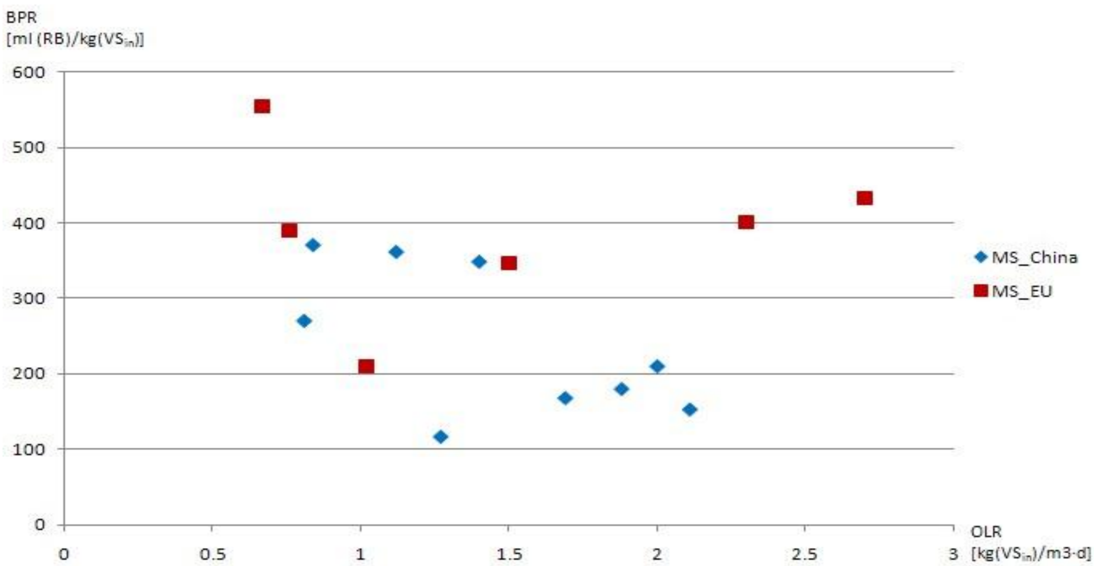


BPR denotes biogas production rate.
OLR denotes organic load rate.

Appendix II

Comparison on the characteristics and biogas production abilities of sewage sludge between China and Europe

Waste composition	Scale	TS [% of ww]	VS [% of TS]	TC [% of TS]	TN [% of TS]	C/N	Temp [°C]	HRT [d]	SMP [ml(CH$_4$)/g(VS$_{in}$)]	CH4 content [% vol]	BPR [ml(RB)/g(VS$_{in}$)]	OLR [kg(VS$_{in}$)/m^3 • d]	Country	[R]
Thickened sewage sludge (Beijing)	Lab	3.8	44.7	n.d	n.d	n.d	35	32	239.8b 243.7b 231/8b	64.8 67.5 66.6	370e 361e 348e	0.84d 1.12d 1.40d	China	Li et al., 2007
Thickened sewage sludge (He Nan)	Lab	9.1	52.7	n.d	n.d	n.d	35	25	110.5b 103.8b 99.1b	62.4 61.8 64.8	117e 168e 153e	1.27d 1.69d 2.11d	China	Li et al., 2007
WAS (Beijing)	Pilot	3.4	38.1c	n.d	n.d	4.5	35	16	183.87b	68.1	270	0.81f	China	Dai et al., 2007
PS (Beijing)	Pilot	3.8	80c	n.d	n.d	7.1	35	16	123.84b	68.8	180	1.88f	China	Dai et al., 2007
MS(Beijing)	Pilot	3.7	87c	n.d	n.d	6.2	35	16	143.43b	68.3	210	2.00f	China	Dai et al., 2007
WAS	Full	2.6	69	n.d	n.d	n.d	37	19.8	142.38b	67.8	210	1.02	Italy	Bolzonella et al., 2006
MS	Pilot	n.d	n.d	n.d	n.d	n.d	35.1 34	15(SRT) 10(SRT)	269 281	67 65	401a 432a	2.3 2.7	Sweden	Jansen et al., 2004
MS	Pilot	n.d	n.d	42	5.2	8.1	56+35 2)	52	332.4b	60	554	0.669	Poland	Sosnowski et al., 2003
Sewage sludge	Pilot	5	58.5	n.d	n.d	n.d	37	20	n.d	n.d	347	1.5	German	Karl et al., 1999
MS	Full	n.d	n.d	n.d	n.d	n.d	37	20	n.d	n.d	390	0.76	Slovenia	Gergor et al., 2008



BPR denotes biogas production rate.
OLR denotes organic load rate.

Appendix III

Co-digestion of sewage sludge and food waste in China

Waste composition	Scale	Composition	TS [% of ww]	VS [% of TS]	TC [% of TS]	TN [% of TS]	C/N		Temp [°C]	HRT [d]	SMP [ml(CH4)/g(VS_in)]	CH4 content [% vol]	BPR [ml(RB)/g(VS_in)]	OLR [kg(VS_in)/m³ • d]	Country	[R]
MS&FW 1:1 (VS base)	Pilot	MS	3.5	66.3c	33.2	4.9	6.8	9.8	35	9	426	65.4	651a	4.13	China	FU et al., 2007
										12	436	66.5	656a	3.1		
		FW	15~30	91.8	45.4	2.6	17.5			16	430	66.7	645a	2.33		
										20	435	68.1	639a	1.86		
MS&FW 3:1 (VS base)	Pilot	MS	3.5	66.3c	33.2	4.9	6.8	7.9	35	9	328	67.5	486a	3.17	China	FU et al., 2007
										12	337	68.9	489a	2.38		
		FW	15~30	91.8	45.4	2.6	17.5			16	337	69.8	483a	1.78		
										20	337	71.6	471a	1.43		
PS&FW 1:1 (VS base)	Pilot	PS	3.5~5.2	60.4C	56.6	5.7	9.9	11.9	35	10	470~482	61.9~65.6	759~735a	4.19	China	Fu et al., 2006
										13				3.22		
		MS	15~30	91.8C	48.2	2.8	17.2			16				2.62		
										20				2.10		
PS&FW 3:1 (VS base)	Pilot	PS	3.5~5.2	60.4C	56.6	5.7	9.9	10.6	35	10	441~447	61.3~64.3	719~695a	3.31	China	Fu et al., 2006
										13				2.55		
		MS	15~30	91.8C	48.2	2.8	17.2			16				2.07		
										20				1.66		
WAS&FW 1:3 (TS base)	Pilot	WAS	3 thickended	71c	11.01	1.92	5.7	12.2	35	10	380	57.8	657	5.62f	China	FU et al., 2006
										15	392	59.8	656	3.96f		
		FW	15~30	91.8c	68.1	3.9	17.5			20	397	62.1	639	2.81f		
WAS&FW 1:1 (TS base)	Pilot	WAS	3 thickended	71c	11.01	1.92	5.7	9.1	35	10	353	61.8	571	4.04f	China	FU et al., 2006
										15	365	61.4	594	2.72f		
		FW	15~30	91.8c	68.1	3.9	17.5			20	373	67.4	553	2.04f		
WAS&FW 3:1 (TS base)	Pilot	WAS	3 thickended	71c	11.01	1.92	5.7	7.1	35	10	236	70.5	382	3.04f	China	FU et al., 2006
										15	241	73.3	329	2.04f		
		FW	15~30	91.8c	68.1	3.9	17.5			20	248	76.2	325	1.53f		

Appendix IV

Co-digestion of sewage sludge and food waste (or source sorted municipal solid waste) in Europe

Waste composition	Scale	Composition	TS [% of ww]	VS [% of TS]	TC [% of TS]	TN [% of TS]	C/N		Temp [°C]	HRT [d]	SMP [ml(CH4)/g(VS_in)]	CH4 content [% vol]	BPR [ml(RB)/g(VS_in)]	OLR [kg(VS_in)/m³ • d]	Country	[R]
MS&FW 4:1 (VS base)	Pilot	MS	n.d	n.d	n.d	n.d	n.d	n.d	34.5	10(SRT)	326	69	472a	2.7	Sweden	Jansen et al., 2004
		FW	4	92	58	4.6	12.6									
MS&OFMSW 4:1 (vol. base)	Pilot	MS	n.d	n.d	45	1.8	25	14.3	56+35 2)	29	319.2b	60	532	3.084	Poland	Sosnowski etal., 2003
		OFMWS	n.d	n.d	42	5.2	8.1									
PS&OFMSW 7:1 (VSS base)	Full	PS	n.d	n.d	n.d	n.d	n.d	n.d	37	20	n.d	n.d	600	1.01	Slovenia	Gergor et al., 2008
		OFMWS	n.d	n.d	n.d	n.d	n.d									
MS&S-MSW 4:1(TS base)	Pilot	MS	n.d	n.d	n.d	n.d	n.d	n.d	37	17	n.d	n.d	518	4.3	German	Karl et al., 1999
		S-MSW	n.d	n.d	n.d	n.d	n.d									
MS&S-MSW 1:1(TS base)	Pilot	MS	n.d	n.d	n.d	n.d	n.d	n.d	37	20	n.d	n.d	529	2.9	German	Karl et al., 1999
		S-MSW	n.d	n.d	n.d	n.d	n.d									
MS&S-MSW 1:2(TS base)	Pilot	MS	n.d	n.d	n.d	n.d	n.d	n.d	37	20	n.d	n.d	459	2.0	German	Karl et al., 1999
		S-MSW	n.d	n.d	n.d	n.d	n.d									
MS&S-MSW 1:1(TS base)	Pilot	MS	n.d	n.d	n.d	n.d	n.d	n.d	37	17	n.d	n.d	450	2.2	German	Karl et al., 1999
		S-MSW	n.d	n.d	n.d	n.d	n.d									
WAS&S-MSW 5.4:1(VS base)	Pilot	WAS	2.6	69	n.d	n.d	n.d	n.d	37	19.8	170.82b	65.7	260	1.21	Italy	Bolzonella et al., 2006
		S-MSW	n.d	n.d	n.d	n.d	n.d									
WAS&S-MSW 1.4:1(VS base)	Full	WAS	n.d	n.d	n.d	n.d	n.d	n.d	36.3	22	275.2b	64	430	0.78	Italy	Bolzonella et al., 2006
		S-MSW	29.64	76.3	n.d	n.d	n.d									

n.d: no data

a) Calculated by BPR=SMP÷CH_4 content

b) Calculated by SMP=BPR ×CH_4 content

c) Calculated by VS [of TS]= VS [of ww]÷TS [of ww]

d) Calculated by OLR= LR ×(VS/TS)÷HRT

e) Calculated by BPR[based on the VS in]=BPR[based on VS removal]×VS removal rate

f) Calculated by OLR=BY [ml(RB)/L·d]÷BPR[ml(RB)/g(VS in)]

g) Calculated by OLR=LR[g(VS in)/L]÷HRT[d]

Appendix V

Data collection and calculation of GWE

Step (I): Data collection

With a context of China, the data used in this thesis is to greatest extent to collect from China by literature review, and interviews with experts and plants managers.

•***Characteristics of MS and FW in China***

The importance of description the characteristics of the waste treated is owing to their great influences on the results present in LCI. For an instance, the amount of carbon sequestration in land is calculated based on the carbon left in the digested sludge and the emission efficient of the land. Refer to the first constraint, the amount of carbon left in the digested sludge is decided by both of the total carbon content and the biogas production potential of the substrate. Therefore, the provision of the information refer to the characteristics of the waste treated is important and necessary.

Table V.1 shows the characteristics of the MS and FW considered in this thesis. The data is collected from literatures that study the mesophilic anaerobic digestion of the sewage sludge, food waste, and their combinations (FU, et al. (2007), Wu, et al. (2008), and LI, et al. (2010)). All of the data used could represent the situations in the studied context, China. In additional, the MS is consisted by PS and WAS with a volume ratio of 1:1 (FU, et al. (2007)).

Table V.1 Characteristics of the MS and FW considered in this thesis

Charateristics	MS	FW	MS&FW ($gVS_{FW}:gVS_{MS}$=1:1)
TS [% of the wet weight]	2.4	22.5	—
VS [%of TS]	66.3	91.8	—
TC [% of TS]	33.2	45.4	—
TN [% of TS]	4.9	2.6	—
C/N	6.8	17.5	9.8
Temperature [℃]	35	35	35
HRT [days]	20	19	20
BPR [ml (RB)/g (VS_{in})]	323	490	639
CH4 content [% volume]	65	74	68

Data sources: [R] FU et al., 2007; [R] Wu et al., 2008; [R] LI et al., 2010.
TS:Total solid content; VS: Volital Solid content; TC: Total carbon content; TN: Total nitrogen content; HRT: Hydraulic retention time; BPR: Biogas production time.

•***Energy production systems in China***

Regarding for the essential impacts from the energy production systems in accounting of GHG emissions from waste management systems and waste technologies (Fruergaard & Astrup (2009)), the framework UODS requires to present that information in the table of Additional Information Background.

Figure V.1 presents the current electricity production systems in China, in which the dominance (78.97%) is from the coal-fired power plants. This kind of electricity production strategy leads to greater amount of GHG emissions without doubt, compared to the lower GHG emissions from the electricity production systems in Sweden that is dominant by hydro and nuclear power,

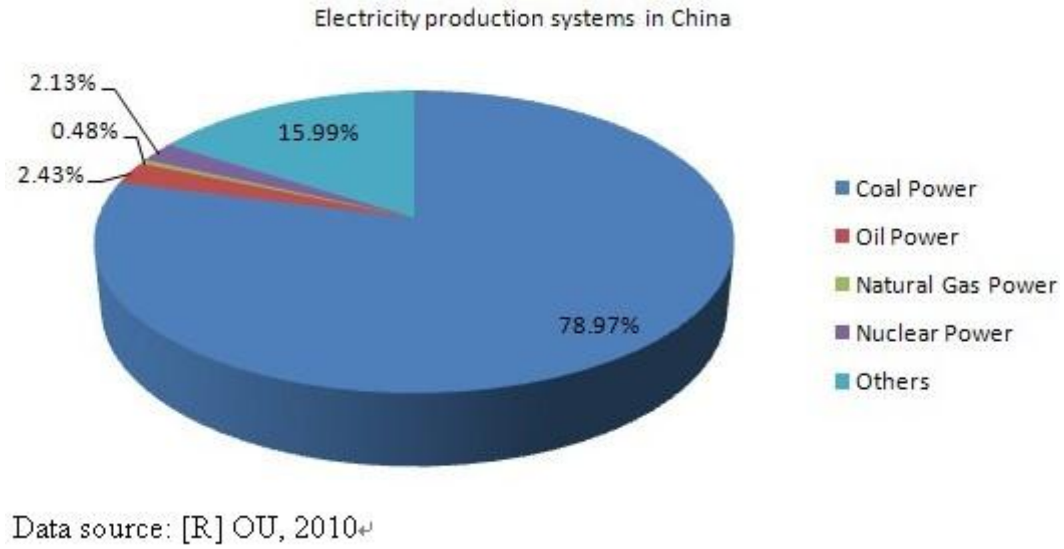


Figure V.1 Electricity production systems in China

Step (II): Calculations of the accounted physical flows (A_N)

•***Raw biogas production***

The amount of raw biogas (RB) produced from anaerobic digester is depended on the characteristics of the MS and FW, and relative technological constraints. Based on data presented in Table IV.1, the calculations on the volume of produced RB in scenarios MS and MS&FW, respectively, are:

$V_{RB} = A_{MS}*TS_{MS}*VS_{MS}*BPR_{MS} = 1* 2.4\%*66.3\%*323=5.14$ [Nm^3 (RB)/tww], and

$V_{RB} =A_{MS}*TS_{MS}*VS_{MS}*(1+\alpha)*BPR_{MS\&FW}$

$=1* 2.4\%* 66.3 \%*(1+1)*639=20.336$[$Nm^3$ (RB)/tww].

α represents the ratio of MS&FW composition in the co-digestion substrate (on the base of VS input).

•***Solid residue production***

The importance of quantifying the amount of solid residue from the biogas production process lies in its influence on the climate change. Even filled into land, the nitrogen content in the solid residue will be emit, and be in a form of nitrous oxide (N_2O) that is one of the important greenhouse gases in the air. On the other side, although the anaerobic digestion transform the carbon content in organic into biogas, there are still some of the carbon left due to the incomplete biodegradation in the studied time period (i.e. 100years). With the time pass, small part of the carbon in the solid residue will emit as biogenic CO_2 in the air, and the others will be bound in the soil. Therefore, to present the factor that describes amount of emission from per ton of waste in wet weight, it is necessary to quantify the amount of solid residue produced.

The amount of total solid matter in the solid residue is equal to the total solid matter content in the waste subtracts the quality of the raw biogas produced. Two formulas used to quantify the amount of produced solid residue separately in different cases. For the anaerobic sewage sludge, the produced solid residue is:

$$M_{SR} = (A_{MS} \times TS_{MS} - M_{RB}) \div TS_{SR}$$

For the co-digestion of sewage sludge and food waste, the formula used is:

$$M_{SR} = [(A_{MS} \times TS_{MS} + A_{FW} \times TS_{FW}) \div (A_{MS} + A)_{FW} - M_{RB}] \div TS_{SR}$$

In the formulas, M_{RB} denotes the quality of the produced raw biogas, which is resulted from the multiplying the volume of produced raw biogas by its corresponding density. TS_{SR} is the solid content in the solid residue, equals to 25%. As results, the amounts of solid residue in the two cases are 0.072 [ton/tww] and 0.069 [ton/tww].The details of calculation are in the Table V.2.

Table V.2 Calculations of the quantities of SR and RB

	M_{SR} [ton/tww]	M_{RB} [kg/tww]
MS	$M_{SR}=(A_{MS}\times TS_{MS}-M_{RB})\div TS_{SR}$ $=(1\times 2.4\%-5.952\times 10^{-3})\div 25\%$ $=0.072$	$M_{RB}=M_{RB}^{CH4}+M_{RB}^{CO2}$ $=V_{RB}^{CH4}\times \rho_{ch4}+V_{RB}^{CO2}\times \rho_{co2}$ $=0.717\times 65\%\times V_{RB}+1.977\times 35\%\times V_{RB}$ $=0.717\times 65\%\times 5.14+1.977\times 35\%\times 5.14$ $=5.952$
MS&FW	$M_{SR}=[(A_{MS}\times TS_{MS}+A_{FW}\times TS_{FW})\div(A_{MS}+A_{FW})-M_{RB}]\div TS_{SR}$ $=[(1\times 2.4\%+0.077\times 22.5\%)\div(1+0.077)-21.152\times 10^{-3}]\div 25\%$ $=0.069$	$M_{RB}=M_{RB}^{CH4}+M_{RB}^{CO2}$ $=V_{RB}^{CH4}\times \rho_{ch4}+V_{RB}^{CO2}\times \rho_{co2}$ $=0.717\times 68\%\times V_{RB}+1.977\times 32\%\times V_{RB}$ $=0.717\times 68\%\times 18.882+1.977\times 32\%\times 18.882$ $=21.152$

•*N_2O and biogenic carbon sequestration in land filling*

The carbon content in the solid residue=the carbon content in the influent sludge - the carbon content in the produced raw biogas (i.e. including the carbon content in the fugitive loss). For the nitrogen, the amount of nitrogen is equal to the amount nitrogen in the untreated sludge.

Table V.3 Calculations of the quantities of C and N content in SR

	M_{SR}^{C} [kg(C)/tww]	M_{SR}^{N} [kg(N)/tww]
MS	$M_{SR}^{C}=M_{MS}^{C}-M_{RB}^{C}$ $=A_{MS}*1000*TS_{MS}*TC_{MS}-M_{RB}^{CH4}*12/16-M_{RB}^{CO2}*12/44$ $=5.202$	$M_{SR}^{N}=M_{MS}^{N}$ $=A_{MS}*1000*TS_{MS}*TN_{MS}$ $=1.176$
MS&FW	$M_{SR}^{C}=M_{MS}^{C}-M_{RB}^{C}$ $=(A_{MS}*1000*TS_{MS}*TC_{MS})+(A_{FW}*1000*TS_{FW}*TC_{FW})$ $-(M_{RB}^{CH4}*12/16+M_{RB}^{CO2}*12/44)$ $=4.893$	$M_{SR}^{N}=M_{MS}^{N}$ $=(A_{MS}*1000*TS_{MS}*TN_{MS})+$ $(A_{FW}*1000*TS_{FW}*TN_{FW})$ $=1.627$

When filled in land, parts of the carbon and nitrogen are bound with soil, whereas, others emit in air. It is hard to assess the emission coefficients since that is depended on a variety of factors, such as the local climate, soil conditions, etc (Interview). Due to the inaccessibility of the emission coefficients of the digested sludge dumped in land in China, the emission coefficients are taken from Bruun et al. (2006), which represents the conditions in Denmark. And the emissions are assumed in the time period of 100 years. It should be noted that the emission coefficients given in Bruun et al. (2006) are in the ranges. To make estimation, average data of the emission coefficients are taken in this thesis, as shown in Table V.4. Emission coefficients for CO_2 from the carbon and N_2O from the nitrogen in land are 0.91 and 0.015. Thus, the carbon sequestered in land is 9 percentage of the carbon that content in the solid residue.

Table V.4 Emission coefficients for CO_2-C and N_2O-N

	CO2 emission from the C filled in land	N2O emission from the N filled in land	Bound biogenic C from the C filled in land
Emission Coefficient	EC_{CO2} =0.91 [R] Bruun et al., 2006 0.86~0.96	EC_{N2O} =0.015 [R] Bruun et al., 2006: 0.013~0.017	$EC_{seq.C}$ =0.09

Note: EC_{N2O}=0.015 expresses that the N content in the N2O emission equals to 1.5%of the N filled in the land. As well, EC_{CO2} =0.91 represents that the C content in the CO2 emission equals to 91% of the C filled in the land.

The amounts of emissions are from the multiplying of emission coefficients and their corresponding carbon or nitrogen quantities in land. And the details of the calculations are shown in Table V.5.

Table V.5 Calculations of the biogenic CO_2, biogenic C sequestration and N_2O from landfill site

	CO_{2bio}-SR^C [kg(CO2)/tww]	Seq.C-SR^C [kg(C)/tww]	N_2O-SR^N [kg(N2O)/tww]
MS	CO_{2bio}-SR^C $=EC_{CO2}*M_{SR}{}^C*44/12$ =0.91*5.202*44/12=17.356	Seq.C-SR^C=$EC_{seq.C}$*$M_{SR}{}^C$ =0.09*5.202=0.468	N_2O-SR^N=$M_{SR}{}^N$* EC_{N2O}*44/28 =1.176*0.015*44/28=0.028
MS&FW	CO_{2bio}-SR^C $=EC_{CO2}*M_{SR}{}^C*44/12$ =0.91*4.893*44/12=16.325	Seq.C-SR^C=$EC_{seq.C}$*$M_{SR}{}^C$ =0.09*4.893=0.440	N_2O-SR^N=$M_{SR}{}^N$* EC_{N2O}*44/28 =1.627*0.015*44/28=0.038

• ***Raw biogas consumed by the biogas boiler***

As shown in Figure 2.1 and Figure 2.2, the produced raw biogas is divided into three categories: the raw biogas consumed by the gas boiler for heat provision, the fugitive loss, and the raw biogas for upgrading.

The volume of raw biogas consumed by the biogas boiler is equal to the heat required by anaerobic digestion divided by the energy content of the raw biogas. The corresponding equation is:

$$V_{RB}^{GB}=(H_{AD}*V_{RB})/(EC_{RB}*\eta_{GB})$$

H_{AD} is the amount of heat required to produce per normal cubic meter (Nm^3) of raw biogas. In this thesis, H_{AD} is assumed to be 1.33 [kWh/ Nm^3]. That is the technological data of the Falkoping Biogas Plant.η_{GB} is the efficiency of the gas boiler, and is assumed to be 80%. EC_{RB} is the energy content of the raw biogas. And the energy content is depended on the percentage of CH_4 contained in the raw biogas. The

Swedish biogas standard specifies that a typical normal cubic meter of CH_4 has a calorific value of ca. 10kWh. Thus, EC_{RB} is assumed to be 6.5 [kWh/ Nm^3] and 6.8 [kWh/ Nm^3], respectively to the digestion MS and the co-digestion MS&FW. The results and data used are shown in Table 3.10.

In addition, owing to the combustion part of the produced raw biogas, the consumption of import fossil fuel for the heat supply is saved. According to Møller et al.(2009), in the case that biogas is used for producing energy consumed on site, the energy produced from biogas is accounted in term of a reduced import of energy to the facilities (i.e. with negative value). Thus, the avoid import heat (AH) is:

$$AH = - H_{AD}*V_{RB}*3.6/\eta_{GB}$$

Table V.6 Data used for calculation of raw biogas consumed by the biogas boiler

	MS	MS&FW
V_{RB}^{GB} [Nm^3/tww]	$V_{RB}^{GB}=(H_{AD}*V_{RB})/(EC_{RB}*\eta_{GB})$	
	1.315	**4.972**
AH [MJ (BM) /tww]	$AH = - H_{AD}*V_{RB}*3.6/\eta_{GB}$	
	-30.706	**-121.708**
V_{RB}[Nm^3/tww]	5.14	20.336
EC_{RB}[kWh/Nm^3]	6.5[a)]	6.8[b)]
H_{AD} [kWh/Nm^3(RB)]	1.33[c)]	
η_{GB}[%]	80[d)]	

a) The methane content in the produced raw biogas is 65% (Wu et al 2009).
b) The methane content in the produced raw biogas is 68% (Fu et al, 2007).
c) Falköping Biogas Plant.
d) Murphy & McCarthy, 2005.

•***Fugitive loss of methane (CH_4)***

Fugitive loss is that the unintentional leakages from the valves, pipes and during the maintenance. It is required to report the emissions of methane (CH_4) from the biological treatment of solid waste in IPCC 2006. And IPCC 2006 gives a default value of emission of CH_4 ranging from 0 to 10 percent of the amount of CH_4 generated (IPCC, 2006). But, due to the variability of fugitive loss from different facilities, the fugitive loss of CH_4 is calculated regard for the technologies applied in cases of this thesis. And the calculations are separately done from the two main facilities: the biogas production facilities and biogas upgrading facilities.

For the fugitive loss of CH_4 from the biogas production facilities, Møller et al 2009 gave the assumption that based on others estimations (e.g. Reeh and Møller, 2001). Finally, the 3% of the amount of CH_4 produced was thought reasonable and applied in the calculation of Møller et al 2009. The operation managers either from Falköping Biogas Plant and Gryaab AB thought the emission could be controlled as low as less than 1% of the amount of CH_4 produced with the covered digesters and sludge containers. Taking account of the relative low technological level in China, it assumes that 3% of the amount of CH_4 produced is fugitive loss of CH_4 from the biogas production facilities. Thus, the weight of the fugitive loss of CH4 during biogas production processes is represented in the following formula that:

$W_{BP}^{FE\_CH4}=\rho_{CH4}*3\%*V_{RB}*MC$

Where, MC denotes the methane content in the produced raw biogas and the density of methane is 0.718 [kg/Nm^3]. Therefore, the fugitive loss of CH_4 during the biogas production is 0.072 [kg (CH_4)/tww] and 0.297 [kg (CH_4)/tww], respectively in the case of anaerobic digestion of sewage sludge, and in the case of co-digestion of the sewage sludge and the food waste.

The upgrading technology is assumed to be water wash with regeneration in this thesis. The amount of the fugitive loss of CH_4 during the upgrading process is proportional to the amount of the raw biogas treated. Petersson and Wellinger summarized the fugitive loss of CH_4 from different upgrading technologies. For the water wash with regeneration, the loss is less than 1 percentage of the methane contented in the raw treated biogas (Petersson and Wellinger, 2009). Thus, the weight of the fugitive loss of CH_4 during the upgrading process is

$W_{UG}^{FE\_CH4}=\rho_{CH4}*1\%*V_{RB}^{UG}*MC$

V_{RB}^{UG} represents the volume of raw biogas treated in the upgrading equipments. That equals the amount of raw biogas produced is subtracted by the amount of raw biogas consumed in biogas boiler and the fugitive loss.

$V_{RB}^{UG}=V_{RB}-V_{RB}^{GB}-V_{BP}^{FE\_RB}$

In the two studied cases, the amounts of raw biogas inflowing to the upgrading facilities are 3.671 [Nm^3/tww] and 14.754[Nm^3/tww], respectively. Corresponding, the amounts of fugitive loss of CH_4 from upgrading facilities are 0.017[kg (CH_4)/tww] and 0.072 [kg (CH_4)/tww].

To sum up, the total fugitive loss of CH_4 is the sum of loss from biogas production facilities and upgrading facilities. In the case of anaerobic digestion of sewage sludge, the fugitive loss of CH_4 is 0.089 [kg (CH_4)/tww]. In comparison, the fugitive loss of CH_4 is 0.369 [kg (CH_4)/tww] in the case of co-digestion of sewage sludge and food waste.

•***Bio-methane production***

The bio-methane (BM) is the end production of the upgrading process that removes off the CO_2 in the raw biogas. According to the Swedish biogas standard, the methane content in the BM (or upgraded biogas) is 97% in volume. Therefore, the amount of BM production is:

$V_{BM}=V_{BM}^{CH4}\div 97\%=(V_{RB}^{UG\_CH4}-V_{UG}^{FE\_CH4})\div 97\%$

As results, the bio-methane productions are 2.435 [Nm^3 (BM)/tww] and 10.239 [Nm^3 (BM)/tww], respectively. Due to the energy content in the bio-methane is 9.67 [kWh/Nm^3], the energy produced from anaerobic digestion of sewage sludge, and co-digestion of sewage sludge and food waste are 84.776 [MJ/tww] and

356.454[MJ/tww], respectively.

• ***Wastewater discharge and fresh water demand***

Either the treatment of the wastewater discharged or provision of the fresh water needed by the processes leads to the GHG emissions. During the biogas production process, the wastewater comes from the centrifugation and the pretreatment of the food waste, as shown in the Figure3.1 and Figure 3.2. The quantification of the wastewater discharged from biogas production (WD_{BP}) is according to the theory mass balance in the water content among the different sludge during the procedures. The details of calculations are in Table V.7.

Table V.7 Calculations of the discharged water during the biogas production

MS		MS&FW	
WD_{BP} [m^3/tww]	$WD_{BP}=WW_1+WW_2$ =0.314+0.608=**0.922**	WD_{BP} [m^3/tww]	$WD_{BP}=WW_3+WW_2$ = 0.218+0.415=**0.633**
WW_1 [m^3/tww]	$WW_1= A_{MS}-A_{MS}*TS_{MS}/TS_{MST}$ =1-1*2.4/3.5=0.314	WW_3 [m^3/tww]	$WW_3= WW_1-FW^W$ =0.314-0.096=0.218
WW_2 [m^3/tww]	$WW_2=A_{MS}*TS_{MS}/TS_{MST}-M_{RB}/1000-M_{SR}$ =1*2.4/3.5-5.952/1000-0.072=0.608	FW^W [m^3/tww]	$FW^W=A_{FW}*(TS_{FW}/TS_{FWW}-1)$ =0.077*(22.5/10-1)=0.096
Nomenclature	WW_1: wastewater discharged from the gravity thicken sink; WW_2:wastewater discharged from the centrifuge; TS_{MST}: total solid content of the mixed sewage sludge that has been thickened in the gravity thicken sink (i.e. the influent sludge =IS in the Appendix). TS_{MST} =3.5%, [R] FU et al, 2007.	WW_2 [m^3/tww]	$WW_2=(A_{MS}*TS_{MS}/TS_{MST}+A_{FW}*TS_{FW}/TS_{FWW})-M_{RB}/1000-M_{SR}$ =(1*2.4/3.5+0.077*22.5/10) -22.780/1000-0.074 =0.415
		WW_3:wastewater discharged from the wet screen; FW^W: food waste sludge passed the wet screen; TS_{FWW}: total solid content in the FW^W; TS_{FWW}=10%, [R] FU et al, 2007.	

Besides wastewater discharged from biogas production process, the upgrading facilities emit wastewater, too. Persson (2003) evaluated main biogas upgrading technologies, and pointed the advantage of water wash with regeneration is its low requirement of fresh water. According to the technological data collected by Persson (2003), about 0.027 m3 fresh water is consumed to upgrade 1 Nm^3 raw biogas in the water wash with regeneration biogas upgrading. Thus, the wastewater from biogas upgrading facilities is assumed to be 0.27 [m3/Nm3 (RB)]. It should note that although called wastewater, the wastewater from water wash without regeneration can be discharged into river directly, without wastewater treatment. Therefore, the GHG emission of water use in the upgrading process only takes account of the provision of fresh water. Table V.8 presents the calculation in details, in which the results of discharge water will be present in the Figure of physical flows.

Table V.8 Calculations of the discharged water and fresh water required during the biogas upgrading

MS		MS&FW
WR_{UG} [m^3/tww]	$WR_{UG}=UG_{WR}*V_{RB}^{UG}$ =0.027*3.671=**0.099**	$WR_{UG}=UG_{WR}*V_{RB}^{UG}$ = 0.027*14.754=**0.398**
WD_{UG} [m^3/tww]	$WD_{UG}=UG_{WD}*V_{RB}^{UG}$ =0.27*3.671=**0.991**	$WD_{UG}=UG_{WD}*V_{RB}^{UG}$ =0.27*14.754=**3.984**
Nomenclature	UG_{WR}: fresh water required to upgrade per Nm3 of raw biogas; UG_{WR} =0.027 [m3/Nm3 (RB)], [R] Persson, 2003. WD_{UG}: wastewater discharged from upgrading per Nm3 of raw biogas; WD_{UG}= 0.27[m3/Nm3 (RB)], [R] Persson, 2003.	

•*Electricity consumption*

Electricity is the primary input energy consumed in the waste treatment and bio-methane production, owing to the heat demand is provided by the produced raw biogas inside the plant. Either the treatment of sludge or the production of bio-methane is a complex procedure that is composed by a series of equipments. To quantify the total electricity consumed in the procedure from the sludge treatment to the bio-methane production, the electricity consumed by equipments (shown in Figure 3.1 and Figure 3.2) are calculated, respectively. Table V.9 presents the calculations and data collection sources.

Table V.9 Calculations of the electricity consumption

MS		MS&FW
El [kWh/tww]	$El=El_{GTS}+El_{AD}+El_{C}+El_{UG}$ = **37.054**	$El= El_{PT}+El_{GTS}+El_{AD}+El_{C}+El_{UG}$ = **47.507**
El_{PT} [kWh/tww]	_______	$El_{PT}=PT_{el}*(A_{MS}+A_{FW})$ =5*(1+0.077)=5.385
El_{GTS} [kWh/tww]	$El_{GTS}=GTS_{el}*A_{MS}*TS_{MS}$ =10*1*2.4%=0.24	$El_{GTS}=GTS_{el}*A_{MS}*TS_{MS}$ =10*1*2.4%=0.24
El_{AD} [kWh/tww]	$El_{AD}=AD_{el}*A_{MS}$ =35*1=35	$El_{AD}=AD_{el}*(A_{MS}+A_{FW})$ =35*(1+0.077)=37.696
El_{C} [kWh/tww]	$El_{C}=C_{el}*M_{SR}*T_{SR}$ =60*0.072*25%=1.083	$El_{C}=C_{el}*M_{SR}*T_{SR}$ =60*0.074*25%=1.113
El_{UG} [kWh/tww]	$El_{UG}=UG_{el}*V_{BM}$ =0.3*2.435=0.731	$El_{UG}=UG_{el}*V_{BM}$ =0.3*10.239=3.072
Nomenclature	GTS_{el}: electricity required to thicken per ton of sludge (on dry weight) in the gravity thicken sink; GTS_{el}=10[kWh/tDS], [R] Chinese National Environment Protect Agency, 2010. AD_{el}: electricity required during the anaerobic digestion process to treat per ton of sludge (on wet weight). Note it includes the electricity required by the stirrer in anaerobic digester and relative pumps. AD_{el}= 35 [kWh/tww], [R] Møller et al., 2009. C_{el}: electricity required to dewater per ton of sludge (on dry weight) in the centrifuge; C_{el} = 60[kWh/tDS], [R] Chinese National Environment Protect Agency, 2010. UG_{el}: electricity required to produce per Nm^3 of bio-methane; UG_{el} =0.3 [kWh/Nm^3 (BM)], [R] Persson, 2003. PT_{el}: electricity required to treat per ton of the waste (on wet weight); PT_{el}=5 [kWh/Nm^3 (BM)], [R] Eriksson, 2009.	

•*Fuel consumed during transportation*

In the proposed biogas commercial model (BCM), the majority of the fuel consumed is from the transportation. In the business scenarios of co-digestion sewage sludge and food waste, the transportation is consisted by the food waste collection and the transportation of the solid residue to the land filling site. In the contrast, the business scenarios regard to the digestion sewage sludge only take the solid residue transportation into account. That is because the actual situation, in which the sewage sludge is transport through pipes. And the electricity consumed in the pumps for sludge transportation has been included in the electricity consumption.

Regarding for the possible differences of performance from the different selection of fuel in transportation, three kinds of fuels (i.e. bio-methane, compressed natural gas and diesel) are evaluated respectively. The fuel consumed in transportation of the waste (i.e. food waste or solid residue) required / produced from treating of per ton of sewage sludge is:

$T_X^{C/D}=D^{C/D}\times A_W\times FE_X\div LC_X$

Where, X means the kind of fuel: bio-methane (BM), compressed natural gas (CNG), or diesel (D); $T_X^{C/D}$ represents the fuel consumption during the transportation (collection/disposal), [Nm^3 (BM)/tww], [Nm^3(CNG)/tww], or [L(D)/tww]; $D^{C/D}$ denotes the distance of transportation, either for the food waste collection (D^C) or solid residue transportation (D^D), [km]; A_W is the amount of transported waste (i.e. food waste or solid residue), [ton/tww]; FE_X denotes the fuel economy of the truck use X, [Nm^3 (BM)/100km], [Nm^3(CNG)/100km], or [L(D)/100km]; LC_X is the load capacity of the truck, [ton/truck].

The technical parameters taken are from the trucks Dong Feng diesel truck CLW3245G and Dong Feng natural gas truck EQ3250GD3GN. It is because that they are the typical types used in the waste management sector in China, and their designs are conform to the regulation of the municipal solid waste transportation (Interview). The data of relative FE_X and LC_X are shown in the Table V.10.

Table V.10 Calculations of fuel required for transport

	MS	MS&FW
$T_X^C=D^C\times A_{FW}\times FE_X\div LC_X$		
T_{BM}^C[Nm^3 (BM)/tww]	——	0.049
T_{CNG}^C[Nm3(CNG)/tww]		0.049
T_D^C[Nm3 (D)/tww]		0.042
$T_X^D=D^D\times M_{SR}\times FE_X\div LC_X$		
T_{BM}^D[Nm^3(BM)/tww]	0.079	0.082
T_{CNG}^D[Nm3(CNG)/tww]	0.079	0.082
T_D^D[Nm3 (D)/tww]	0.067	0.069
D^C [km]	30	
D^D [km]	50	
A_{FW} [ton/tww]	——	0.077
M_{SR} [ton/tww]	0.072	0.074
LC [ton/truck]	15, [R] CLW3245G; EQ3250GD3GN	
FE_X: FE_{BM}[Nm^3(BM)/100km]	33, [R] EQ3250GD3GN	
FE_X: FE_{CNG}[Nm^3(CNG)/100km]	33, [R] EQ3250GD3GN	
FE_X: FE_D[L(D)/100km]	28, [R] CLW3245G	

According to the situation in Beijing, the distances of food waste collection (D^C) and solid residue transportation (D^D) are assumed to be 30 km and 50 km. Compared to other studies (i.e. Møller et al.,2009; Murray et al., 2008;), the assumptions of transportation distances are reasonable and can represent the average transportation distance in China.

• ***Diesel consumed during pretreatment of food waste***

The collected food wastes need to be chipped into small pieces before making into food waste sludge. In Sweden, the grinding of food wastes could be done either by the waste suppliers or the wastewater treatment plant, depending on the negotiations. In China, since the food wastes suppliers in this thesis are assumed to be restaurants, the willingness that restaurants committed with the grinding is very limited, according to the interviews with restaurants managers. Hence, the food wastes grinding is included in the plant in this thesis.

Grinding per dry ton of food waste requires about 6.6 L of diesel (Brown et al., 2008). Therefore, the diesel consumed during the pretreatment is equivalent to:

$Diesel_G=G_D*A_{FW}*TS_{FW}$=6.6 [L/tDS] * 0.077[ton/tww]*22.5%=0.114[L (D)/tww].

In a conclusion, the accounted physical flows (A_N) are shown in the Table V.11.

Table V.11 Accounted Physical Flows A_N

	Indirect Emission Sources						Direct Emission Sources			Substituted Emission Sources		
	Upstream	MS	MS&FW	Downstream	MS	MS&FW		MS	MS&FW		MS	MS&FW
Accounted Physical Flows (A_N [unit/tww])	Electricity consumption El [kWh/tww]	37.054	47.507	Wastewater treatment WD_{BP} [m^3/tww]	0.092	0.633	CH4 fugitive emission: $W_{BP}^{FE\_CH4}+W_{BP}^{FE\_CH4}$ [kg (CH_4)/tww]	0.089	0.369	On site consumptions savings: Avoided heat consumption a) AH [MJ(RB)/tww]	-30.760	-121.708
	Clean water provision WR_{UG}[m^3/tww]	0.099	0.398	N2O from solid residue filled in land N_2O-SR^N[kg(N_2O)/tww]	0.028	0.038	Raw biogas in boiler (biogenic) V_{RB}^{GB} [Nm^3(RB)/tww]	1.315	4.972	Avoided CNG consumed for transport $T_{BM}^C+T_{BM}^D$ b) [Nm^3(BM)/tww]	-0.079	-0.131
	Heat requirement a) HR [MJ(RB)/tww]	30.760	121.708									
	Diesel for grinding (production& provision) $Diesel_G$ [L(D)/tww]	____	0.114	C sequestered in solid residue filled in land Seq. C-SR^C[kg(C)/tww]	0.468	0.440	Diesel for grinding (combustion) $Diesel_G$ [L(D)/tww]	____	0.114			
	Fuel for transportation (production & provision)			Biogenic CO2 from solid residue filled in land CO_{2bio}-SR^C [kg(CO_2)/tww]	17.356	16.325	Fuel for transportation (combustion)			Substituted CNG by the produced BM: FS^{CNG} [MJ(CNG)/tww] c)	-84.776 (-82.011)	-356.454 (-351.907)
	$T_{BM}^C+T_{BM}^D$ b) [Nm^3(BM)/tww]	0.079	0.131				$T_{BM}^C+T_{BM}^D$(Biogenic) b) [Nm^3(BM)/tww]	0.079	0.131			
	$T_{CNG}^C+T_{CNG}^D$ [Nm^3(CNG)/tww]	0.079	0.131				$T_{CNG}^C+T_{CNG}^D$ [Nm^3(CNG)/tww]	0.079	0.131			
	$T_D^C+T_D^D$ [L(D)/tww]	0.067	0.111				$T_D^C+T_D^D$ [L(D)/tww]	0.067	0.111			
Not	• Construction • Decommissioning • Embedded energy in waste • Polymer consumption • (in accessibility of data)			• Decommissioning • Energy consumed during the SR deposit in land (in accessibility of data) • Energy consumed in distribution of BM (zero, Korres, et al. (2010))			• Unaccounted waste stream • Staff commuting • Business travel			• Unaccounted substituted FW treatment and disposal (in accessibility of methods and data)		

a) The heat required by the digester is considered offset by 1.315 and 4.972 [Nm^3/tww] of raw biogas (RB), respectively for the MS and MS_FW.

b) In the scenarios MS_BMT and MS&FW_BMT, the CNG consumed in transport is offset by 0.079 and 0.131[Nm^3/tww] of bio-methane (BM), respectively.

c) The values in the blankets are in the scenarios MS_BMT and MS&FW_BMT.

Step (III): Collections and assumptions of data used for GWF_N

As defined in the framework UODS, GWF_N represents the GHG emissions released from per unit of the accounted physical flow N. For an instance, the GWF_{El} means the GHG emissions generated from production and provision of per kWh electricity, with a unit of [kg ($CO_{2.e}$)/kWh].

Data collection of the GWF_N in this thesis is from the previous studies refer to the climate change impacts of the accounted N in the context of China. The present of GWF_N is followed the emissions categories (i.e. indirect upstream, indirect downstream, direct and substituted emission) in the framework UODS. Hence, related assumptions and methods of data using should be clarified clearly.

According to framework UODS, the different data of GWF_N for the accounted fuel are used to comply the different constraints in different emission categories. To be more specific, take the example of the different GWF_{CNG} (i.e. for transportation). In the category Indirect Upstream Emission, the emissions of CNG (GWF_{CNG}) expresses that the emissions from production and provision of the consumed CNG. On contrary, the GWF_{CNG} applied in the category of Direct Emission is estimated to the emissions owing to the combustion of CNG in transportation. Refer to the GWF_{CNG} in the Substituted Emission, due to the assumption that equal amount of CNG is replaced by the produced bio-methane (BM), the substituted emissions covers the emissions generated during the entire life time of per MJ CNG from production to the end combustion. Hence, in the Substituted Emission category, actually, GWF_{CNG} is the combination of those GWF_{CNG} used in the categories of direct and indirect emissions.

Please note that the emissions from the combustion of the produced RB or BM on site are taken into account in the term of Direct Emission. It is assumed that there is no leakage from the combustion in gas boiler and vehicle engines. That means all the carbon content in the RB or BM convert into CO_2 during the combustion. In addition, according to IPCC (2006), the biogenic CO_2 is not taken into account in the GHG emissions, the emission factors of RB and BM combustion on site are considered to be zero.

Besides, no GWF for the fugitive CH_4 emission, N2O and C sequestration in landfill site is used. That is because that these accounted flows are actually, the GHG emissions. Therefore, there is no need to present the data again.

Moreover, to avoid the double-counting environmental benefits, the accounted consumptions savings in the column Substituted Emission Sources will be as the reductions in the column Indirect Upstream Emission Sources. Therefore, no GWF_N is used or present in this column.

Finally, all the GWF_N of the accounted physical flows N and their corresponding data sources are shown in Table V.12.

Table V.12 Global warming factors for the accounted physical flows (GWF_N) and their data sources

	Indirect Emission Sources		Direct Emission Sources	Substituted Emission Sources
	Upstream	Downstream		
GWF_N [kg (GHG)/unit (N)]	Production & provision of electricity: GWF_{El}=1.07 [kg(CO_{2e})/kWh]; [R] OU, 2010.	Treatment of wastewater: GWF_{WD}=0.15 [kg(CO_{2e})/m³]; [R] Møller et al., 2009.	Combustion of diesel: $GWF_D{}^{Com}$ = 2.62 c) [kg(CO_{2e})/L(D)]; Calculated based on [R] OU, 2010.	Substituted CNG during its life time: $GWF_{CNG}{}^{L}$ = 0.075 [kg(CO_{2e})/MJ(CNG)]; [R] OU, 2010.
	Provision of water from waterworks: GWF_{WR}=0.15 [kg(CO_{2e})/m³]; [R] Møller et al., 2009.		Combustion of CNG: $GWF_{CNG}{}^{Com}$ = 2.53 d) [kg(CO_{2e})/Nm³(CNG)]; Calculated based on [R] OU, 2010.	
	Production & provision of diesel: $GWF_D{}^{P\&P}$ = 0.99 a) [kg(CO_{2e})/L(D)]; Calculated based on [R] OU, 2010.		Combustion of BM: $GWF_{BM}{}^{Com}$ = 0 e) [kg(CO_{2e})/Nm³(BM)]; Estimated based on [R] IPCC2006.	
	Production & provision of CNG: $GWF_{CNG}{}^{P\&P}$ = 0.44 b) [kg(CO_{2e})/Nm³(CNG)]; Calculated based on [R] OU, 2010.		Combustion of RB: $GWF_{RB}{}^{Com}$ = 0 f) [kg(CO_{2e})/Nm³(RB)]; Estimated based on [R] IPCC2006.	

a) $GWF_D{}^{P\&P}$ =35.28 [MJ/L(D)]*28.1[g(CO_{2e})/MJ (D)] (OU, 2010)/1000 = 0.99 [kg (CO_{2e})/L (D)].
b) $GWF_{CNG}{}^{P\&P}$ = 39.6 [MJ/Nm3 (CNG)]*11[g(CO_{2e})/MJ (CNG)] (OU, 2010)/1000 =0.44 [kg (CO_{2e})/Nm³ (CNG)].
c) $GWF_D{}^{Com}$ =35.28 [MJ/L (D)]*74.3[g(CO_{2e})/MJ (D)] (OU, 2010)/1000 = 2.62 [kg (CO_{2e})/L (D)].
d) $GWF_{CNG}{}^{Com}$ = 39.6 [MJ/Nm3 (CNG)]*64[g(CO_{2e})/MJ (CNG)] (OU, 2010)/1000 =2.53[kg (CO_{2e})/Nm³ (CNG)].
e) IPCC 2006: CO2 emissions from combustion the biogenic carbon content in the bio-fuels are not taken into account in the GHG emissions.
f) IPCC 2006: Biogenic CO2 emissions from the combustion of biogas from wastewater treatment plant are not taken into account in the GHG emissions.

Step (IV): Calculations of emissions factor (EF_N)

As defined before, the EF_N denotes the GHG emissions released from the treatment of per FU of MS in the proposed BCM refer to the accounted physical flow N, and $EF_N = A_N * GWF_N$. Based on Table V.11 and Table V.12, the results of EF_N are shown in Table V.13 below.

Table V.13 Results of emission factors (EF_N)

	Indirect Emission Sources						Direct Emission Sources			Substituted Emission Sources e)		
	Upstream	MS	MS&FW	Downstream	MS	MS&FW		MS	MS&FW		MS	MS&FW
EF_N a) [kg (GHG)/tww]	Production & provision of electricity: EF_{EI} [kg(CO_{2e})/tww]	39.648	50.832	Wastewater treatment EF_{WD} [kg(CO_{2e})/tww]	0.138	0.095	CH4 fugitive emission $EF_{CH4}^{FE} = W_{BP}^{FE\_CH4} + W_{BP}^{FE\_CH4}$ [kg (CH_4)/tww]	0.089	0.369	Substituted CNG from production to combustion		
	Clean water provision: EF_{WR} [kg(CO_{2e})/tww]	0.015	0.060	N2O from solid residue filled in land EF_{N2O}^{SR} b) [kg(N2O)/tww]	0.028	0.038	Biogenic CO2 from raw biogas combustion in boiler EF_{RB}^{GB} [kg(CO_{2e})/tww]	0	0	EF_{CNG}^{FS} [kg(CO_{2e})/tww]	-6.358	-26.734
	Diesel for grinding (production& provision) $EF_{DG}^{P\&P}$ [kg(CO_{2e})/tww]	___	0.113	C sequestered in solid residue filled in land $EF_{Seq.C}^{SR}$ c) [kg(C)/tww]	0.468	0.440	Diesel for grinding (combustion) EF_{DG}^{Com} [kg(CO_{2e})/tww]	__	0.300	g)	(-6.151)	(-26.393)
	Fuel for transportation (production & provision)			Biogenic CO2 from solid residue filled in land EF_{CO2bio}^{SR} d) [kg(CO2)/tww]	17.356	16.325	Fuel for transportation (combustion)					
	BMT f) [kg(CO_{2e})/tww]	0	0				EF_{BMT}^{Com} [kg(CO_{2e})/tww] (Biogenic)	0	0			
	$EF_{CNGT}^{P\&P}$ [kg(CO_{2e}/tww]	0.035	0.057				EF_{CNGT}^{Com} [kg(CO_{2e}/tww]	0.201	0.331			
	$EF_{DT}^{P\&P}$ [kg(CO_{2e})/tww]	0.067	0.110				EF_{DT}^{Com} [kg(CO_{2e})/tww]	0.177	0.291			

a) $EF_N = A_N * GWF_N$; b) $EF_{N2O}^{SR} = N_2O\text{-}SR^N$; c) $EF_{Seq.C}^{SR} = Seq.C\text{-}SR^C$; d) $EF_{CO2bio}^{SR} = CO_{2bio}\text{-}SR^C$; e) the value of substituted emission is negative.
f) In scenarios using BM for transport, the required NG is offset by BM. Hence, it is considered there is no import fuel for the transport. Therefore, the emission from the upstream fuel production and provision is zero. As well, because that the heat requirement is satisfied by fraction of the produced RB, therefore, there is no emissions on the upstream for the heat supply. g) The values in the blankets are in the scenarios MS_BMT and MS&FW_BMT.

Step (V): Calculations of global warming effect (GWE_N)

The global warming effect (GWE) used here is defined as the CO_2 equivalent of the GHG emissions released. Thus, the $GWE_N = EF_N * GWP$. In this assessment, the accounted GHG emissions are: fossil CO_2, biogenic CO_2, biogenic C sequestration, N_2O and CH_4. And the global warming potential of these accounted GHG emissions are: GWP $CO_{2fossil}$=1; GWP $CO_{2biogenic}$=0; GWP $CO_{2biogenic}$ sequestration = (-44/12); GWP CH_4= 21; GWP N_2O=310. Based on Table V.13, the results of GWE_N are shown in Table V.14.

Table V.14 Results of global warming effects (GWE_N)

	Indirect Emission						Direct Emission			Substituted Emission (-)		
	Upstream			Downstream								
		MS	MS&FW		MS	MS&FW		MS	MS&FW		MS	MS&FW
GWE_N a) [kg($CO_{2,e}$)/tww]	Production & provision of electricity: GWE_{EI} b)	39.648	50.832	Wastewater treatment GWE_{WD}	0.138	0.095	CH4 fugitive emission GWE_{CH4FE} f)	1.868	7.749	Substituted CNG from production to combustion GWE_{CNGFS}	-6.358 (-6.151)	-26.734 (-26.393)
	Clean water provision: GWE_{WR}	0.015	0.060	N2O from solid residue filled in land GWE_{N2O} c)	8.68	11.78	Biogenic CO2 from raw biogas combustion in boiler GWE_{RBGB}	0	0			
	Diesel for grinding (production& provision) $GWE_{DGP\&P}$	—	0.113	C sequestered in solid residue filled in land $GWE_{Seq.C}$ d)	-1.716	-1.613	Diesel for grinding (combustion) GWE_{DGCom}	—	0.300			
	Fuel for transportation (production & provision)			Biogenic CO2 from solid residue filled in land GWE^C_{CO2bio} e)	0	0	Fuel for transportation (combustion)					
	BMT	0	0				GWE_{BMTCom} (Biogenic)	0	0			
	$GWE_{GTP\&P}$	0.035	0.057				$GWE_{CNGTCom}$	0.201	0.331			
	$GWE_{DTP\&P}$	0.067	0.110				GWE_{DTCom}	0.177	0.291			

a) $GWE_N = EF_N * GWP$

b) $GWE_{EI} = EF_{EI} * GWP_{CO2fossil}$=39.648 (50.832) [kg ($CO_{2.e}$)/tww]*1= 39.648 (50.832) [kg ($CO_{2.e}$)/tww]

c) GWE_{N2O}=N_2O-SR^N *GWP_{N2O}=0.028 (0.038) [kg (N2O)/tww] *310=8.68 (11.78) [kg($CO_{2.e}$)/tww]

d) $GWE_{Seq.C}$=Seq.C-SR^C *$GWP_{BioCSeq.}$ = 0.468 (0.44) [kg(C)/tww] * (-44/12) =-1.716 (-1.613) [kg ($CO_{2.e}$)/tww]

e) GWE_{CO2bio}=CO_{2bio}-SR^C * GWP_{BioCO2} = 17.356 (16.325) [kg (CO_{2bio})/tww] *0=0 (0) [kg ($CO_{2.e}$)/tww]

f) GWE_{CH4FE}= EF_{CH4}^{FE} * GWP_{CH4} = 0.089(0.369) [kg (CH4)/tww]*21=1.868 (7.749)[kg ($CO_{2.e}$)/tww]

Step (VI): Life cycle inventory of global warming effect

The LCI of GWE for the possible six business scenarios in the proposed commercial model is summarized in Table V.15.

Table V.15 Life cycle inventory of GWE of the six business scenarios

	Indirect Emission: Upstream		Indirect Emission: Downstream		Direct Emission		Substituted Emission (-)		
	IEU	Percentage of Total	IED	Percentage of Total	DE	Percentage of Total	SE	Percentage of Total	Total Emission
MS_BMT	39.663	68.1%	7.102	18.1%	1.868	3.2%	-6.151	10.6%	42.483
MS&FW_BMT	51.005	51.6%	10.262	13.6%	8.049	8.1%	-26.393	26.7%	42.923
MS_CNGT	39.697	67.7%	7.102	18%	2.070	3.5%	-6.358	10.8%	42.511
MS&FW_CNGT	51.062	51.2%	10.262	13.5%	8.380	8.4%	-26.734	26.8%	42.970
MS_DT	39.730	67.7%	7.102	18%	2.045	3.5%	-6.358	10.8%	42.519
MS&FW_DT	51.115	51.3%	10.262	13.5%	8.339	8.4%	-26.734	26.8%	42.982

GWE_N [kg($CO_{2,e}$)/tww]	Upstream	MS	MS&FW	Downstream	MS	MS&FW	Direct Emission	MS	MS&FW	Substituted Emission (-)	MS	MS&FW
	Production & provision of electricity: GWE_{El} [b)]	39.648	50.832	Wastewater treatment GWE_{WD}	0.138	0.095	CH4 fugitive emission GWE_{CH4FE} [f)]	1.868	7.749	Substituted CNG from production to combustion GWE_{CNGFS}	-6.358 (-6.151)	-26.734 (-26.393)
	Clean water provision: GWE_{WR}	0.015	0.060	N2O from solid residue filled in land GWE_{N2O} [c)]	8.68	11.78	Biogenic CO2 from raw biogas combustion in boiler GWE_{RBGB}	0	0			
	Diesel for grinding (production& provision) $GWE_{DGP\&P}$	__	0.113	C sequestered in solid residue filled in land $GWE_{Seq.C}$ [d)]	-1.716	-1.613	Diesel for grinding (combustion) GWE_{DGCom}	__	0.300			
	Fuel for transportation (production & provision)			Biogenic CO2 from solid residue filled in land GWE^{C}_{CO2bio} [e)]	0	0	Fuel for transportation (combustion)					
	BMT	0	0				GWE_{BMTCom} (Biogenic)	0	0			
	$GWE_{GTP\&P}$	0.035	0.057				$GWE_{CNGTCom}$	0.201	0.331			
	$GWE_{DTP\&P}$	0.067	0.110				GWE_{DTCom}	0.177	0.291			

The total global warming effect (GWE^{tot}) of the studied commercial model, i.e. production of sludge-based biogas, is calculated as:

$GWE^{tot} = GWE^{IEU} + GWE^{IED} + GWE^{DE} + GWE^{SE} = \sum GWE^{N} = \sum EF_N * GWP$.

Appendix VI

Review of the previous LCA studies on sewage treatment and sludge disposal

LCA on sewage sludge	Studied context	Studied stages of the facilities	Studied AD treatment processes & Disposal or End-use of sludge	Result of GWE & Equivalent result [b)]
Hwang & Hanaki (2000)	Japan	Construction & Operation	Thickening, AD, Biogas CHP, Dewatering, Thermal treatments of digested sludge, Rejected water treatment	[kg C/t DM (MS)], (LCI), GWE>0
Suh & Rousseaux (2001)	EU	Operation	Thickening, AD, Biogas application (Obscure), Transport of digested sludge, Silo storage, Agriculture application.	Normalized result, GWE>0
Lundin, et al., (2004)	Sweden	Operation	Handling of digested sludge, Transport, Agriculture application	Normalized result, GWE<0
Houillo & Jolliet (2005)	Switzerland	Operation	[Raw sewage sludge (undigested) treatments & disposal] Thickening, Dewatering, Liming, Storage, Transport, Landfill or Storage on the farm & Agriculture application	>450[kg $CO_{2,e}$/t DM (MS)] =>112.5 [kg $CO_{2,e}$/tww (MS)]
Hospido, et al., (2005)	Spain	Operation	AD, Biogas for the heat required by digester (1/3) & torch (2/3), Dewatering, Transport, Agriculture application	250[kg $CO_{2,e}$/t DM (MS)], =2.5 [kg $CO_{2,e}$/tww (MS)]
Murray, et al., (2008)	China [a)]	Construction & Operation	AD, Biogas (CHP), Dewatering, Transport, Agriculture application	-283[kg $CO_{2,e}$/t DM (MS)], =-6.8 [kg $CO_{2,e}$/tww (MS)]
Pasqualino, et al., (2009)	Spain	Operation	Wastewater Line; Sludge line: Thickening, AD, Alternatives for using biogas, Dewatering, Alternatives for digested sludge disposal, (Transport)	0.119[kg $CO_{2,e}$/m^3watewater], where, sludge line takes 27.09%, -0.0704 [kg $CO_{2,e}$/m^3watewater] =-12.08[kg $CO_{2,e}$/tww (MS)]
Hospido, et al., (2010)	Spain	Operation	AD, Biogas for the heat required by digester (total), Agriculture application of the digested sludge	1.062[kg $CO_{2,e}$/1.01 (MS)] =106.2[kg $CO_{2,e}$/tww (MS)]

a) Since the data of Chinese is inaccessible, the main of data used are from USA. Therefore, the result is not suitable to represent the Chinese level.
b) The equivalent result is calculated by multiplying the total solid content (TS=DM of the wet weight) of the MS. And the data of TS is from the relative literature.

Appendix VII

Data collection and calculation of inventory of cash flows

(I). Basic data collection and calculations

To approach a reliable CBA study, it is important and necessary to present the basic data used for the calculations of the related cash flow.

The data used in this thesis is tried to reflect real situations in the China's market. However, the investment on equipments used is estimated by the investment on equipments in Sweden, because there are few Chinese suppliers of such equipments now. Other information used, such as the costs and revenues, represent the current situation in China.

Table VII.1 Summary of the accounted physical flows of the six possible business scenarios based per day

Summary of the Accounted physical flows of the BCM with the six possible business scenarios. All the quantities (kWh, tww, ton, L, Nm^3, m^3) are referred to the unit day ([d]).		
	MS	MS&FW
Inputs:		
Mixed sewage sludge [tww/d]	583	583
Food waste [tww/d]	0	45
Electricity [kWh/d]	21614	27712
Fresh water [m^3/d]	58	232
Diesel for FW grinding [L/d]	0	67
Fuel for transport (BMT)	0	0
CNG for transport [Nm^3/d] (CNGT)	46	77
Diesel for transport [L/d] (DT)	39	64
Outputs:		
Bio-methane [Nm^3/d] (BMT)	1374	5897
Bio-methane [Nm^3/d] (CNGT, DT)	1421	5973
Solid residues [ton/d]	42	43
Wastewater from BP [a] [m^3/d]	538	369
Wastewater from UG [b] [m^3/d]	578	2324
a) Wastewater discharged from the biogas production (BP) facilities needs to be treated in the WWPT. b) Wastewater discharged from the upgrading (UG) facilities can flow into river directly.		

Table VII.1 summarizes the counted physical flows of the proposed commercial model. In order to estimate the cost and revenue, the counted physical flows are divided into two columns: Inputs, and Outputs. And all the quantities (kWh, tww, ton, L, Nm^3) are referred to the unit day [d]. The data presented in Table VII.1 are calculated based on the results in Table V.11 in the formula as: A_N [unit/tww]* W_{MS}^d [tww/d]. W_{MS}^d denotes the daily amount of sewage sludge produced from the WWTP. And W_{MS}^d is result from: W_{MS}^d = capacity of WWTP * sludge (dry solid) production rate from WWPT ÷the dry matter content in the sludge (i.e. TS). The average sludge production rate from the municipal WWPT in China is 1.4 ton (dry solid) per 10^4 m^3 wastewater (Wu et al., 2009). As shown in Table V.1, the total solid content in the MS is 2.4%. So, 583 tww of MS is produced from the studied-scale (i.e. 100,000 [m^3 wastewater /day]) WWTP. In addition, the above calculations indicate that W_{MS}^d and the other data in Table VII.1 are decided by the scale of WWTP.

Table VII.2 Summary of the basic data for calculation monetary flows

Summary of the basic data for calculation monetary flows.		
	Data	Data Source
Investments:		
Biogas production [SEK/ton · yr]	1225	SBA, SGC, SGA, 2008
FW pretreatment [SEK/ton · yr]	4175	SBA, SGC, SGA, 2008
Biogas upgrading [SEK/Nm³ (RB) · yr]	5.14	Persson, 2003
Hybrid CNG & BM truck [SEK/truck]	400000	Shao, 2010
Diesel truck [SEK/truck]	300000	Shao, 2010
Costs refer to the physical flows:		
Electricity price [SEK/kWh]	0.6	NDRC, 2008
BM price for consumption on site [SEK/Nm³]	0	Assumed by this thesis
CNG price [SEK/Nm³]	4	TIAN FU Morning Paper, 2010.
Diesel price [SEK/L]	6.88	BEIJING EVENING NEWS, 2010.
SR deposit price of land filling [SEK/ton]	52	Zhang et al., 2006.
Treatment fee of wastewater from BP [a] [SEK/m³]	0	Assumed by this thesis
Fresh water price [m³/d]	0	Assumed by this thesis
Maintenance Cost:		
Biogas production [SEK/yr]	300000	Falköping Biogas Plant, 2010.
Biogas upgrading [SEK/yr]	200000	Persson, 2003
Hybrid CNG & BM truck [SEK/truck · yr]	10560	Shao, 2010
Diesel truck [SEK/truck · yr]	8800	Shao, 2010
Labor Cost:		
Average salary [SEK/person · yr]	3780	BeiJing Statistical Bureau, 2010
Revenue:		
MS treatment fee [SEK/ tww]	200	Lu, 2010; Li, 2010
FW treatment fee [SEK/ tww]	0	Assumed by this thesis
BM price in the market [SEK/Nm³]	4	Assumed by this thesis

Table VII.2 lists the monetary data and their data sources. Owing to the biogas upgrading is in the experimental or demonstration phase in China, the investments include all the technology processes in the commercial model are estimated according to the investment costs of plants in Sweden. The purchasing costs of the trucks are from the inquiring with Chinese vehicle dealers (Shao, 2010.). And the type of trucks considered here are coincident with the trucks used in the environmental and energy analyses before (15 ton). Because the proposed commercial model is assumed to be expanded on a WWTP, it is assumed that no costs on either the fresh water provision or the discharged wastewater treatment. In addition, in the scenarios BMT, the BM consumed for the transport on site is in the assumption of no payment. On the contrary, the costs of the other two fuels used in the commercial model are referred to the latest market prices announced by the local development and reform bureaus. Moreover, the solid residues produced from the commercial model are assumed to deposit into land. Hence, the disposal fee required by the land filling site is taken into account.

Apart the investment and costs linked with the physical flows, this study also takes account of the maintenance costs and labor costs. As well as the investment costs, the maintenances costs related to the biogas production and upgrading facilities are estimated based on the experiences in Sweden. The maintenance costs of trucks are according to the information from truck dealers. The labor cost is estimated by multiplying of the average salary and the numbers of employee in the commercial model. During the work in this thesis, it is founded that it is very hard to estimate the number of employee, because the labors number is decided by many factors including technology, economy and social. And the range of differences in the numbers of the employee of the visited plants is so large that it is almost impossible to find the relationship between the capacity of the plant and the number of labors. But, although it is hard to give the estimation, this thesis includes the labor cost, since it is a part that should not be neglect in the CBA studies. And according to the visited plants and experts estimation, it is roughly assumed that the numbers of labor in the departments of biogas production, upgrading and transportation are respectively, 100, 20 and 3. More details should be specified on the assumption that 3 people work for the transport. This number is assumed based on the number of trucks used for the transport in the commercial model. Refer to Table 5.1, the daily food waste requirement and solid residues generation are respectively 0 and 42 ton (MS), and 45 and 43 ton (MS&FW). Due to the load capacity of truck is 15 ton, thus, there would be maximum 3 trucks required for the daily transport. Consequently, the number of labor in the transport department is assumed to be 3.

The revenues used in this thesis includes the sludge treatment fee, food waste treatment fee and the revenue due to the selling of produced bio-methane (BM). To be reliable and able to reflect the current market in China, all of the assumptions made are based on the investigation summarized in Chapter 2. The MS treatment fee is paid by the municipal government. And the proposed BCM needs to compete with other sludge treatment plans in the project open tendering, where the MS treatment fee is always the essential concerns of the decision makers in municipal government. The price 200 SEK per wet ton of raw MS is a conservative estimation for wining out in the bidding (Lu, 2010; Li, 2010). In contrast, the FW treatment price is assumed to be zero in the consideration of accessibility of FW competed with others (e.g. pig raisers). There has been no specific regulation on the price of bio-methane in China until now. The conservative estimation is assumed to be as the same price as vehicle use natural gas (i.e. 4 [SEK/Nm^3]).

(II) Inventory of counted cash flows

Based on Table VII.1 and Table VII.2, the summary of cash flows of the proposed commercial model is shown respectively in the six business scenarios in Table VII.3. All data presented in Table VII.3 are disregarded of the time dynamics. In other words, the no discount rate is taken into account in this Table.

Table VII.3 Summary of cash flows of the six business scenarios

Summary of cash flows (Investments, Costs, and Revenues) of the BCM in its six business scenarios						
	MS_BMT	MS_CNGT	MS_DT	MS&FW_BMT	MS&FE_CNGT	MS&FW_DT
Investment [MSEK]:	**265.963**	**265.963**	**265.683**	**346.604**	**346.604**	**346.315**
Biogas production [a)]	260.823	260.823	260.823	329.303	329.303	329.303
Biogas upgrading	4.017	4.017	4.017	16.146	16.146	16.146
Hybrid CNG and BM trucks	1.123	1.123	0	1.123	1.123	0
Diesel trucks	0	0	0.842	0	0	0.842
Costs [MSEK/yr]:	**11.642**	**11.71**	**11.736**	**13.168**	**13.281**	**13.328**
Consumption Costs:	5.533	5.601	5.632	7.059	7.172	7.224
Electricity	4.734	4.734	4.734	6.069	6.069	6.069
SR deposit	0.799	0.799	0.799	0.822	0.822	0.822
Diesel for FW grinding	0	0	0	0.168	0.168	0.168
Transport fuel	0	0.068	0.099	0	0.113	0.165
Maintenance Costs	0.53	0.53	0.525	0.53	0.53	0.525
Biogas production	0.3	0.3	0.3	0.3	0.3	0.3
Biogas upgrading	0.2	0.2	0.2	0.2	0.2	0.2
Hybrid CNG and BM trucks	0.03	0.03	0	0.03	0.03	0
Diesel trucks	0	0	0.025	0	0	0.025
Labor Costs	5.579	5.579	5.579	5.579	5.579	5.579
Revenues [MSEK/yr]:	**44.590**	**44.657**	**44.657**	**51.193**	**51.304**	**51.304**
MS treatment	42.583	42.583	42.583	42.583	42.583	42.583
BM selling	2.006	2.074	2.074	8.609	8.721	8.721

Appendix VIII

Swedish experience in commercializing production of biogas from sewage sludge

Compared to China, Sweden has rich experience in producing of biogas from sewage sludge. Moreover, a relatively mature industrial system of biogas has been built in Sweden, including material supply, biogas production, biogas use and waste disposal. In the industrial system of biogas, production of biogas is a profitable business.

This section reviews the existing Swedish commercial models for production of biogas from sewage sludge. In order to propose suggestions on eco-efficiently producing biogas in China, an eco-efficient Swedish commercial model that biogas is used as vehicle fuel is deeply elaborated by using cases of Falköping municipal wastewater treatment plant and Gryaab wastewater treatment plant at Göteborg.

Existing Swedish commercial models

Unlike China, anaerobic digestion has a long history of treating sewage sludge in Sweden. The energy crisis happened in the 1970's boosted the production and use of biogas in the country. Consequently, anaerobic digestion technology and a series of biogas producing and treating technologies were rapidly developed and diffused in wastewater treatment plants (WWTPs), which have sewage sludge treatment.

Owing to that rapidly development in the past forty years, Sweden has built an industrial system of biogas, which involves a variety of commercial models for production of biogas. Figure 2.2 illustrates the Swedish industrial system of biogas and the relevant commercial models for production biogas from sewage sludge.

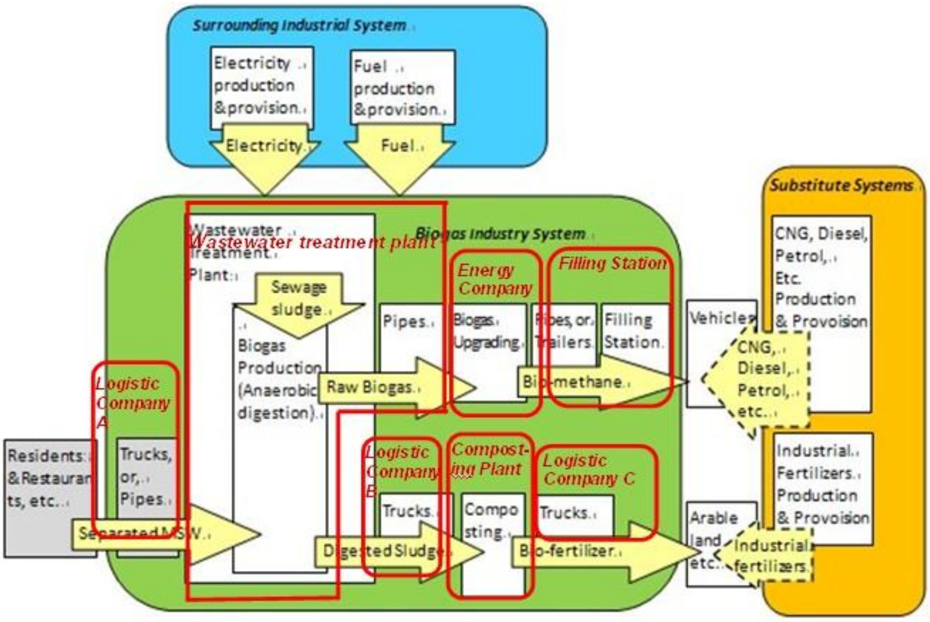


Figure VIII.1 Swedish industrial system of biogas and the relevant commercial models for production biogas from sewage sludge

The industrial system of biogas discussed in this thesis is a conceptual system that includes all the treating and operating procedures in biogas production, which starts at the inflowing of material and ends at the outflow of the final biogas products. The words 'commercial model for production of biogas' studied in this thesis takes from a company stand to describe which treating and operating procedures are involved into their business.

Divided by the use of biogas, the Swedish commercial models can be categorized as: Co-generation of heat and electricity (CHP), heat generation (i.e. heat is used for the local district heating and the on-site operation), vehicle fuel (i.e. BM is used as bio-natural gas in vehicle). Divided by the treatment and disposal of digested sludge, the Swedish commercial models can be categorized as: land filling the dehydrated digested sludge, composting the dehydrated digested sludge for soil conditioner. Recently, municipal solid organic waste (MSOW) is used to co-digest with sewage sludge in some WWTPs, such as the Gryaab WWTP at Göteborg and Boden municipal WWTP. That is because the biogas production rate of sewage sludge is increased by adding MSOW. To acquire a larger production of biogas, some WWTPs like Falköping municipal WWTP built a digestion that particularly used for anaerobic digesting the MSOW.