A Comparative Study of Swedish and Chinese Biogas Production with a Brief Economical Feasibility Analysis

ALEXANDER OLSSON

ROYAL INSTITUTE
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Master of Science and Engineering Thesis
Alexander Olsson
alols@kth.se
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Supervisor at KTH
Lars J. Pettersson
lpet@kth.se

Supervisor at IVL
Östen Ekengren
osten.ekengren@ivl.se

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Abstract

This Master of Science and Engineering thesis in Chemical Engineering treats biogas production in China. The thesis is divided into two parts. The first part contains an energy potential and situation analysis of biogas in China and a comparison with the situation in Sweden. The biogas potential in China is 950-2180 TWh depending on source. Specially, the potential from fish waste is 11 TWh.

Part 1 also includes batch experiments where co-digestion of corn straw and swine manure is performed using substrate from Dajugezhuang in Tianjin. The experiments were executed at Tianjin Academy of Environmental Science. The experiments do not show a significant reduction in COD when co-digesting manure with straw and are connected with uncertainty. The experiments should be executed again with the recommendations given in this report. It is discovered that the inoculum affects the C:N-ratio a lot. When co-digesting experiments are being performed, an inoculum that have a C:N-ratio close to the desired must be used. This is due to that the organic loading rate must be kept low.

Part 2 of this thesis is an economical feasibility analysis and market investigation of biogas in China. A model is created using excel, where economic data from biogas plants in China are used to estimate the profit of producing biogas in China. The model indicates that the most feasible choice is to upgrade the biogas and inject it to the gas grid. This is due to the lower investment cost for an upgrading unit compared to an electricity-generating unit. The model uses electricity and gas prices from different provinces in China. Guangdong is the province with the highest electricity price and Ningxia the province with the lowest electricity price. The gas price in Guangdong is also high, but highest in Guangxi and Yunnan. The lowest gas price is found in Ningxia.

Part 2 also discuss problems with the current situation for biogas producers in China. Investment subsidies from the government instead of product subsidies has led to a situation where China has over 30 million biogas reactors, but very low yield. The current situation means low incentives for selling the products from anaerobic digestion, bio-fertilizers, bio-methane, electricity and heat. The grid connection limit on electricity generators of >500 kW limits the number of grid-connected plants to less than 10.

Sammanfattning

Detta examensarbete i kemiteknik behandlar biogasproduktion i Kina. Examensarbetet är uppdelat i två delar. Den första delen innehåller en energipotential och nulägesanalys av biogas i Kina och en jämförelse med situationen i Sverige (kapitel 1). Biogas potentialen i Kina är 950-2180 TWh beroende på olika källor. Speciellt är potentialen från fiskarens 11 TWh.

Del 1 omfattar även satsvisa utrötningsförsök där samrötning av majshalm och svingödsel sker med hjälp av substrat från Dajugezhuang i Tianjin. Experimenten utfördes vid Tianjin Academy of Environmental Science. Experimenten visar inte en signifikant minskning av COD vid samrötning av grisgödsel med halm och försöken är behäftade med osäkerhet. De bör därför genomföras igen efter de rekommendationer som ges i denna rapport. Det upptäcks att den ymp som används påverkar C:N-kvoten mycket. När samrötningsexperiment genomförs, ska en ymp som har en C:N-kvot nära den önskade för försöket användas. Detta beror på att den organiska belastningen måste hållas låg.

Del 2 i detta examensarbete är en feasibility-analys och marknadsundersökning av biogas i Kina. En modell skapades i Excel, där ekonomiska data från biogasanläggningar i Kina används för att uppskatta resultatet att producera biogas i Kina. Modellen visar att det mest ekonomiska sättet att använda biogasen är att uppgradera den och injicera det till gasnätet. Detta beror på den lägre investeringskostnaden för en uppgraderingsanläggning jämfört med ett elkraftverk. Modellen använder el- och gaspriser från olika provinser i Kina. Guangdong är provinsen med det högsta elpriset och Ningxia provinsen med det lägsta elpriset. Gaspriset i Guangdong är också hög, men högst i Guangxi och Yunnan. Det lägsta priset på gas finns i Ningxia.

Del 2 diskuterar också problem med den nuvarande situationen för biogasproducenter i Kina. Investeringsstöd från staten i stället för subventioner av produkterna har lett till en situation där Kina har över 30 miljoner biogasreaktorer, men mycket lågt utbyte i reaktorerna. Den nuvarande situationen innebär få incitament för försäljning av produkterna från rötningsprocessen, bio-gödsel, bio-metan, el och värme. Den nätanslutningsgräns som finns för elproducenterna på >500 kW, begränsar antalet nätanslutna anläggningar i Kina till mindre än 10 stycken.

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Abbreviations

AD - Anaerobic digestion
BMW – Bioorganic Municipal Waste
BOD – Biological Oxygen Demand
CDM – Clean Development Mechanism
CHP – Combined Heat and Power
COD – Chemical Oxygen Demand
FFA – Free Fatty Acids
IRR – Internal Rate of Return
LHV – Lower Heating Value
MLBP – Medium and Large Biogas Plant
MSW – Municipal Solid Waste
Nm^3 – Normal cubic meter
Ndm^3 – Normal Liter
NPV – Net Present Value
OLR – Organic Loading Rate
ROI – Return On Investment
TN – Total Nitrogen
TKN – Total Kjeldahl Nitrogen
TOC – Total Organic Carbon
TP – Total Phosphorus
TPES – Total Primary Energy Supply
TS - Total solids
TWh – Terra Watt-hour
VS - Volatile substances
VFA - Volatile fatty acids
WWTP – Waste Water Treatment Plant

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Introduction

This Master of Science and Engineering Thesis is executed on behalf of IVL – Swedish Environmental Research Institute and act as an investigation of the biogas market for future investments in China. The aim has been to collect enough information about the biogas market in China to give IVL a good background of the investment situation in the country. The aim has also been to disprove the myth that the Chinese substrate should be different to the Swedish and therefore not suitable to produce biogas from.

This thesis can be used by anyone who wants a background to biogas production and the Chinese biogas market. The excel model attached to this thesis can be used to evaluate the feasibility of a biogas project in China.

Part 1 – Biogas in China

1. Biogas in China & Sweden – An Overview

1.1 China

Peoples Republic of China (here after called P.R.C. or China) is the world's largest emitter of greenhouse gases and the largest energy producer[1] in the world (IEA, 2011). If China continues to increase the energy production as the country has lately, by 2020 China will account for more than half of the total energy production in the world. (Jiang et. al., 2011) At the same time the energy intensity is 8.96 MWh per 2000 USD GDP compared with the world average of 3.61 (not shown in Table 1.1) and the OECD average of 2.09 MWh per 2000 USD GDP. That is, more than four times as much energy is used to produce an increase in the economy in China as in an OECD country.

Table 1.1, Energy and CO_2 statistics (IEA, 2011)

Country/ Region	**Energy-production [TWh]**	**TPES[2] [TWh]**	**TPES[2]/ GDP [MWh/ 2000USD**	**CO_2/ pop. [tCO_2/ capita]**	**CO_2/ GDP [kg CO_2/ 2000USD]**	**CO_2 emissions [Mt of CO_2]**
U.S.A.	19600	25200	2.21	16.90	0.46	5195
P.R.C.	24200	26300	8.96	5.13	2.33	6832
OECD	44300	60900	2.09	9.83	0.41	12050
Sweden	353	528	1.86	4.48	0.15	41.7

Biogas production has a long history in China, with the first biogas reactor in the world being created at the end of the 19th century in the country (Deublein & Steinhauser, 2008). The Chinese government promoted biogas early as a way for farmers to produce their own, cheap energy with residues that was readily available.

For any country it is interesting to look at the potential to produce biogas from available and easily collectable waste material. Manure, plant residues, municipal solid waste (MSW) and other organic waste material can often be a problem and create environmental problems. By producing biogas from these substrate a clean energy source can be obtained and at the same time the environmental problem is reduced. The estimation of the biogas potential from waste products that follows does not look in to gasification of biomass, as this is another technic.

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[1] Production is the production of primary energy, i.e. hard coal, lignite, peat, crude oil, LNGs, natural gas, biofuels and waste, nuclear, hydro, geothermal, solar and the heat from heat pumps that is extracted from the ambient environment. Production is calculated after removal of impurities (e.g. sulfur from natural gas). (IEA, 2011)

[2] Total Primary Energy Supply

Glaser (2006) estimated the biogas potential in China to 950 TWh or 8% of the power-mix, as the total primary energy supply (TPES) in China at the same time was 11 500 TWh (Deublein & Steinhauser, 2008). The biogas potential cannot be assumed to increase at the same rate as the increase in TPES. Due to development of biogas technology and better utilization of the substrate it is though reasonable to assume that the potential is increasing.

Chen et. al. (2010) estimates the biogas production from collectable manure alone to 870 TWh, which will reach 980 TWh and 1300 TWh in 2010 and 2020 respectively with increasing cattle breeding. They further estimate that available agricultural residues can give 1200 TWh and that this figure will increase with the energy demand and does not compete with other uses of agriculture residues. The authors arrive at a total biogas potential of 2180 TWh in 2010 without considering MSW and wastewater sludge.

Li et. al. (2005) estimates the biomass available for sustainable energy production to almost 2500 TWh, taking in to account the limitation in collection and other uses of the biomass. This amount cannot be taken to be available for biogas production via anaerobic digestion, as the volatile substance fraction (VS-fraction) has not been calculated (more about VS in chapter *3.1 Preparation and Substrate Analysis*). If burnt, the biomass can usually give a somewhat higher amount of useful energy. The authors exclude human manure from urban citizens, hence excluding the entire amount of biomass from wastewater treatment plants. This fraction of the substrate is estimated to constitute 7% of the biogas potential with limitations in Sweden (Linné et. al., 2008). Li et. al. (2005) also excludes biogas production from municipal solid waste (MSW) and only calculates the production of landfill gas (LFG), as this is how China treats most of its MSW today.

Chen et. al. (2010) arrives at almost three times as much available manure compared with Li et. al. (2005) and a little less available crop residues. This is the reason that the two studies estimates the potential differently. In table 1.2 the total available energy from waste material is given, the biomass cannot be digested into biogas and must be excluded in a biogas potential estimation.

Table 1.2 from Li et. al. (2005)

Types of Biomass	TWh 1997	TWh 2005 (prediction)	TWh 2010 (prediction)
Agricultural residues	1450	1550	1470
Animal manure	306	444	582
Biomass conservation	199	29.0	29.0
Biomass substitution	0	127	254
MSW from landfill gas	13.9	21.6	25.3
Wastewater from industry	28.3	28.3	28.3
Black Liquor	43.7	57.6	79.8
Total	2040	2260	2470

1.1.1 Estimation of China's Biogas Potential

Using the data from Li et. al. (2005) and adding data from Linné et. al. a more thorough estimation of the biogas potential can be made.

According to Linné et. al. (2008), one person produces 50 kg TS/year as inflow to a wastewater treatment plant (WWTP). If China has an urban population of 520 million people this would give 26 million tons of TS treated in WWTP. The average gas yield from wastewater is 195 Nm^3 CH_4/ton TS_{in}, which would give a yearly gas production of 5.07 billion Nm^3 CH_4 or almost 50 TWh. 520 million people, or 40% of the Chinese population comes from the assumption that 40% of the households in China are connected to a WWTP (Li et. al., 2005).

"The biogas potential from household wastewater in China is almost 50 TWh"

Furthermore the biogas production from black liquor and the energy from biomass conservation and substitution are neglected as it is assumed these fractions are gasified to produce syngas instead of digested to produce biogas.

The values from Li et. al. (2005) can be recalculated from LHV for straw to the energy content in biogas if the same substrate would be anaerobically digested instead. Linné et. al. (2008) gives the energy value for digestion of straw into biogas to 5.1 MJ/kg and Li et. al. (2005) gives the LHV to 14.23 MJ/kg. By using these two values a fraction to be used in the conversion of the potential from incineration to anaerobic digestion can be calculated.

$$\frac{Heating\ value\ of\ digested\ straw}{Heating\ value\ of\ incinerated\ straw} = \frac{5.1}{14.23}\left[\frac{MJ/_{kg}}{MJ/_{kg}}\right] = 0.358 \quad [1.1]$$

$$\text{Energy if incinerated} \cdot \text{fraction of heating value} = 1470 \cdot 0.358\ [TWh] =$$

$$= 528\ [TWh] \quad [1.2]$$

Instead of using landfill as a method for managing MSW and collecting the landfill gas, the organic waste can be digested in a biogas reactor directly. By taking the amount MSW produced in China 2010 from Li et. al. (2005) (the amount is 228.0 Mton/yr) and using the methane yield from Raninger et. al. (2010) for MSW (117 m^3 CH_4/ton wet weight) we can calculate the methane production from the digested MSW as

$$ton\ MSW\ per\ year \cdot methane\ yield\ per\ ton \cdot heating\ value\ of\ methane =$$

$$= 228.0 \cdot 10^6 \cdot 117 \cdot 9.8 \cdot 10^{-9}\left[\frac{ton\ MSW}{year}\frac{m^3CH_4}{ton\ MSW}\frac{TWh}{m^3CH_4}\right] =$$

$$= 261\left[\frac{TWh}{year}\right] \quad [1.3]$$

After this the total potential including wastewater from cities can be calculated.

The above described modifications to Li et. al. (2005) gives the result presented in Table 1.3.

Table 1.3 partly from Li et. al. (2005) and partly assumed values

Types of Biomass	TWh 2010 (prediction)
Agriculture residues	528
Animal manure	582
MSW	261
Wastewater from industry	28.3
Wastewater from cities	50
Total	**1450**

"Agricultural residues and manure gives a farm-based potential of 1110 TWh"

"In the cities the potential is 339 TWh from MSW and wastewater"

The executed evaluations of the biogas potential in China lack data on the potential from MSW and wastewater treatment plants. The majority of the potential in most countries can be assumed to come from the agricultural sector and only a small amount from

MSW and wastewater treatment plants, and the benefit of treating these fractions is reduction of greenhouse gas emission, reduction of landfill space and reduction of eutrophication, rather than extensive energy production. Both Chen et. al. (2010) and Li et. al. (2005) therefore gives valid estimations of the biogas potential in China but arrives at very different amounts.

From the data given by Glaser (2006), Chen et. al. (2010) and Li et. al (2005) it can be concluded that China has a biogas potential of *950-2180 TWh.*

Table 1.4, biogas potential with limitations due to other uses of the biomass

Reference	Biogas with limitation 2010 (TWh)
Glaser (2006)	950 (2006)
Chen et. al. (2010)	2180
Li et. al. (2005)	1450

"China has a biogas potential from waste material of over 1000 TWh"

1.1.2 Status to Date

There are 4000 companies in China related to biogas production and the biogas sector had a gross output of 26 billion RMB in 2010. (Raninger et. al., 2012)

In the *Medium and Long-Term Development Program for Renewable Energy* the Chinese government sets a production target of 44 billion m^3 biogas in 2020, also including biogas from gasification, an increase from 7 billion m^3 in 2005. It is unclear if this target regards biogas of any quality or volume methane, however the target is ambitious nonetheless. (NDRC, 2007)

The number of biogas plants in China 2009 was 30.5 million. Over 50 000 medium and large size biogas plants produces 0.92 billion m^3 of biogas. (Jiang et. al., 2011) Ma et. al. (2010) refers to China Energy Statistical Year Book with the fact that China's rural households consumes a 7 billion m^3 biogas. Most of the biogas reactors in China are small-scale production plant where the biogas is used directly in the household. The total output of biogas was 14 billion m^3 or 80 TWh according to Wang et. al. (2012).

1.1.3 Problems

Despite the numerous biogas plants in China and the huge potential, the excising projects have reported many problems and only 60% are operating normally (Chen et. al., 2009). Furthermore, the quality of the substrate has been questioned (IVL, 2012b). A project for the production of biogas by gasification of biomass investigated by Han et. al. (2008), showed that only one out of seven biogas plants investigated were in good condition ten years after startup. The project aimed to prevent crop residues from being burnt directly on the field and thereby increase the local air-quality. Even though families could save 740 RMB/year on their electricity bill, sell plant residues and though new jobs were created, lack of education and management led to the failure of the project. The only station in good condition was also the only station with continuous founding for maintenance and technical improvement. The lack of coordination of responsibilities between different governmental levels is criticized in the study. This fact leads to that the biogas stations do not have an addressee when encountering problems. Further more, the evaluation states that the direct economic benefit of the biogas production must be visible, due to the low prices and availability of coal, electricity and liquefied petroleum gas (LPG). (Han et. al., 2008)

Many of the small-scale biogas digesters projects in the rural areas of China have failed due to lack of management and educational support. Lack of assistance has led to poor maintenance and operation of the plants. (Jiang et. al., 2011)

About 10 technical standards have been developed for middle and large size biogas reactors. Raninger et. al. (2012) criticizes these standards for not being state of the art and for not being followed.

In short it can be stated that the Chinese government have spent billions of RMB on biogas plants with poor operation and that there are few positive results, this could be the reason for the view in China that biogas can not generate a profit.

1.1.4 The Future for Biogas in China

According to China's 12th five-year plan biogas production will be promoted as a way to handle the waste problem. 50 % of 800 selected cities above county level will get waste separation and treatment facilities during the period. (IVL, 2012a)

In Medium and Long-Term Development Plan for Renewable Energy in China (NDRC, 2007) it is reported that PRC aims at increasing the biogas production from 7 billion m^3 in 2005 to 44 billion m^3 in 2020. This means 4700 large-scale biogas projects on livestock farms and 1600 projects utilizing industrial waste would be built from 2007-2010 and by 2020 the total amount of livestock farm large-scale projects should be 10 000 and projects utilizing industrial waste should be 6000. Thus, 9700 large-scale projects should start during the period 2010-2020. However, the plan also states that MSW should be incinerated and says nothing about using MSW to produce biogas. (NDRC, 2007)

1.1.5 Available Biomass in China by Province

Any type of biomass can be fermented in to biogas, but the available biomass will vary from different places. In rural areas agricultural residues as straw and manure are readily available, but in urban areas MSW and sewage sludge is instead the dominating substrate.

Biogas production is most effective when it is a byproduct of solving a problem. Straw is often used as fuel-wood in rural areas for heating and cooking. Manure is produced by all animals and has to be taken care of as it is a hygienic problem and can run off to water reservoirs and case eutrophication. By producing biogas from manure and straw, farmers can solve the problems of eutrophication and air pollution. In cities, large amounts of MSW is produced and dumped or put in landfills. By instead produce biogas of MSW, the volumes are reduced and space that would be used for landfills can be used for housing instead.

Table 1.5, the 10 provinces with highest amount available agricultural and forest residues for energy, Liao et. al. (2004)

Order	**Province**	**Agricultural residue (thousand ton)**	**Province**	**Forest residue (thousand ton)**
1	Shandong	44 070	Heilongjiang	29 486
2	Henan	30 637	Inner Mongolia	26 049
3	Hebei	29 549	Sichuan	24 624
4	Jiangsu	27 949	Yunnan	20 874
5	Heilongjiang	26 372	Jilin	11 200
6	Jilin	24 079	Jiangxi	10 676
7	Sichuan	21 632	Hunan	9517
8	Hubei	16 894	Guangxi	9264
9	Anhui	15 790	Guangdong	9219
10	Inner Mongolia	15 739	Shanxi	8927

"Shandong is the province with most agricultural waste"

"Heilongjiang is the province with most forest waste"

It can also be interesting to map out the large animal breeders in China to see where farm based biogas production from manure has the largest potential.

Table 1.6, Cattle farms with >100 animals by province, Li et. al. (1999)

Area	State own	Milk cows	Beef farm	Total
Beijing	16	34	2	52
Tianjin	14	23	4	41
Hebei	32	11	5	48
Shanxi	31	13	6	50
Inner Mongolia	138	46	46	230
Liaoning	141	10	15	166
Jilin	163	8	10	181
Heilongjiang	120	18	3	141
Shanghai	27	86	12	125
Jiangsu	26	8	1	35
Zhejiang	65	11	1	77
Anhui	24	7	0	31
Fujian	100	16	0	116
Jiangxi	131	7	0	138
Shandong	17	15	2	34
Henan	94	10	3	107
Hubei	48	9	0	57
Hunan	81	10	3	94
Guangdong	136	24	3	163
Guangxi	49	8	1	58
Sichuan	134	87	30	251
Guizhou	43	7	2	52
Yunnan	88	9	0	97
Tibet	6	2	3	11
Shaanxi	18	7	1	26
Gansu	18	2	0	20
Qinghai	16	2	9	27
Ningxia	15	2	0	17
Xinjiang	287	53	20	360
Total	2078	545	182	2805

"Xinjiang is the province with most large cattle farms"

Table 1.7, large pig farms by province, Li et. al. (1999)

Area	Animals= 500-1k	Animals= 1k-5k	Animals>5k	Sum
Beijing	77	115	48	240
Tianjin	53	63	24	140
Hebei	33	37	11	81
Shanxi	7	2	1	10
Inner Mongolia	6	2	0	8
Liaoning	96	25	4	125
Jilin	30	25	10	65
Heilongjiang	36	29	14	79
Shanghai	154	158	78	390
Jiangsu	54	69	30	153
Zhejiang	33	31	15	79
Anhui	14	9	5	28
Fujian	16	21	8	45
Jiangxi	36	5	1	42
Shandong	103	36	28	167
Henan	34	29	17	80
Hubei	9	12	4	25
Hunan	15	20	9	44
Guangdong	30	68	37	135
Guangxi	79	9	3	91
Hainan	2	0	0	2
Sichuan	23	18	10	51
Guizhou	6	3	0	9
Yunnan	7	4	1	12
Tibet	0	0	0	0
Shaanxi	5	2	0	7
Gansu	3	1	1	5
Qinghai	1	0	0	1
Ningxia	1	0	0	1
Xinjiang	1	1	0	2
Total	964	794	359	2117

"Shanghai is the province with most large pig farms"

Xinjiang is the province with the most large cattle farms. However, Xinjiang is a very big province and the cattle breeding farms are spread over a large area and can be in remote places far from the biogas market. Shanghai is a densely populated city with province status, with a high demand for biogas.

1.2 Sweden

1.2.1 Estimation of the Swedish Biogas Potential

If biomass gasification is incorporated in the biogas production the realistic potential in Sweden is 59 TWh (Linné et. al., 2008), which is the same as 46% of the Swedish transport sectors energy consumption in the year 2008 (Nordberg, 2011).

The potential from waste products like MSW, wastewater sludge, agriculture residues and manure is estimated to 10.6 TWh (Linné et. al., 2008)

1.2.2 Status to Date

The situation in Sweden is very different from the one in China. In Sweden there were only 230 plants in 2009 (including landfill biogas), producing 1.4 TWh of biogas mainly using sewage sludge as substrate. (Petersson, 2011)

Many projects are successful and economically viable thanks to different subsidies, like climate investment programs (LIP and KLIMP) and benefits for car owners using renewable fuels. (Held et. al., 2008)

1.2.3 Problems

The availability of substrate has been report to be a problem. Competition of the raw material for biogas production leads to higher prices and the need for better coordination of the logistics (Held et. al., 2008).

The gas stations reported lack of fuel for their costumers (SVD, 2010). This is especially a problem for taxi drivers who are forced to drive on biogas to reach requirements for the classification as an environmental car (Palmborg, 2012).

1.3 Comparing Sweden and China

Table 1.8, comparing the biogas situation in Sweden and China

Variable	China	Sweden
Production of biogas [TWh]	80	1.4
Production method	Large number of small reactors	Small number of centralized large-scale reactors
Potential [TWh]	1440[1]	10.6
Utilized potential [%]	5.6	13
Problems	Administration, maintenance, yield	Availability of substrate, supply of fuel gas

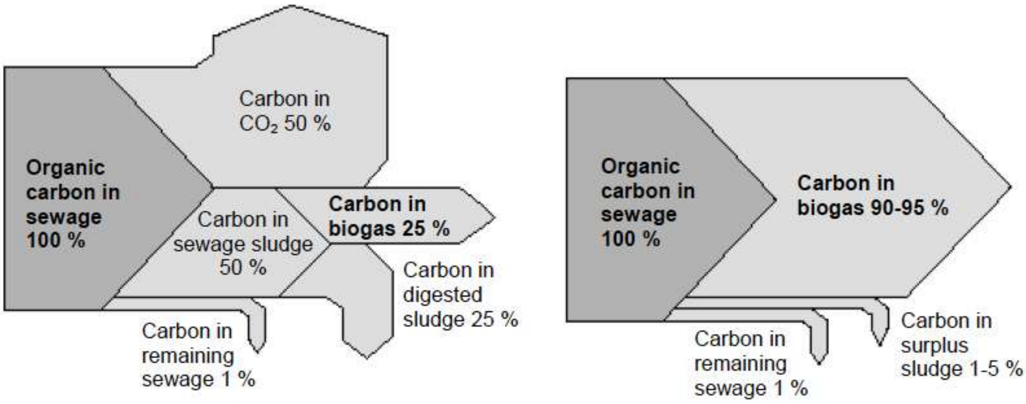
1 Li et. al. was chosen as a comparable value to Linné et. al. estimation of the Swedish potential.

2. Background - Biogas Production

2.1 Microbiology of Biogas Production

In an environment with a lack of oxygen a certain type of anaerobic bacteria that produces CH_4 and CO_2 as end products in the degradations process will thrive. In an aerobic degradation process bacteria turn chemical energy in to heat. In anaerobic degradation CH_4 contains most of the energy and only very little heat is produced. The energy produced by aerobic bacteria is of low value and is hard to utilize, instead the methane forming bacteria produces high value energy in form of CH_4 that can be collected and used in different applications. If digesting 1 kg of sugar aerobic digestion gives 9 MJ heat and only 50% of the sugar is degraded. The anaerobic bacteria produce only 0.4 MJ heat and degrades 95% of the sugar, the rest of the energy, 14 MJ, is released as methane. (Nordberg, 2011)

Figure 2.1 shows the benefit of digesting sewage sludge anaerobically without first using an aerobic method (the activated sludge process). The sludge volume decreases much more and the carbon can be collected as biogas.



Activated sludge process

Anaerobic sewage degradation

Figure 2.1, from Levlin (2010)

Biogas production is essentially a four-step process. (Deublein & Steinhauser, 2008)

1) **Hydrolysis** is the first step. Here the substrate is broken down into smaller parts by different enzymes that can break the covalent bonds and split up the carbohydrates, proteins and fats into mono- and oligomers. The hydrolysis is often the limiting step in the biogas production process and pre-treatment of the substrate could therefore speed up the whole process.
2) In **fermentation** the products of the hydrolysis are turned into various 1-5 carbon atom molecules like methanol and acetic acid in the acidogenic phase.

CO_2 and H_2 are also formed here. Acetic acid and H_2 can be directly used by the methane forming bacteria, but other products of the fermentation must first pass the third step.

3) The **anaerobic oxidation** is the part where the products that can be used by methane forming bacteria are produced. The products are acetate, formate, methanol, carbon dioxide, different methylamines, methanethiol (CH_3SH) and dimethylsufide ($(CH_3)_2S$).
4) In the **methanogenesis** acetic acid and the other substrates are used by methane forming bacteria to form CH_4 and CO_2.

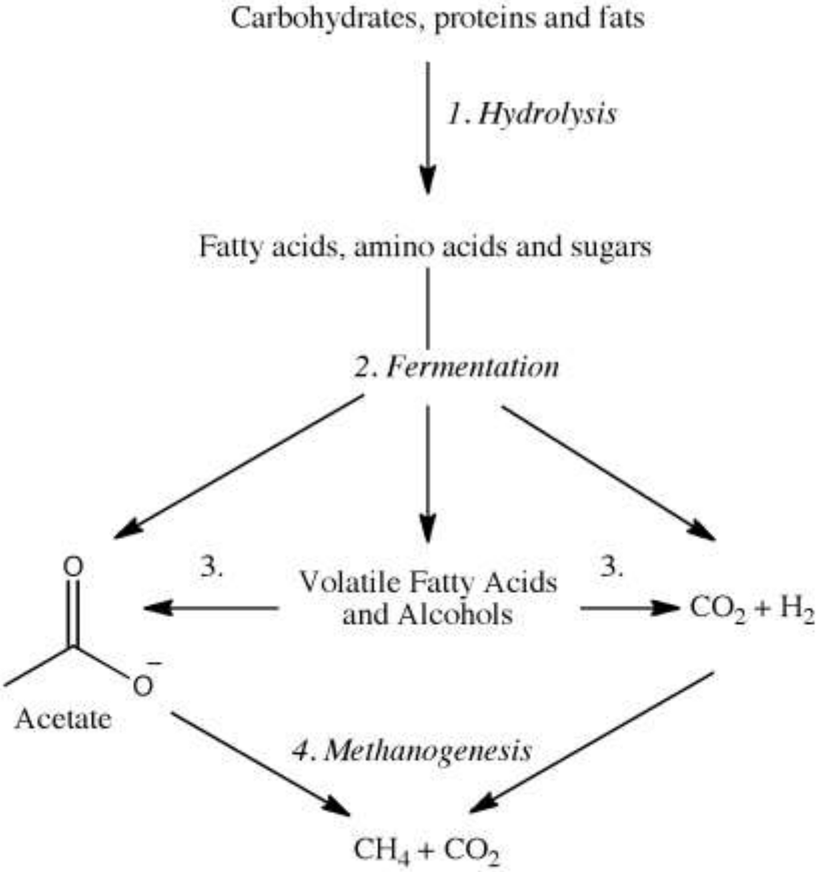


Figure 2.2 the biogas forming steps, after Deublein & Steinhauser (2008)

The whole process is complex and each step is internally dependent on the other steps. Methane forming bacteria use H_2 to form CH_4 and CO_2. It is necessary that the methanogenic microorganisms remove H_2 as it is formed, since formation of acetate can only occur with a low hydrogen partial pressure. If this does not happen acetogenic bacteria will produce other substrate than those useful for methanogenesis. (Deublein & Steinhauser, 2008)

Compared to aerobic bacteria that regenerate after a few hours, anaerobes take weeks. Methanogenic bacteria are very sensitive to environmental changes and this makes the process difficult to handle. Due to the slow regeneration it can take weeks for the process to recover after a disturbing accident. The production must be optimized with regard to the methanogenic bacteria because of their slow growth rate. However, hydrolysis and fermentation work optimally under different conditions than methanogenesis, like lower temperature and pH. A solution to this optimization problem is to divide the biogas production process into a two-step reactor where the first step is optimized with respect to hydrolysis and fermentation, and the second step with respect to methane formation. (Deublein & Steinhauser, 2008)

2.2 Process Parameters

2.2.1 Hydraulic Retention Time

The **Hydraulic Retention Time (HRT)** is the active volume, V [m^3], divided by the volume flow out of the reactor, Q_o [m^3/day]

$$\mathrm{HRT} = \frac{\mathrm{V}}{\mathrm{Q_0}}[\mathrm{day}] \quad [Def\ 2.1]$$

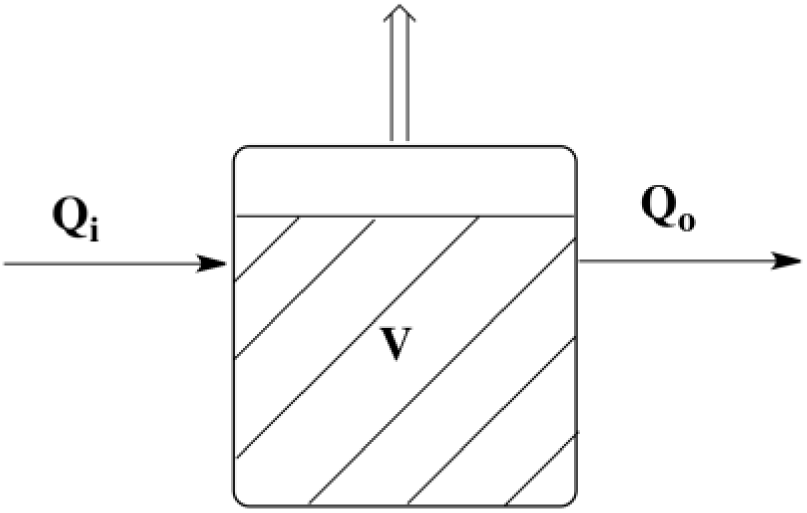


Figure 2.3, Hydraulic Retention Time (HRT)

HRT should be 15-50 days depending on the substrate, pre-treatment etc.

2.2.2 Organic Loading Rate

The **Organic Loading Rate (OLR)** is a function of HRT

$$\mathrm{OLR} = \frac{\mathrm{S_0}}{\mathrm{HRT}}\left[\frac{\mathrm{kg\ VS}}{m^3,\mathrm{day}}\right] \quad [Def\ 2.2]$$

S_0 – organic matter in [kg VS/m^3]

VS – Volatile Substance (defined in chapter *3.1 Preparation and Substrate Analysis*)

The OLR must be set so that the methane-producing microorganisms have time to digest the material. If the OLR is too high, overload of certain intermediate products will occur and this will lead to process break down. A OLR of 2-8 [kg VS/m^3,day] is usually beneficial, again depending on the substrate, pre-treatment etc.

2.2.3 Temperature

Temperature influences the methane formation extensively. There are two ranges where different methane forming microorganisms thrive

1. *Mesophilic conditions* with temperatures in the range 32-42°C
2. *Thermophilic conditions* with the temperature range 48-55°C

The mesophiles are more sensitive to higher than lower temperatures, thus the 42-48°C range is not suitable for methane production. The energy balance is generally better in the mesophilic range, but the thermophilic range has the benefit that hygienic treatment of the digestate after the digestion is omitted due to the high temperature during the process. Furthermore, the thermophilic process usually has shorter HRT. (Deublein & Steinhauser, 2008)

The effect of temperature is different depending on substrate. E.g., for digestion of swine manure a temperature drop from 37-20°C only gives 25% less methane production. If the carbon digested to a large extent comes from fat, the process is less affected by temperatures down to 20°C. If the carbon instead comes from carbohydrates, a temperature drop has a greater effect on the methane production. (Bohn, 2007)

2.2.4 Concentration of Inhibitors

Different compounds can inhibit the biogas production, most importantly ammonia and free fatty acids. Free fatty acids lowers the pH and the acid environment stops the biogas production.

Ammonia acts as a buffer to acidic compounds

$$NH_3 + H^+ \rightarrow NH_4^+ \quad [2.1]$$

Reaction 2.1 creates innocuous NH_4^+.

When pH is increasing reaction 2.1 is reversed

$$NH_4^+ \rightarrow NH_3 + H^+ \quad [2.2]$$

and harmful ammonia is created again.

Reaction 2.1 and 2.2 is depending on pH according to figure 2.4.

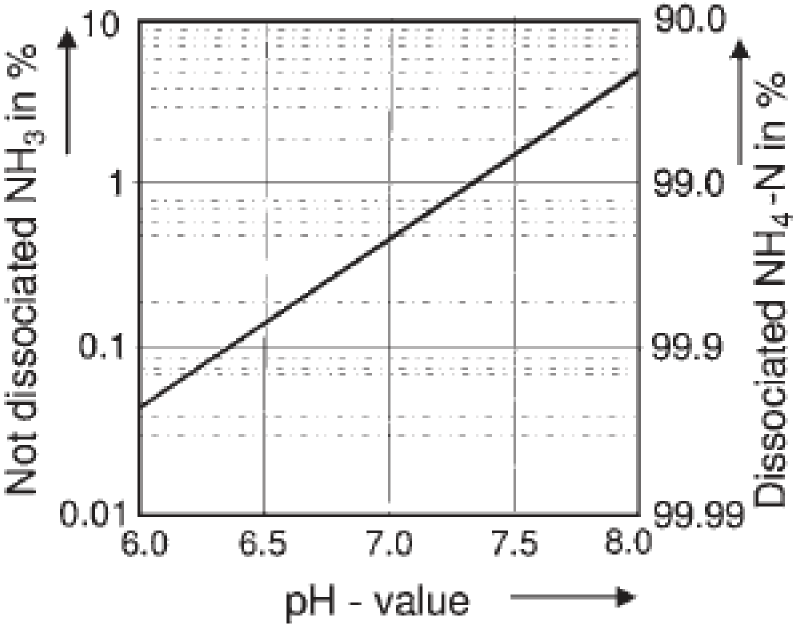


Figure 2.4, from Deublein & Steinhauser (2008)

Ammonia inhibits the biogas process at concentrations of 2-3 g/dm^3 but can have an impact in smaller amounts depending on temperature. Microorganisms can adjust to a somewhat higher level of ammonia and therefore ammonia inhibition must be compared from case to case. (Carlsson & Uldal, 2009)

The inhibiting effect of ammonia is reduced with decreasing temperature because of the lower content of free ammonia (Deublein & Steinhauser, 2008). An increase in temperature may therefore lead to ammonia inhibition.

"Ammonia (NH_3) inhibits biogas production,

NH_3 increases with temperature and pH"

2.3 Methane

Methane is an energy rich gas. When combusted in a car engine or a gas turbine, methane releases 890.36 kJ/mol of energy and only four grams of methane contains enough energy to produce 1 kWh.

Methane is combusted to form CO_2 and H_2O

$$CH_4 + 2\,O_2 \rightarrow CO_2 + 2\,H_2O\ (g)\ [2.3]$$

If a flue gas condenser is applied to the combustion plant it is possible to make use of the water vapor created when combusting methane (the higher heating value) and hence get even more energy out of the biogas.

Table 2.1, after Felder & Rousseau (2005)

Formula	Mol. Wt. [g/mol]	$\Delta\hat{\mathbf{H}}_f$(25°C, 1atm) [kJ/mol]	$\Delta\hat{\mathbf{H}}_c$(25°C, 1atm) [kJ/mol]
CH_4	16.04	-74.85(g)	-890.36(g)

The energy in 1 m^3 of pure methane contains a little more energy than 1 dm^3 of gasoline

$$1\ m^3\ CH_4(g) = 1.04 \cdot 1\ \mathrm{dm}^3\ C_8H_{18}\ (l)\ \ [2.4]$$

Therefore the price of the upgraded biogas is easily compared with the reigning vehicle fuel today, gasoline.

2.4 Substrate

The substrate is the material used to form biogas and therefore the nutrients for the microorganisms participating in the degradation of it. Substrates used in biogas reactors are manure from animal breeding, municipal solid waste (MSW), industrial waste, wastewater sludge and plant residues such as straw, but any biodegradable organic matter can be used (i.e. matter easily degraded naturally). Since anaerobic digestion is a biological process the substrate must contain everything the microorganisms need to produce biogas and any material satisfying that could be used, but in general waste products are preferred since they need to be taken care of anyway.

The theoretical yield of methane that can be obtained from a substrate is calculated using Bushwell's formula (Symons & Bushwell, 1933)

$$C_nH_aO_b + \left(n - \frac{a}{4} - \frac{b}{2}\right)H_2O \rightarrow \left(\frac{n}{2} - \frac{a}{8} + \frac{b}{4}\right)CO_2 + \left(\frac{n}{2} + \frac{a}{8} - \frac{b}{4}\right)CH_4\ \ [2.5]$$

and the theoretical methane production, B_u, can be calculated according to

$$B_u = \frac{(n/2 + a/8 - b/4)22.4}{12n + a + 16b} \left[\frac{\mathrm{dm}^3\ CH_4}{kg\ VS}\right] \quad [2.6]$$

The methane production for cellulose can be calculated from the chemical formula

$$C_6H_{10}O_5 + H_2O \rightarrow 3CO_2 + 3CH_4$$

$$B_u = \frac{3 \cdot 22.4}{162} = 0.415 \left[\frac{\mathrm{dm}^3\ CH_4}{kg\ VS}\right]$$

2.4.1 Municipal Solid Waste

Collection and Treatment
Chinese households produced municipal solid waste (MSW) at the rate of 0.98 kg per capita and day in 2006, which is almost twice the speed of production in 1980. The total amount of waste being produced in China has risen from 31.3 million tons in 1980 to 212 tons in 2006. (Zhang et. al., 2010) However, the waste generation in the cities is much higher and reaches 2.62 kg per capita and day (Li et. al., 2005). Of the collected amount MSW in 2007, 91.4% went to landfills, 6.4% was incinerated and 2.2% was composted.

Table 2.2, MSW treatment methods, from Li et. al. (2005)

Treatment method	%
Landfills	91.4
Incineration	6.4
Compost	2.2

Recycling of the MSW is performed by the informal sector in China and hence is hard to measure. The treatment rate of the MSW was 62% in 2007, thus 38% of the MSW is dumped or take care of in an unknown way, partly recycled or reused. To this comes the fact that the landfills in China are sometimes more or less open dumps and therefore nowhere near the internationally accepted standards. (Zhang et. al., 2010)

It is reported that MSW in China has much higher fraction organic garbage, such as food waste, than other countries (Zhang et. al., 2010 and Raninger et. al., 2010). This would make it suitable for anaerobic digestion instead of incineration.

To produce biogas from MSW the bioorganic municipal waste (BMW) has to be separated from the inorganic and slowly degradable waste. This can be done using source separation in the households. This method was used successfully in China by Raninger et. al. (2010). According to Raninger et. al. (2006) Chinese authorities have the unanimous opinion that the residents are not able to separate the waste according to source and they rely on future technologies to separate the waste by technological means. Furthermore, the authors mean that these technologies have failed and that manual source separation is a must to utilize the bioorganic fraction of MSW. Though two projects, one in Shenyang and one in Heng County in Guanxi province, they showed that a positive attitude towards source separation of MSW exist.

However, there are technologies for mechanical source separation. A plant with the capacity to separate 50 000 ton/year of MSW was recently taken into operation in Huddinge, Sweden. The technology separates metal, plastic and other unwanted material from the BMW. (SRV, 2012)

In Sweden the households generate 1.4 kg MSW per capita and day but only 1.4 % of the waste is put in a landfill, 98.6% is recycled. (Avfall Sverige, 2010)

A landfill cost 12.5 yuan/m^3, a biogas reactor costs almost 20 times as much (Cui et. al., 2011). However, the actual cost of treating MSW in landfills is hard to estimate. E. g. Beijing is expected to run out of landfill space in 2013 or 2014 and the city has taken measures like perfume guns to handle the smell from the 200 landfills that surround the city like a seventh ring road (Guardian, 2010). Furthermore, it is possible to get gate fees from the polluter if MSW is used as a substrate (SGPOBU, 2010). This could make biogas profitable due to the extra income for treating MSW.

Another way to treat MSW is producing compost of it. In Boden, a town in the north of Sweden, composting MSW costs 700 SEK/ton MSW, the cost when treating it anaerobically is 200 SEK/ton MSW.

Incineration or Biogas Production of MSW

Li et. al. (2005) are using a lower heating value (LHV) of 4 MJ/kg for incineration of MSW. This can be compared with reported values of 3.78 MJ/kg that can be achieved by anaerobic digestion of MSW (Norberg, 2011). Also Karlsson (2005) states that biogas produces slightly less energy per kg MSW than incineration and if fuel gas condensation technology is used the energy recovery of the incineration process will be even higher. The lower energy production has several explanations. One is that lignin and plastics are two compounds that hardly get decomposed in the process. Lignin constitutes 15-30% of wood and has a LHV of more than twice the value of cellulose and hemicellulos that are decomposable (Thomsen et. al., 2008). Hence, a part of the energy in the wood is not found in the methane produced, but is left in the byproduct.

However, biogas has the advantage that it can be upgraded to vehicle fuel, it is a very clean gas that burns without emitting particles and the byproduct can be used as a bio-fertilizer because the nutrients in the substrate are preserved. If source separation into a high calorific fraction with non-recyclable remaining waste, a recyclable fraction and a BMW-fraction can be achieved, then each fraction can be utilized differently. That is: the remaining waste can be incinerated, the recyclable waste recycled and the BMW digested into biogas. This gives a much better utilization of the waste. (Held et. al., 2008)

Table 2.3 from Zhang et. al. (2010)* , Raninger et. al. (2010)** and Raninger et. al. (2006)***

MSW	China* (%)	European average (%)	Shenyang**, Liaoning, China (%)	Heng*** county, Guanxi, China (%)
BMW	52.6	30.0	73.7	81.1
Paper	6.9	32.0	6.5	8.9
Plastics	7.3	7.0	6.8	1.4
Glass	1.6	10.0	1.6	
Metal	0.5	8.0	0.3	1.5
Textile	4.7	4.0	4.1	4.6
Wood	6.9	-	1.0	2.1
Ash	19.2	9.0	1.5	-

** The total is 95.5%, this is due to that hazardous waste, compex products and others are not shown.

"Chinese MSW contains around twice as much BMW as European MSW"

2.4.2 Agricultural Residues and Manure

Agricultural residues and manure constitutes the absolute majority of the total biogas potential in China (Chen et. al. 2010 and Li et. al. 2005). In Sweden agricultural residues and manure constitutes around 80% of the total potential (Linné et. al. 2008).

Manure has a relatively low biogas potential (Linné et. al. 2008) but is available in large amounts and has to be taken care of if the animals are kept inside. To produce biogas from manure can be seen as good manure management. (More about manure in chapter *2.5 Co-digestion*)

Agricultural resides such as straw contains a lot of carbon and high amount of total solid (TS). Local environmental problems caused by burning straw in the fields can be avoided by digesting straw. (More about straw in chapter *2.5 Co-digestion*)

2.4.3 Wastewater Sludge

The official wastewater treatment rate in China was 75% in 2010 and this figure has grown steadily the resent years. The wastewater treatment plants in China have a total capacity to treat 65 million tons per day. (People's Daily, 2011)

In chapter *1.1.1 Estimation of Chinas Biogas Potential*, the potential of wastewater sludge is estimated to 5.07 billion Nm^3 CH_4 or 50 TWh per year. This is a huge potential. Digestion of wastewater sludge is very beneficial not only from an energy perspective, but also for the fact that the sludge amount is reduced much more than if aerobic methods are used (see chapter *2.1 Microbiology of Biogas Production*).

2.4.4 Fish Waste

In 2004, there were 8745 fish processing plants in China with a total production of aquatic products that reached 13.82 million tons. In China it is custom to buy a fish fresh, but processed aquatic products still accounted for 28% of total output of aquatic products. The processed products are mainly frozen products with 5.99 million tons, sarumi (fish paste) and dried products of 1.70 million tons, 144 000 tons of canned products and 1.68 million tons for animal protein feed. (FAO, 2012)

Fish waste has a very high energy content and can produce as much as 930 Nm^3 CH_4/ton VS or 537 Nm^3 CH_4/ton wet weight (Carlsson & Uldal, 2009).

If the frozen and canned processed fish products are assumed to produce fish waste of 25% of the total amount of fish (Arvanitoyannis & Kassaveti, 2008), an amount of 2.4 million tons of fish waste is produced. This equals a biogas potential from fish waste of 1.1 billion Nm^3 CH_4, or 11 TWh.

"The biogas potential from fish waste in China is 11 TWh"

2.5 Co-digestion

When two or more substrates are being digested together the process is called co-digestion. Manure is usually a good substrate for biogas production with a variety of nutrients and minerals. The main problem with digestion of manure alone is the lack of fat and the excess of nitrogen, which leads to an alkali environment in the reactor. When co-digesting substrates with different chemical properties, optimally, all the nutrients that the microorganisms involved in the methane production needs can be provided.

There are several examples of increased methane production by co-digestion and even indigestible substrates can become digestible if co-digested. This is true for olive oil wastewater that is co-digested with manure. If digested alone, the free fatty acids (FFA) in the olive oil wastewater decreases the pH and leads to an acidic environment that will end the biogas production. Manure contains a high amount of ammonia and acts as an alkaline buffer for the high amount of FFA in the olive oil wastewater. Ammonia is also an important source of nitrogen for the bacteria in the reactor. (Angelidaki & Ahring, 1997) For the same reason waste from slaughterhouses or the fish industry could be co-digested with manure to prevent too high amounts of FFA in the reactor.

2.5.1 Nutrients

A form of co-digestion is addition of a nutrient solution to the process. If the substrate digested lacks nutrients, this will be a limiting factor for the production of methane.

Addition of nutrients will speed up the process and the reactor volume is therefore better utilized.

2.5.2 C:N-ratio and Benefits of Co-digesting Manure with Straw

C:N-ratio is defined as the ratio between total organic carbon (TOC) and total Kjeldahl nitrogen (TKN) (Sievers & Brune, 1978)

$$C:N \equiv \frac{mass\ TOC}{mass\ TKN} \quad [Def\ 2.3]$$

In China another method than the Kjeldahl method is used to measure the nitrogen content. In the Chinese literature, the Kjeldahl method is considered unnecessarily cumbersome and time-consuming (Zhang et. al., 2009). *Determination of Total Nitrogen in Waste Water by Alkaline Potassium Persulfate Digestion-UV Spectrophotometric Method* (standard GB11894-89), is used in China and is assumed to be equivalent to the Kjeldahl method. In this report the difference between these two methods is assumed to be of little influence to the C:N-ratio analysis. TOC is determined by the method *Soil–Determination of Organic Carbon–Potassium Dichromate Oxidation Spectrophotometric Method* (HJ 615-2011).

According to Carlsson & Uldal (2009) a C:N-ratio of 20:1 is beneficial for biogas production and it should not be higher than 30:1 or lower than 15:1. If ammonia is produced due to a lower ratio, 10-15:1, pH will rise and this could be toxic to the microorganisms in the reactor. If the ratio is larger than 30:1 the production of biogas will stop. According to another source the C:N-ratio should be 16:1-25:1 (Deublein & Steinhauser, 2008). It is important to understand that the C:N-ratio only gives a hint of the availability of the carbon and nitrogen, which is what really determines the conditions in the reactor and therefore values in the literature vary. Carbon could exist in the form of lignin and plastic, which is unavailable to the microorganisms (Carlsson & Uldal, 2009).

Chicken manure contains high amounts of ammonia and a low C:N-ratio, 3-10:1. It also contains a lot of phosphorus. Manure from swine also contains a lot of nitrogen. (Carlsson & Uldal, 2009).

It was suggested in the 1970's that agricultural crops could be used to improve the digestion process using most types of manure (Hills, 1979). Straw is an abundant resource in agricultural areas and could be collected to increase the C:N-ratio when digesting manure[3].

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[3] Hills (1979) defined C:N as the ratio between available carbon (TOC minus the lignin carbon) and available nitrogen.

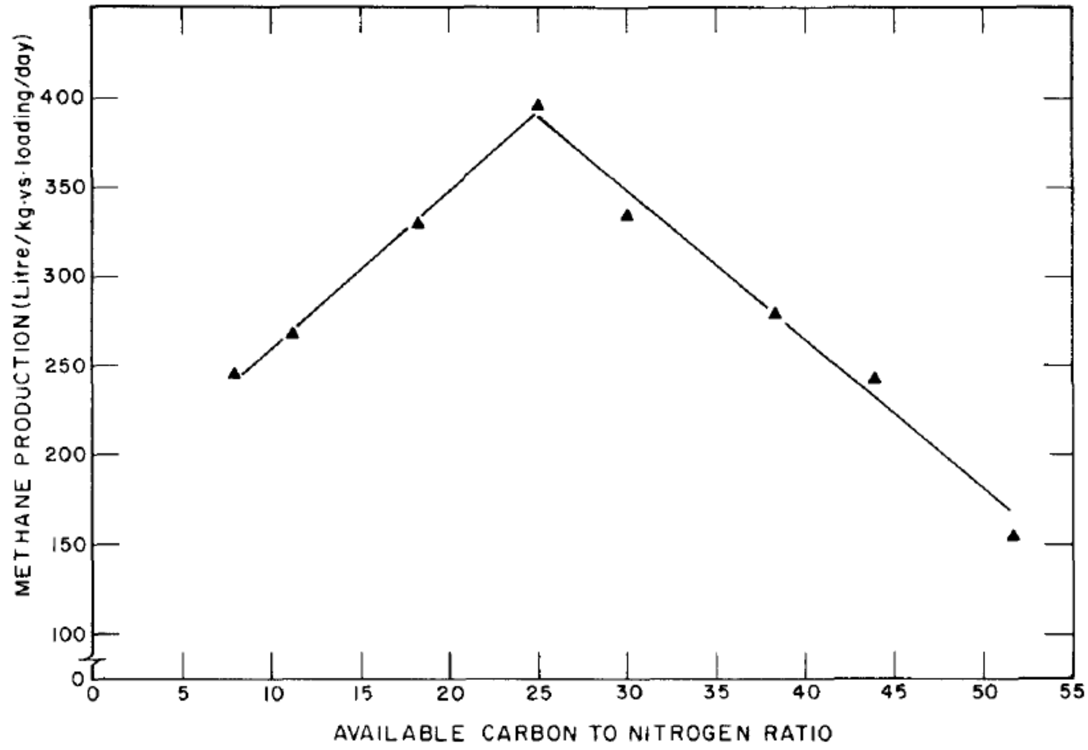


Figure 2.5, from Hills (1979)

The difficulty of producing ethanol from straw is well known. Due to its lignin content the cellulose and hemicellulose are less accessible to the fermentation microorganisms (Thomsen et. al. 2008). It has been reported that several substrates used for anaerobic digestion benefit from alkali pre-treatment or mechanical pre-treatment to solubilize the cellulose molecules and make them more easily accessible to degradation. (Mata-Alvarez et. al., 2000) In a master thesis investigating the benefit of pretreating straw it was found that extrusion could be an economically feasible method to increase the biogas production from straw (Borgström, 2011). Møller et. al. (2004) reported that cutting straw down to 1 mm compared to 30 mm gave significant effect on the speed of methane production, from 145-161 dm^3/kg VS when digesting for 60 days. When the batch experiments were allowed to continue for 110 days the effect was non-significant, suggesting that mechanical pretreatment by grinding can reduce the retention time. The pre-treatment increases the available surface area of the substrate and can lead to more rapid digestion (Mata-Alvarez et. al., 2000).

However, recent research has shown major increases in methane yield when co-digesting straw with swine manure, without pre-treatment. Wu et. al. (2010b) carried out batch experiments with a C:N-ratio of 20-25:1 and found that corn straw increased the cumulative methane production 16 times and wheat straw increased it with more than 6 times when co-digested with swine manure. When using a C:N-ratio of 25:1 the methane production from wheat straw increased to ca. 10 times that of manure alone. They explain this with the fact that the volatile substance (VS) in the straw is more easily degradable than the VS in manure that has already passed though the digestive track of the animal. The wheat straw used in the study contained 18% lignin compared to the corn straw used that contained 8%. The wheat straw had a carbon content of ~46% compared to ~39% for corn straw which led to the use of a smaller amount wheat straw than corn straw as the experiments were based on amount of VS. Wang et. al. (2009) added just 4.6 kg of non-pretreated wheat straw per ton swine manure and could see an increase in methane production of 10%. They could not see any benefit in using wet explosion as a pre-treatment method of the substrate when co-digesting with swine manure and digesting under thermophilic conditions (55°C). Evidences of successful co-digestion of straw and energy crops with cow manure are also found in the literature (Somayaji & Khanna, 1994 and Lehtomaki et. al., 2007). Pre-treatment at elevated temperatures could have a negative effect on the methane production due to formation of inhibitory compounds (Wang et. al., 2009). Thermochemical or steam pre-treatment of straw should thus be avoided.

Møller et. al. (2004) found that the biodegradability of wheat straw was 0.45 defined as the ultimate methane yield from batch experiments, B_o, divided with the theoretical methane production, B_u, calculated with Bushwell's formula [2.5] [2.6].

$$\frac{B_o}{B_u} \text{ - The biodegradability of any substrate} \qquad [2.7]$$

The biodegradability of cattle manure spanned from 0.21-0.44 and for pig manure 0.47-0.78 depending on different diets for the animal. Møller et. al. (2004) suggests that wheat straw should be co-digested with manure due to its high volumetric methane production.

Table 2.4, biodegradability of different substrate $^{B_o}/_{B_u}$, (Møller et. al., 2004)

Wheat straw	Pig manure	Cattle manure
0.45	0.47-0.78	0.21-0.44

"The biodegradability of pig manure is high,
this makes pig manure a good substrate"

If the low C:N-ratio can be adjusted by adding straw to pig manure, a substrate with high biodegradability and an optimum C:N-ratio can be achieved, utilizing the more of the manure than if it is digested alone.

2.5.3 Co-digesting Manure with Bioorganic Municipal Waste (BMW)

Raninger et. al. (2010) collected municipal solid waste (MSW) in Shenyang, Liaoning province China. They separated the BMW and digested it alone and in a mixture with cattle manure (2:1 and 1:2). The BMW alone produced 117 Ndm^3/kg wet weight and the cattle manure alone 65 Ndm^3/kg wet weight. When co-digested, much higher yields than if the fractions would have been weighted and added together was achieved. E.g., if manure and BMW was digested in a ratio of 2:1 the following result of weighting and adding the fractions is achieved:

$$\frac{2}{3}\cdot 65+\frac{1}{3}\cdot 117=82.3\left[\frac{Ndm^3}{Kg}\right]$$

This should be compared with the achieved yield of 105 Ndm^3/kg wet weight.

The result 117 Ndm^3/kg wet weight is interesting to compare with the figure 125 NL/Kg wet weight used for BMW by Linné et. al. (2008) to calculate the potential for biogas in Sweden.

Table 2.5, from Raninger et. al. (2010)

Substrate	**Weighted and added [Ndm^3/kg]**	**Actual yield [Ndm^3/kg] (after 40 days digestion)**
BMW	NA	117
Cattle manure	NA	65
BMW:manure = 1:2	82.3	105 (after 50 days)
BMW:manure = 2:1	99.7	107

Raninger et. al. (2010) showed that more biogas is produced if BMW and manure are co-digested, that if the substrates are digested alone.

Feng et. al. (2011) did the same thing as Raninger et. al. (2010) (actually just repeating the same experiment) and achieved a somewhat lower biogas production.

Table 2.6, data from Feng et. al. (2011)

Substrate	**Weighted and added [Ndm^3/kg]**	**Actual yield [Ndm^3/kg] (after 40 days digestion)**
BMW	NA	94
Cattle manure	NA	53
BMW:manure = 1:2	66.7	101
BMW:manure = 2:1	80.3	105

2.5.4 Co-digesting Fish Waste and Sewage Sludge

IVL (2012b) found that fish waste can be digested with sewage sludge in ratios up to 2:3 sewage sludge:fish waste. Earlier research shows difficulties digesting fish waste due to accumulation of free fatty acids and suggests ratios under 10% on mass basis of fish waste (Callaghan et. al., 1999 and Ward, 2010). If the new results are due to a large buffer capacity in sewage sludge for free fatty acids, then this knowledge will severely simplify digestion of all sorts of slaughter waste. Read more about fish waste as a substrate in chapter *2.4.4 Fish Waste.*

2.6 Methods for Biogas Production

Biogas can be produced in any type of reactor and two types of fermentation methods exist: wet fermentation and dry fermentation.

2.6.1 Wet Fermentation

Wet fermentation is simply a substrate that contains, or is mixed with, water to give TS < 10%. Due to the low TS the substrate can be pumped into and out of the reactor. This is the most applied method due to mechanical reasons, but often requires that the substrate is mixed with water and dewatering of the digestate.

2.6.2 Dry Fermentation

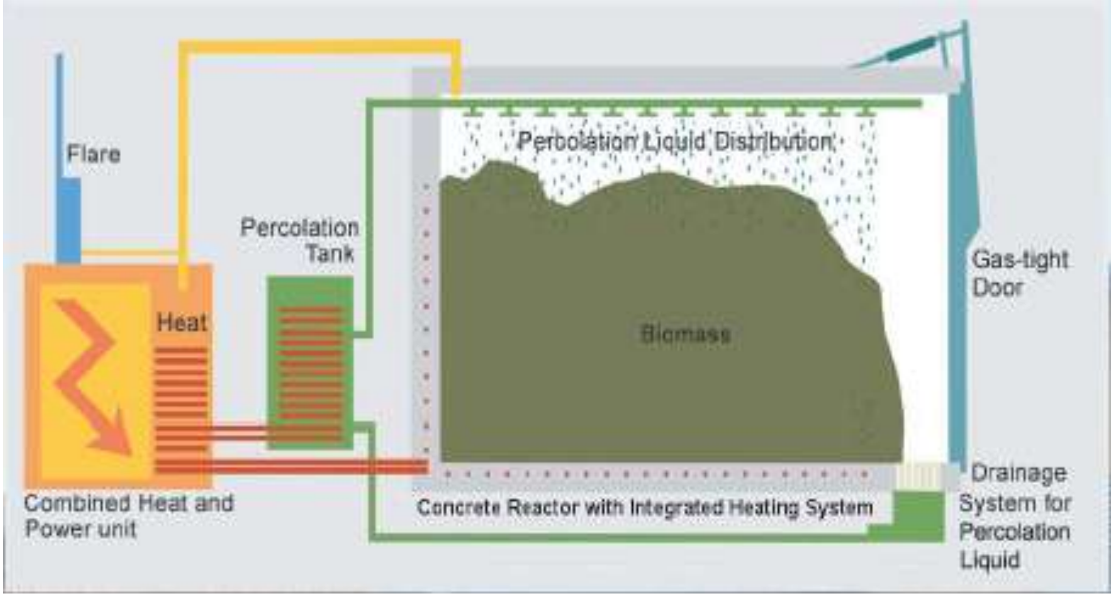
Dry fermentation is especially useful when the substrate is dry from the beginning. This method operates at TS 20-35% and does not require the substrate to be diluted with water. The size of the reactor can be minimized and excessive use of water omitted (Nordberg, 2011).

When the digestion process is finished, the dry fermentation process leaves a dry digestate that can be used as a fertilizer without first being dewatered and this reduces the energy demand for drying.

The dry fermentation plant in Borlänge Sweden experienced technical difficulties and had to shut down. The problem was that the stirrer that was going to push the substrate forward in a continuous reactor was not able to do so due to the high TS-content of the substrate. To facilitate mixing and transport the substrate can be mixed with wooden chips. (Rylander & Weine, 2005)

According to www.bioenergiportalen.se there is only one dry fermentation biogas plant in Sweden, in Järna south of Stockholm (Bioenergiportalen, 2008).

Figure 2.6, dry fermentation anaerobic digestion (SP Multitech, 2012)



2.6.3 Batch Reactor

Simply filling a batch reactor with substrate and inoculum from an earlier batch gives a high yield. However, the gas production will vary over time to give only small amounts towards the end when almost all degradable matter is converted.

2.6.4 Continuous Stirred-Tank Reactor (CSTR)

This continuous method is applied when the substrate can be pumped to the reactor, i.e. TS = 2-10%. The gas production is even and the organic loading rate (OLR) is adjusted to the inoculum to prevent process failure. A CSTR is the most used technology.

2.6.5 Plug Flow Reactor (PFR)

In a PFR the yield is increased due to a guaranteed residence time and no mixing along the reactor. This method can be applied for dry fermentation.

2.7 Rural Biogas Production - Yuqiao-reservoir

In accordance with the objective of this thesis to gather information about the biogas market in China, the special situation with small-scale reactors was investigated. This is also a good way to understand more about how biogas production is used in China to minimize environmental problems.

Yuqiao-reservoir in the north part of Tianjin is a very important drinking water reservoir for Tianjin. Due to extensive farming and animal breeding around the reservoir Yuqiao suffers from eutrophication. Biogas production was suggested as a manure management method and it was decided to build small biogas reactors for every family in Dajugezhuang, a small village north of Yuqiao.

The project to deal with the eutrophication "Clean Water for Sustainable Cities in China", gives the villager the opportunity to use manure from their animals to produce biogas, the families that do not raise animals buy manure from other families that have an excess of manure.

A study visit was made to Dajugezhuang and three families were visited. One pig and duck farmer with excess of manure (see chapter *2.7.1 Large Farm*), one family without animals (see *2.7.2 No Animal No Biogas*) who bought manure and one family with only one pig (see *2.7.3 Small Farm*).

Co-digestion with straw is evidentially beneficial for biogas production and an increase in biogas production can be obtained even without pre-treatment of the straw. The answer to the question if co-digestion can lead to less eutrophication of the Yuqiao-reservoir is however more complex than this. Adding straw to the digester will lead to that less manure can be digested, given a constant digester volume. Addition of straw is however small in volume due to a high total solid value (TS-value), that is straw contains little water. If the addition of straw can give co-digestion effects and lead to a more stabile process, more manure can be broken down and this will lead to better utilization of the reactor volume. Other uses for straw must also be considered especially since burning straw could be a good way to use its energy content. Furthermore the increase in workload for the farmers that have to collect the straw from the fields must be considered.

2.7.1 Large Farm

The farm with an excess of manure had a large stack of manure at the input to the biogas chamber. The manure was dry and contained some straw. The farmer uses 30-40% of the manure to make biogas, the rest is either just dumped and this leads to severe pollution of the watercourses around, or used directly as fertilizers.

Picture 2.1, manure from the large farm

The farmers did not add the straw on purpose. The pressure meter connected to the gas collector displayed 4 kPa on a scale 0-16 where 0-4 was said to be to low and 12-16 dangerously high.

Picture 2.2, pressure meter before biogas stove

4 kPa was evidently high enough and a blue burning flame could be seen from the biogas stove.

Picture 2.3, biogas stove

Straw was abundant and only 10% of the collected straw was used as firewood. Straw was used as insulating material for the greenhouses and this insulation was changed a couple of times per year. Excessive straw was burnt directly or dumped.

Picture 2.4, straw is used as insulation for greenhouses

Manure with pieces of straw in it and residue from the biogas reactor were collected.

2.7.2 No Animals No Biogas

The family without animals was not running the digester at the moment. This was due to the cold season. The family was planning to start using biogas soon again as the weather became warmer. No samples were collected.

2.7.3 Small Farm

The family with only one pig had recently sold their boar and had a sow. According to the family the biogas production was not good when using the sow's manure, but better with the boar's manure. The sow's manure was much wetter than the manure from the large farm, probably due to the fact that it was fresher.

Picture 2.5, sow manure is not good for biogas production according to the farmers

Picture 2.6, fresh sow manure

The sow's manure, corn straw and residue from the biogas reactor were collected.

2.7.4 Straw

Straw was seen in collected bundles all over the village. Straw was used as firewood and as insulation to the greenhouses and was reported to be in excess. Black ash-remains after burning straw in the fields could also be seen.

The villagers at the small farm (*2.7.3 Small Farm*) said they were afraid adding straw to the reactor might clog the reactor and cause a stop. The corn straw was present as big leaves and stalks and could cause problem if not digested properly. Some kind of pretreatment is recommended to get the size down to a couple of cm to prevent inconvenient stops in the pipes.

Picture 2.7, straw from corn

Picture 2.8, straw is abundant only 10% is used as firewood

2.7.5 Inventory of Resources in Yuqiao

An inventory of the resources in Yuqiao-reservoir was made by Spohn & Lu et. al. (2008) with focus on locating the source of eutrophication. Table 2.7 gives the result of the analysis of nutrients in manure.

Table 2.7 Average concentration of contaminants in waste of livestock and poultry (kg/ton), from Spohn & Lu et. al. (2008)

Animal		COD	BOD	NH_3-N	TP	TN
Cattle	Manure	31.0	24.53	1.71	1.18	4.73
	Urine	6.0	4.0	3.47	0.40	8.0
Pig	Manure	52.0	57.03	3.08	3.41	5.88
	Urine	9.0	5.0	1.43	0.52	3.3
Sheep	Manure	4.63	4.10	0.80	2.60	7.5
	Urine	No record	No record	No record	No record	14.0
Chicken's manure		45.0	47.87	4.78	5.37	9.84
Duck's manure		46.3	30.0	0.80	6.20	11.0

Table 2.8 represents the daily production of organic waste in Dajugezhuang and gives the possible mixture in the biogas reactor.

Table 2.8 Evaluation of the volume of organic waste in Dajugezhuang

Type	Yield [tons/day]	%
Fresh Manure of animal	11.55	73.9
Fresh Manure of people	1.72	11.0
Straw	1.44	9.2
Kitchen garbage	0.92 (0.8 kg per person)	5.9
Total	15.63	100

Methane production and C:N-ratio is essential to the biogas production. The values vary a lot depending on the fodder given to the animals, in Table 2.9 some values are presented.

Table 2.9 from Carlsson & Uldal (2009)* and Spohn & Lu et. al. (2008)**

Substrate	**C:N***	**m^3CH_4/ton VS***	**TS** % [gTS/gww[1]]**	**VS** % [gVS/gww[1]]**
Cattle manure + urine	6-20	213	9.3	7.5
Swine manure + urine	5	268	13.5	11.1
Chicken's manure	3-10	247	25.3	18.4
Average manure	-	-	14.5	12.3
Straw	90	207	78[1]	71[1]

ww – waste water

Given the data in Table 2.8 and 2.9 and assuming that only manure and straw is digested, a maximum possible manure:straw-ratio can be calculated:

$$Manure{:}Straw = \frac{VS\ in\ manure}{VS\ in\ straw} = \frac{11.55 \cdot 0.123}{1.44 \cdot 0.71} = 1.4 = 1.4{:}1$$

A maximum Manure:Straw-ratio of 1.4:1 with respect to VS is found.

However, the collectable amount of straw is probably the limiting factor and therefore a lower ratio must be chosen. 3:1 represents 25% straw as VS and this is about half of the total straw and can be assumed to be collectable.

It should be noticed that 25% on VS-basis represents only 6% on a wet weight basis, thus 60 g straw is added for every 1 kg of total substrate.

The ratio between carbon and nitrogen was introduced in chapter *2.5.2 C:N-ratio and Benefits of Co-digesting Manure with Straw*. If values from Table 2.9 are applied, the C:N-ratio obtained by adding 25% straw to the reactor is 26:1.

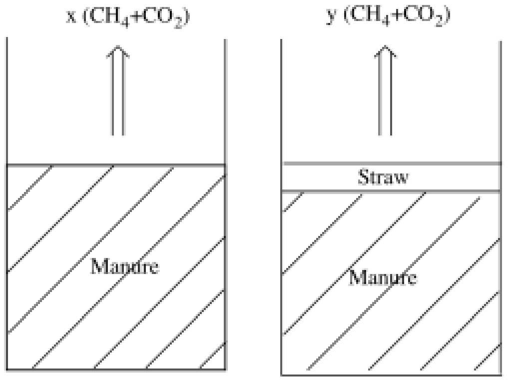
"25% straw and 75% manure on VS basis gives a C:N-ratio of 26:1"

2.7.6 Climate in Yuqiao

It has been reported that cold temperatures during winter leads to insufficient or no biogas production in the Yuqiao-reservoir area. Temperature is a crucial parameter to the methane formation. It has been reported that lowering the temperature from 37°C to 33°C gives 9% less methane yield (Linné et. al., 2008). Bohn et. al. (2007) have reported that low-cost systems operating at temperatures below mesophilic conditions (32-42°C) show stabile digestion of manure down to 11°C but with optimal methane yield at 30°C. However the degradation achieved is lower and the required retention time longer. If carbon is present in the form of fat, the process is less sensitive to temperature changes than if carbon is present in the form of carbohydrates, suggesting that temperature can have a large influence when co-digesting manure with straw and that it might be suitable to digest straw in the summer only (Bohn et. al., 2007).

2.7.7 Hypothesis and Desired Effect

The project aims to investigate if co-digestion with straw can decrease the COD removed as biogas (assumed to be only CH_4 and CO_2)



$$y(CH_4 + CO_2) - (CH_{4,straw} + CO_{2,straw}) \geq x(CH_4 + CO_2) \qquad [2.10]$$

$y(CH_4 + CO_2)$ – gas production from co-digestion of swine manure with straw
$x(CH_4 + CO_2)$ – methane production from digestion of only swine manure
$CH_{4,straw} + CO_{2,straw}$ – theoretical gas production from straw

The value for the digestion of straw could be obtained from the literature as biochemical methane potential (BMP) or calculated from an elementary analysis using Bushwell's formula [2.5] [2.6]. Analysis of VS-reduction and COD-reduction provides the answer to the postulated question if co-digestion with straw can increase the biogas production and thereby give an increase in the reduction of COD.

The hypothesis is that addition of straw to the reactor will significantly reduce the amount of COD compared to the control experiment where only manure is digested.

2.8 Benefits of Biogas

Biogas has a major advantage over other fuels as it is derived from a waste source. It is essentially a byproduct in a waste management process and as such a "free lunch". But biogas production is not the only alternative for the waste sources and the biogas production does not degrade everything in the waste, a residue is left that has to be managed.

2.8.1 Other Options – Composting

Compost has a low nutrient content and is used because of its amending properties, it gives texture to the soil through the high content of organic matter. Compost can also increase water capacity, pH and cat ion exchange capacity in the soil. (Tambone et. al., 2010)

Essentially composting is a net energy user whereas anaerobic digestion (AD) is a net energy generator if the methane is taken care of. However, the investment in a biogas production plant is large. A Life Cycle Analysis (LCA) on the performance of different ways to treat organic household waste showed that AD was the method of choice over composting, incineration and a combination of digesting and composting, both in ecological and economical terms. This is due to the energy balance of AD. (Mata-Alvarez et. al., 2000)

2.8.2 Bio-manure

If post-treatment to reduce water content and the amount of volatile fatty acids of the residue from biogas production is executed, the byproduct can be used as a bio fertilizer, so called bio-manure. Sometimes the residue could need to be hygienized, especially if the process is not in the thermophilic range of temperatures. (Mata-Alvarez et. al., 2000)

Manure treated in an anaerobic digester makes the nitrogen more accessible to plants and this leads to lower amounts of run-off, and hence lower eutrophication, and a better utilization of the manure. In organic farming mineral fertilizers are not allowed and a bio-manure has to be produced. This can be done through anaerobic digestion of clover leys. The production of the bio-manure is accompanied by biogas production and this byproduct can be utilized to produce electricity and/or heat. (Held et. al. 2008)

Furthermore, when manure is used as a fertilizer directly its release of CH_4 and N_2O is much greater than if the manure is digested anaerobically. Hence, even though the biogas would be flared the production would lead to a decrease in the production of greenhouse gases. Losses of methane are much smaller when the manure is digested first than if used fresh. (Held et. al. 2008) Anaerobic digestion of manure as a treatment method is utilized in the area around the Yuqiao-reservoir mainly because it is an effective way to manage the manure and stop the eutrophication of the important water reservoir (Spohn & Lu, 2008).

2.8.3 Clean Vehicle Fuel

When methane is burnt in a vehicle engine, particles in the exhaust gas is much lower compared to exhaust gases from a vehicle using diesel or gasoline. This makes biogas an excellent fuel to use in the Chinese cities since pollution from particles manly created by traffic makes the Chinese cities some of the most polluted in the world.

If biogas is produced from crops a vehicle can reach further than if another biofuel is produced from the same crop. (Raninger, 2011b) However, methane is a gas and storage and transport is not as easy as with liquid fuels.

2.8.4 No or little competition with food crops

The discussion of how to produce biofuels without competing with the production of food is very serious. Biogas is largely produced from residuals and in many cases unwanted byproducts or waste. The benefit of taking care of these waste fractions by anaerobic digestion is not only that the waste-problem is being tackled in an efficient way, but also that a product is being created. Biogas production is simply turning shit into benefit.

2.8.5 Reduces Greenhouse Gas Emissions

According to Mata-Alvarez (2000) AD of MSW releases less greenhouse gases (GHG) than any other treatment option. As an example of the additional energy generation from a biogas plant, the authors uses a plant treating 15 000 tons/year of organic fraction MSW. This plant needs 0.75 GWh/year to be run, whereas the net generation from the plant is 2.40 GWh/year.

3. Experiments for Testing Biodegradation

The experiments for testing the biodegradability include preparatory analysis of the substrate, an anaerobic degradation experiment that can be carried out in batch reactors or flow reactors, and analysis of the degraded digestate.

Guwy (2004) reviewed the existing technology for testing anaerobic biodegradability. Both gasometric methods and methods analyzing the substrate consumption and product formation were reviewed.

3.1 Preparation and Substrate Analysis

The inoculum can be collected from an existing biogas plant with similar conditions to those in the experiment. Larger particles should be sorted out and the inoculum should be incubated for 3-7 days in the same temperature as the experiments are to be carried out in. This is to ensure degradation of the majority of the organic matter still in the inoculum and is done to minimize the error in the measurements. The inoculum can be homogenized by shaking the bottle for several minutes before distributing the inoculum to the batch reactors. The inoculum must not be frozen and long exposure to oxygen should be avoided. (Carlsson & Schnürer, 2011)

Substrates should be collected in a large amount and later be homogenized to give a representative picture of the actual constitution (Hansen et. al., 2004). Substrate may be frozen (Hansen et. al., 2004), but this could lead to pre-treatment due to lysis of the cell membranes and increase the biogas production (Carlsson & Schnürer, 2011).

Straw can be cut down to 2-5 cm so that the liquid can cover them. This should not have a pre-treatment effect as straw would have to be cut down to a few mm to be considered as pre-treated (Wang et. al. 2009).

Volatile Substance (VS) analysis can give an indication of the amount of degradable matter in the substrate and is helpful when designing the organic loading rate (OLR) for the experiment. VS-analysis for the inoculum should be performed before the incubation time to mimic the OLR at the reactor from where it is taken.

VS is defined as

$$VS = TS - Ash \quad [3.1]$$

TS – Total Solid after dewatering in 105°C for 20 hours
Ash – Amount of ash left after incineration in 550°C for 2 hours

Volatile substances such as fatty acids and alcohols may be evaporated during the drying of the substrate and lead to a slight underestimation of the organic content when determining the VS-content. (Carlsson & Schnürer, 2011)

C:N-ratio is an important parameter in biogas production and useful to analyze. If the effect of co-digestion on the C:N-ratio is investigated, it is naturally necessary to carry out. This also gives the possibility to design the experiment so that the results can give suggestions on the optimal C:N-ratio for digestion in large scale. (Carlsson & Schnürer, 2011)

Protein/Fat/Carbohydrates analysis makes it possible to calculate a theoretical methane potential using Bushwell's formula [2.5] [2.6]. The theoretical potential can be compared with the actual result to determine the degradation of the substrate. This analysis also makes it possible to determine the possibility of system failure due to overload of compounds that are toxic to the process, such as ammonia and fatty acids. (Carlsson & Schnürer, 2011)

Batch experiments should be carried out using 0.1-2 dm^3 bottles with an organic loading rate (OLR) of 0.5-3 g VS substrate/ dm^3 liquid volume and twice as much inoculum as substrate. This is to mimic the conditions in a biogas plant. The substrate should be mixed with untreated tap water to reach the desired volume of approximately 25% of the bottle volume. All experiments must be carried out in triplicates due to the insecurity in biological experiments. (Hansen et. al., 2004) (Carlsson & Schnürer, 2011) Two reference experiments should be carried out. One with only water and inoculum, and one with cellulose added. The first experiment is called a blank and this experiment is performed to determine the methane production from the inoculum. The second experiment is a control experiment and is done to evaluate the quality of the inoculum. The inoculum is evaluated according to that the methane production from cellulose should reach 70% of the expected value 415 Ncm^3 CH_4/g cellulose. If the methane production from the cellulose is lower than this value, it is recommended that the experiment should be discarded due to the bad quality of the inoculum. (Carlsson & Schnürer, 2011)

3.2 Gasometric Methods

After the initial analysis and preparation it is time to seal the bottles and measure the biogas production.

Gasometric methods are used to determine the Biochemical Methane Potential (BMP). The methods presented in the literature to obtain the ratio between CO_2 and CH_4 are different ways to analyze the product gas and together with chemical analysis of the amount of volatile substance (VS) in the substrates, a BMP [Nm^3 CH_4 /kg VS] can be obtained.

Essentially five different ways to analyze the gas content exists (Carlsson & Schnürer, 2011)

1) **Analysis with a gas bag**
   This method uses a bag to collect the produced gas and decide the volume produce. Gas samples can be taken from the bag to analyze the methane content.

2) **Analysis with NaOH**
   This is a simple and uncertain method that uses the fact that CO_2 is soluble in a solution of NaOH in water and methane is insoluble. The gas is led from the reactor to a bottle containing water and NaOH. The CO_2 is scrubbed and stays in the solution and the gas now containing very small amounts of other gases than methane could either be led to another bottle where the amount of methane can be measured with the water replacement method or with a pressure meter. Another method is to just let the pressure of methane replace the NaOH solution and collect the amount replaced, this could however lead to insufficient amounts of solution to scrubb the CO_2.

3) **Pressure test and gas analysis**
   In this method pressure is measured with a syringe needle that is connected to a pressure meter. After this is done a sample of the gas is taken and the methane content is analyzed. Overpressure is released after this using a gasbag or a water trap to prevent air from entering the reactor.

4) **Sampling at overpressure**
   This is a method that takes some practice to get right. A gas sample of a known volume is taken at overpressure using a syringe with a pressure lock. The amount of methane is analyzed and, using the gas law, the pressure in the reactor can be decided. After the release of overpressure another gas sample is taken and analyzed and the quantity of methane can thereafter be decided.

5) **Online measurement**
   This tool is very convenient but often expensive. It can be applied directly on the reactor to measure the gas production in real time, as the gas is produced.

3.3 Substrate Consumption and Product Formation Method

A way to detect an increase in anaerobic biodegradability is to measure the content of organic matter in the substrate before and after the degradation. This can be done analyzing Chemical Oxygen Demand (COD) and VS before and after degradation.

3.3.1 Measuring the Carbon Reduction

Chemical Oxygen Demand (COD) uses a strong oxidizing agent, such as potassium dichromate ($K_2Cr_2O_7$), to fully oxidize all organic compounds to the end products CO_2, H_2O and NH_3. This method is often used when determining the amount of organic matter that can be degraded in water and as a consequence consume oxygen in the water (Spohn & Lu et. al., 2008). To monitor the COD is thereforee beneficial in the Yuqiao-reservoir case.

$$C_nH_aO_bN_c + \left(n + \frac{a}{4} - \frac{b}{2} - \frac{3}{4}c\right)O_2 \rightarrow nCO_2 + \left(\frac{a}{2} - \frac{3}{2}c\right)H_2O + cNH_3 \quad [3.2]$$

If dichromate is used, it does not oxidize ammonia into nitrate. The nitrification can therefore be ignored in the standard chemical oxygen demand test. (Wikipedia, 2012)

Total Organic Carbon (TOC) is a very quick method to determine organic carbon in a water sample. Its speed and low detection limit makes it suitable for on-line detection of contaminants in drinking water. In this report TOC is used to determine the C:N-ratio because the definition of C:N-ratio demands it. It could also be used to evaluate the reduction of carbon.

Lignin is not degradable in the anaerobic process but a part of VS (SIS, 2004) (Carlsson & Schnürer, 2011). Thereforee knowledge of the amount of lignin in a substrate is useful. The values of lignin in different substrates are well covered in the literature and thereforee additional analysis of lignin has not been included in this report.

Intermediates, end products and the activity of different enzymes can be measured with specific methods. This gives good monitoring of the entire process and gives the opportunity to detect unwanted or assumed behavior during the process. The methods specificity usually makes them expensive. (Guwy, 2004)

3.3.2 Method of Choice

COD is chosen as the detection method due to its frequent use in water pollution situations. It is also assumed to be the cheaper method of the two. The method has to be the same for the substrate and the digestate to be comparable.

4. Method

4.1 Batch Experiments

Experiences from lab scale batch reactor experiments indicate that trends and correlations are to be sought, rather than exact values for biochemical methane potential (BMP) (Bohman et. al., 2011). As this project aims to improve the production in existing biogas reactors it is more valuable to show these trends rather than decide the exact BMP, as the reaction parameters will never be the same as in a controlled laboratory environment.

It was unfortunately not possible to use any of the gasometric methods described in chapter *3.2 Gasometric Methods* due to practical issues at the laboratory at Tianjin Academy of Science and a substrate consumption method was chosen instead, as described in chapter *3.3.2 Method of Choice*.

4.1.1 Inoculum

Inoculum was collected from two different biogas plants in Dajugezhuang by the Yuqiao-reservoir. Before use the substrates were stored in an ice-box to minimize the degradation of COD. It was not possible to visit the Yuqiao-reservoir one more time to collect substrate just before the experiments. Since BMP would not be determined during the experiment this was assumed to have little effect on the sought result.

The inoculum was incubated in plastic containers in a water bath at 37°C for 7 days before VS and TS were measured.

4.1.2 Substrate

The two reactors described in chapter *2.7.1 Large Farm* and *2.7.3 Small Farm* were chosen to represent all of the reactors. Substrate was collected from these two reactors and mixed to give a representative substrate for Dajugezhuang.

The experiments were carried out in triplets because they are characterized by uncertainties. The temperature for the digestion experiment was chosen to be 37°C due to that digestion occurred at mesophilic temperatures around Yuqiao-reservoir. Straw was added to the manure with 25% of VS from the recommendations from Spohn & Lu et. al. (2008) to see if co-digestion would give a significantly greater reduction of COD.

The manure was kept at around 0°C during the incubation period for the inoculum and TS and VS were measured after 7 days.

The following chemical analyses were performed on the substrate:

- Total Solid (TS), Swedish standard SS-028113
- Volatile Solid (VS), Swedish standard SS-028113
- Chemical Oxygen Demand (COD), Chinese standard GB11914-89
- Total Organic Carbon (TOC), Chinese standard HJ 615-2011
- Total Nitrogen (TN), Chinese standard GB11894-89

The following chemical analysis was performed on the digestate after reaction:

- Chemical Oxygen Demand (COD), Chinese standard GB11914-89

The reduction of COD will determine if the hypothesis is valid or invalid.

4.1.3 Chemical Analysis of Substrate and Inoculum

TS and VS were measured in accordance with Swedish Standards Institute's standard SS-028113 (SIS, 2004).

4.1.4 Preparation of Bottles

The bottles were prepared with each individual substrate, inoculum and tap water to obtain the chosen organic loading rate (OLR) of 2 g VS/L liquid for the substrate and 4 g VS/dm^3 liquid for the inoculum according to the recommendations by Carlsson & Schnürer (2011). Tap water should be used due to the lack of minerals in distillated water (Carlsson & Schnürer, 2011). After preparation the bottles were flushed with nitrogen gas and after that sealed with a rubber plug. A rubber tube was connected to each bottle with the outlet in a bucket of water to enable gas to get out of the bottle but prevent air from entering the bottle.

Picture 4.1, 9 bottles sealed with a rubber plug and with gas outlet in a bucket of water

The 9 bottles were sealed at Thursday 2012-03-29. During the biogas production period they were shaken an equal amount per day. Gas production could be seen during the shaking procedure. On Tuesday 2012-05-08, 40 days after the start of the experiment, the bottles volume were measured in a graduated cylinder and a representative amount was transferred quickly to a smaller bottle and thereafter stored at 4°C until analyzed.

4.1.5 Carbon Balance

The available carbon for biogas production is hard to decide, but the COD-test is assumed to quantify all the available carbon plus other compounds and also some unavailable carbon. A carbon balance can only be made if the total moles of carbon in and out are known. This requires that an elementary analysis is made on the substrates and the inoculum (consult [3.2], chapter 3.3.1). This report does not include such an analysis. However, assuming that the methane production is dependent on the COD-reduction, a qualitative analysis of the methane production can be made without knowing the elementary composition of the substrate.

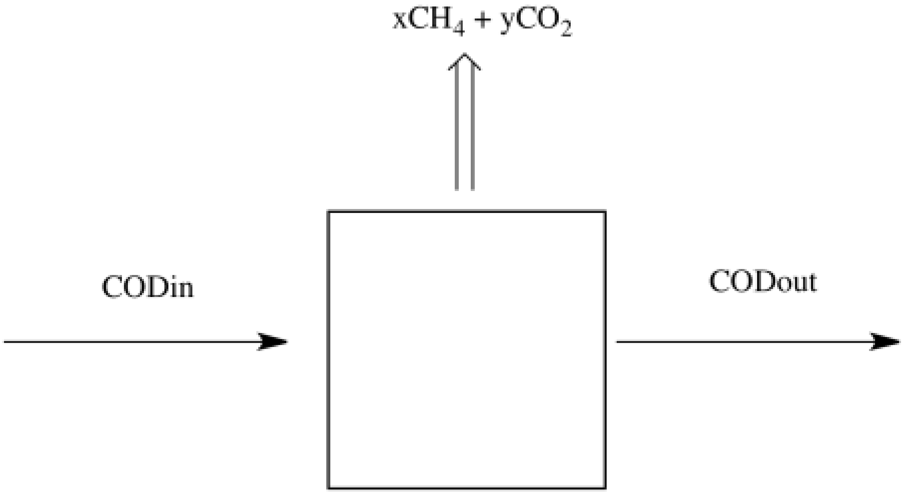


Figure 4.1, carbon balance for biogas production

$$xCH_4 + yCO_2 = C_{CODin} - C_{CODout} \quad [4.1]$$

5. Results and Discussion

Due to an accident during the experiments water from the air-trap entered some of the bottles. One of the water baths that kept the temperature at 37°C failed during the night and caused a negative pressure in the bottles, which led to that water entered through the tube that was kept in a bucket of water to prevent air from entering the bottles. Unfortunately the bottles with manure (bottles 4-6) all got water into them, and the bottles with straw and manure (bottles 1-3) did not. Water also entered bottles 8 and 9. It is hard to say what effect this has on the COD-reduction and therefore no certain conclusions can be made from the experiments. The OLR-values were still over 0.5 [g/dm^3], the lowest recommended value of OLR after the accident.

Table 5.1, OLR and the new volume after accident

Bottle	New volume [cm^3]	New OLR [g/dm3]
1	310	2.12
2	340	2.08
3	305	2.23
4	560	1.09
5	490	1.29
6	525	1.17
7	350	NA
8	530	NA
9	415	NA

5.1 VS and TS

TS and VS were measured in accordance with Swedish Standards Institute's standard SS-028113 (SIS, 2004).

Table 5.2, results from chemical analysis of TS, VS of wet weight (ww) and VS of TS

Substrate	TS of ww [%]	VS of ww [%]	VS of TS [%]
Inoculum	1.70	0.929	54.7
Manure	34.0	21.1	62.1
Straw	92.5	84.3	91.2

5.2 C:N-ratio

5.2.1 Calculation Procedure

The C:N-ratio was calculated using definition [Def 2.3]

$$C:N \equiv \frac{mass\ TOC}{mass\ TKN} \quad [Def\ 2.3]$$

The assumption that the total nitrogen (TN) determined by the Kjeldahl method is essentially equal to the TN determined by the Chinese standard GB11894-89, hence $mass\ TKN \approx mass\ TK$ is made so [Def 2.3] becomes:

$$C{:}N \approx \frac{mass\ TOC}{mass\ TN}$$

5.2.2 Result

The data from the chemical analysis of the substrate is presented in table 5.3.

Table 5.3, data from chemical analysis

Substrate	TOC [%]	TN [%]	C:N-ratio
Swine	35.30	2.49	14.18
Corn straw	52.60	2.14	24.58
Inoculum	25.50	2.25	11.33

5.2.3 Total C:N-ratio in Bottle

The total C:N-ratio in the bottle can be calculated using the C:N-ratio for each compound:

$$C{:}N - ratio = \frac{\sum_{i=1}^{n}(C{:}N)_i \cdot m(TS)_i}{\sum_{i=1}^{n} m(TS)_i} \quad [5.1]$$

Using bottle 1 as an example and with subscript 1 meaning straw, subscript 2 manure and subscript 3 inoculum we have:

$$C{:}N - ratio = \frac{(C{:}N)_1 \cdot m(TS)_1 + (C{:}N)_2 \cdot m(TS)_2 + (C{:}N)_3 \cdot m(TS)_3}{m(TS)_1 + m(TS)_2 + m(TS)_3}$$
$$= \frac{(C{:}N)_1 \cdot m_1 \cdot \%TS_1 + (C{:}N)_2 \cdot m_2 \cdot \%TS_2 + (C{:}N)_3 \cdot m_3 \cdot \%TS_3}{m_1 \cdot \%TS_1 + m_2 \cdot \%TS_2 + m_3 \cdot \%TS_3}$$
$$= \frac{24.58 \cdot 0.2268 \cdot 0.925 + 14.18 \cdot 2.2 \cdot 0.340 + 11.3 \cdot 133.8 \cdot 0.017}{0.2268 \cdot 0.925 + 2.2 \cdot 0.340 + 133.8 \cdot 0.017} = 12.85$$

The amount of nitrogen in the inoculum is very high and determines the overall C:N-ratio in the bottle. The explanation to the high amount of nitrogen in the inoculum is probably the fact that only manure is being digested in the reactors in Yuqiao.

Since ammonia is not oxidized in the dichromate method used to determine COD, a higher value of TN than the total amount of COD can be obtained in the chemical analysis (Wikipedia, 2012). The high TN-value is probably due to a lot of free ammonia in the digestate, even though this cannot be said certainly since no analysis of the free ammonia was made in this project. High ammonia is reported to inhibit the biogas production. The inhibiting effect of ammonia is reduced with decreasing temperature because of the lower content of free ammonia (Deublein & Steinhauser, 2008). The biogas reactors in Yuqiao operated at ambient temperature. During the experiment the temperature was increased from around 15°C to 37°C for the experiments.

According to Deublein & Steinhauser (2008, p. 124) the ratio between COD and nitrogen should be 5-6:1

Table 5.4, ratio between COD and TN

Bottle/Substrate	COD:TN
1	7.59
2	7.68
3	7.73
4	6.78
5	6.75
6	6.61
7 (Inoculum)	0.62
8 (Inoculum)	0.62
9 (Inoculum)	0.62
Straw	35.61
Manure	20.92

Ammonia inhibits the biogas process at concentrations of 2-3 g/dm^3 but is dependent on temperature and pH. Microorganisms can adjust to a somewhat higher level of ammonia and therefore ammonia inhibition must be compared from case to case. (Carlsson & Uldal, 2009)

Table 5.5, ammonium content and pH in manure (Deublein & Steinhauser, 2008)

Substrate	Ammonium nitrogen of TN	pH value
Manure from pig	70-72%	7.7-7.9
Manure from cattle	47-58%	7.8
Manure from poultry	85%	8.2

Spohn & Lu et. al. (2008) reported ammonium nitrogen levels of 52% of TN for the swine manure and 43% for the swine urine in Yuqiao and total amounts of 3.08 g/kg and 1.43 g/kg in manure and urine respectively.

Ammonia concentrations in the bottles are high, around the upper limit for a working biogas process. However, biogas was evidently produced in Yuqiao with the same manure. The increase in temperature during the experiments could have led to higher concentrations of ammonia in the batch experiments.

5.2.4 Result

As can be seen in table 5.6 the C:N-ratio does not vary according to the estimated values. Any effect of co-digestion could therefore be questioned and is probably not an effect of the increase in C:N-ratio.

Table 5.6, total C:N-ratio in each bottle

Bottle	C:N-ratio
1	12.9
2	12.8
3	12.8
4	12.2
5	12.2
6	12.2
7	11.3
8	11.3
9	11.3

5.3 COD-reduction

5.3.1 Calculation Procedure

The total COD for manure and straw was calculated using the TS-analysis and the COD-analysis of each substrate, and then divided with the volume due to the variable volume in the bottles:

$$Total\ COD =$$
$$= mass \cdot TS \cdot COD \left[g\ total\ substance \cdot \frac{g\ solid}{g\ total\ substance} \cdot \frac{g\ COD}{g\ solid} \right] \quad [5.2]$$

The COD-analysis for the inoculum is expressed as g/total liquid and must be calculated according to the following formula:

$$Total\ COD = Volume \cdot COD \left[L\ liquid \cdot \frac{g\ COD}{L\ liquid} \right] \quad [5.3]$$

The amount COD is expressed as g COD/L.

The density of the inoculum can be assumed to be the same as water, since the TS of the inoculum is 1.7%.

Bottle 1 is taken as calculation example, again subscript 1 denotes straw, subscript 2 means manure and subscript 3 means inoculum:

$$m_1 = 0.2268\ g$$

$$m_2 = 2.2\ g$$

$$COD_{1,tot} = m_1 \cdot TS_1 \cdot COD_1 = 0.2268 \cdot 0.925 \cdot 0.762 = 0.160\ [g\ COD]$$

$$COD_{2,tot} = m_2 \cdot TS_2 \cdot COD_2 = 2.2 \cdot 0.340 \cdot 0.521 = 0.390\ [g\ COD]$$

$$V_3 = 133.8\ mL$$

$$COD_{3,tot} = V_3 \cdot COD_3 = 0.1338 \cdot 13.9 \left[L \cdot \frac{g}{L}\right] = 1.86\ [g\ COD]$$

$$COD_{bottle\ 1} = \frac{COD_{1,tot} + COD_{2,tot} + COD_{3,tot}}{Volume\ liquid} = \frac{0.160 + 0.390 + 1.86}{0.310}\left[\frac{g\ COD}{L}\right]$$
$$= 7.77\ \left[\frac{g\ COD}{L}\right]$$

In total bottle 1 contains 0.160 g COD from straw, 0.39 g COD from manure and 1.86 g COD from the inoculum, a total of 2.41 g COD. The volume is 0.310 L and thus bottle 1 contains 7.77 g COD/L.

The standard deviation, s, was calculated using equation [5.4]

$$s = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(x_i - \bar{x})^2} \quad [5.4]$$

$x_i -$ $the\ value\ of\ sample\ i$

$\bar{x} - the\ mean\ value\ of\ all\ samples$

$N - amount\ of\ samples$

5.3.2 Result

The results for all 9 bottles are shown in table 5.7, where COD diff is the difference between COD before and COD after the experiment. Actual diff is the actual reduction of the substrate COD, subtracting the COD-reduction (0.134) from the inoculum given by bottles 7-9. The reduction is divided with the COD before value to display degradation as part of the initial COD value, this is due to the change in volume that accidently occurred.

Table 5.7, COD analysis

Bottle	COD before [g/L]	COD after [g/L]	COD diff	Actual diff *	Mean Value
1	7.77	6.10	0.215	0.082	0.124*
2	7.44	5.38	0.277	0.143	
3	7.91	5.69	0.281	0.147	
4	4.23	2.84	0.328	0.194	0.181*
5	5.02	3.74	0.255	0.122	
6	4.65	2.97	0.362	0.228	
7	5.24	4.87	0.070	NA	0.134
8	3.43	2.76	0.194		
9	4.38	3.78	0.137		

*After subtraction with 0.134, which is the COD-reduction from the inoculum

The final result is:

$$COD - reduction\ in\ inoculum = 13.4\% \pm 6.20\%$$

$$COD - reduction\ (with\ straw) = 12.4\% \pm 3.67\%$$

$$COD - reduction\ (without\ straw) = 18.1\% \pm 5.44\%$$

To see if the condition [2.10] is fulfilled, a theoretical biogas production from straw of $207\ \left[\frac{Nm^3\ CH_4}{ton\ VS}\right]$ can be used.

$$y(CH_4 + CO_2) - (CH_{4,straw} + CO_{2,straw}) \geq x(CH_4 + CO_2) \qquad [2.10]$$

$y(CH_4 + CO_2)$ – gas production from co-digestion of swine manure with straw
$x(CH_4 + CO_2)$ – methane production from digestion of only swine manure
$CH_{4,straw} + CO_{2,straw}$ – theoretical gas production from straw

However, since the COD-reduction was measured another approach has to be taken. Assuming that the methane production is proportional to the COD reduction, the variables are changed to

$$yCOD - COD_{straw} \geq xCOD \qquad [5.5]$$

$yCOD$ – COD-reduction from co-digestion of swine manure with straw
$xCOD$– COD-reduction from digestion of only swine manure
COD_{straw} – COD from straw added to the reactor

$xCOD = 18.1\% \pm 5.44\%$

$yCOD - COD_{straw} = 5.71\% \pm 4.10\%$

$5.71 < 18.1 \Rightarrow condition\ [5.5]\ not\ fulfilled$

The COD-reduction when subtracting the COD added from straw is smaller than the COD-reduction of only manure. Condition [5.5] is not fulfilled.

5.4 Discussion

The desired C:N-ratio was not obtained in the batch experiments and no conclusion from the co-digestion effect can be drawn. Due to the accident with water entering the bottles, any effect of co-digestion would be associated with great uncertainty. The experiments would therefore have to be performed again, but the time restrain on this project led to that this could not be concluded in this report.

Surprisingly low C:N-ratio

The manure contains much less nitrogen than manure and the corn straw used contains much more nitrogen than wheat straw as reported by Wang et. al. (2009). The high nitrogen content in the inoculum was also surprising (see table 5.3).

Table, 5.8 comparing with data from Wang et. al. (2009)

Parameter	**Wheat straw***	**Corn Straw****	**Swine manure***	**Swine manure****
TS (%)	92 ± 0.03	92.5	2.1 ± 0	34.0
VS (%)	86 ± 1.67	84.3	1.4 ± 0	21.1
Total COD (g/g-TS)	0.96 ± 0.01	0.762	0.97 ± 0.01	0.521
Total-N (mg/g-TS)	6.79 ± 0.10	21.4	107.55 ± 0.90	24.9
NH_4^+-N (mg/g-TS)	0.82 ± 0.02	NDa	87.09 ± 2.80	NDa
Total carbohydrates (% of TS)	48 ± 0.15	NDa	NDa	NDa
Lignin (% of TS)	20 ± 0.40	NDa	NDa	NDa

* Data from Wang et. al. (2009)
** Data from experiment
NDa = No Data

Furthermore, there is a big difference between different types of straw, which makes the characterization of the substrate very important.

Table 5.9, C:N-ratio in different straw from Wu et. al. (2010)

Straw type	Wheat	Corn	Oat
C:N	131	26.7	46.3

Due to that the analysis of the substrate and inoculum took a long time the assumption made was that the C:N-ratio in the inoculum would have a small effect on the total C:N-ratio for each bottle. This was shown to be false, the C:N-ratio in the inoculum has a great effect on the total C:N-ratio. However, this could not have been done differently since to keep the OLR at a reasonable level the added amount of straw and manure must be kept low. This makes it impossible to use inoculum with such a low C:N-ratio for a co-digestion experiment where the C:N-ratio has to be increased by a factor 2.

Ammonia inhibition

Bohn et. al. (2007) tried to mimic ambient temperature digestion and showed that biogas production can be kept stable if the temperature is slowly increased. This gives the microorganisms time to adjust to the new situation. The temperature in the biogas reactor where the inoculum was collected was kept at ambient temperature. During the incubation time the temperature was set at 37°C, approximately twice the temperature of the origin. This could have an effect on the microorganisms.

The free ammonium content increases with temperature. High ammonium content is known to have an inhibiting effect on biogas production.

6. Conclusions

The potential for biogas in China is huge. Agricultural residues and manure gives a farm-based potential of 1110 TWh and in the cities the potential is 339 TWh from MSW and wastewater. When producing biogas from agricultural residues and manure, eutrophication is reduced and the local air-pollution limited since the runoff of manure to watercourses is lowered and straw burnt directly in the fields is reduced. In the cities, MSW is becoming a bigger and bigger problem, biogas production is a way to solve this problem and at the same time produce a clean fuel for vehicles or electricity generation. Sewage sludge production can be reduced by instead of aerobic methods using anaerobic methods, and especially co-digestion with fish waste is expected to be beneficial. Anaerobic digestion of fish waste would add another 11 TWh to the Chinese biogas potential.

Due to the accident with entering water, the only lesson that can be learned from the experiments regarding the effect of co-digestion is that the inoculum must be adjusted for a period of time, where the C:N-ratio is successively increased by adding small amounts of straw to the inoculum. It is not possible to simply use the inoculum in Yuqiao, with a very low C:N-ratio, due to that the OLR has to be kept at a certain level. Alternatively, another source of inoculum could be used for the co-digestion experiments, although this inoculum could behave differently from the one in Yuqiao.

Co-digestion should lead to that the substrate is better utilized than if digested alone. This effect is not present in the experiments, but as discussed before no conclusion can be drawn from this.

Another conclusion is that the ammonia levels in the biogas reactor should be investigated in future research. Ammonia inhibition is probably limiting the amount of biogas being produced in the Yuqiao reactors. Measurements of the ammonia level in the reactor should be executed and the variation over the year should be analyzed.

Measuring the reduction in COD is less accurate than measuring the biogas production. It is therefore desired to do the experiments again with a gasometric method, measurement of ammonia concentration and pH analysis.

The quality of the 14 billion m^3 biogas China produces is questionable. The reactors around Yuqiao-reservoir produce biogas 8 months per year, compared to 11 months “on the paper”, and the rest of the year the temperature is seldom the desired 30°C, which is proven to give good biogas production. China has an ambitious target of 15% renewable energy in the energy system 2020 and takes great pride in achieving this target. An investigation of the ammonia levels and the efficiency of the farm reactors should be of interest to anyone who has an interest in if the biogas part of the renewable energy generation target really is achieved.

Part 2 - Economical Feasibility Analysis

1. Introduction

1.1 Present Situation

The question of how to make biogas feasible in China has been postulated and this brief economical feasibility analysis will seek the answer to that question.

The construction of biogas plants in China has since long been driven by government investment subsidies. This has led to a major boom in the number of plants and since the 50s over 30 million plants have been built producing an estimated 14 billion m^3 of biogas. Most of these reactors are small household reactors and the main driving force has been manure management. Anaerobic digestion is a good way to treat effluents from animal husbandries. During the first ten years of the 21st century more biogas-driven investments led to an increase in the amount of larger biogas plants. (Raninger et. al. 2012)

A different approach than investment subsidy is to subsidies the products delivered by the biogas plants and thus creating a market-based economy for biogas. By subsidizing electricity produced by biogas, compressed bottled biogas (CBG), biogas delivered to the natural gas grid and bio-fertilizers produced from the biogas residue, biogas plant operators receive an incentive to run their plants as efficient as possible and produce as much product as possible to a minimized price. By instead subsidizing investments, the government has created a large amount of insufficiently operating plants. Many parties have noticed this (see for instance Raninger (2012) and Dicke (2010)) and especially the German biogas sector are driving the development towards market-based mechanisms.

1.2 Opportunities

There is an ever-growing demand for renewable energy in China. New investment in renewable technology reached 33.7 billion USD in 2009, more than anywhere else in the world. But most of this was invested in wind and solar, only 3 billion was invested in biomass projects of varying kinds. (UNEP, 2010) At the same time, biomass resources are vast in the rural areas where grid connection is a problem and in the urban areas the waste problems are becoming more and more serious. Biogas can be produced from manure and straw in rural areas and lead to an improved air and water quality, and less reliance on fossil fuels. In the urban areas biogas can be produced from municipal solid waste (MSW) and sewage sludge, and thereby reduce the amount of organic material put in landfills.

Private investors have increasing opportunities to enter the Chinese biogas market, as advanced environmental standards will force medium and large scale livestock farms to invest in environmental technology. (Xin, 2007)

2. Products

Anaerobic digestion (AD) of biomass can essentially give four products:

1. **Bio fertilizer**, from the digestate also called the biogas residue
2. **Electricity**, by burning the biogas and producing electricity in a turbine
3. **Heat**, by burning the biogas and using the heat
4. **Bio methane**, which is obtained after upgrading the biogas to a certain amount of methane

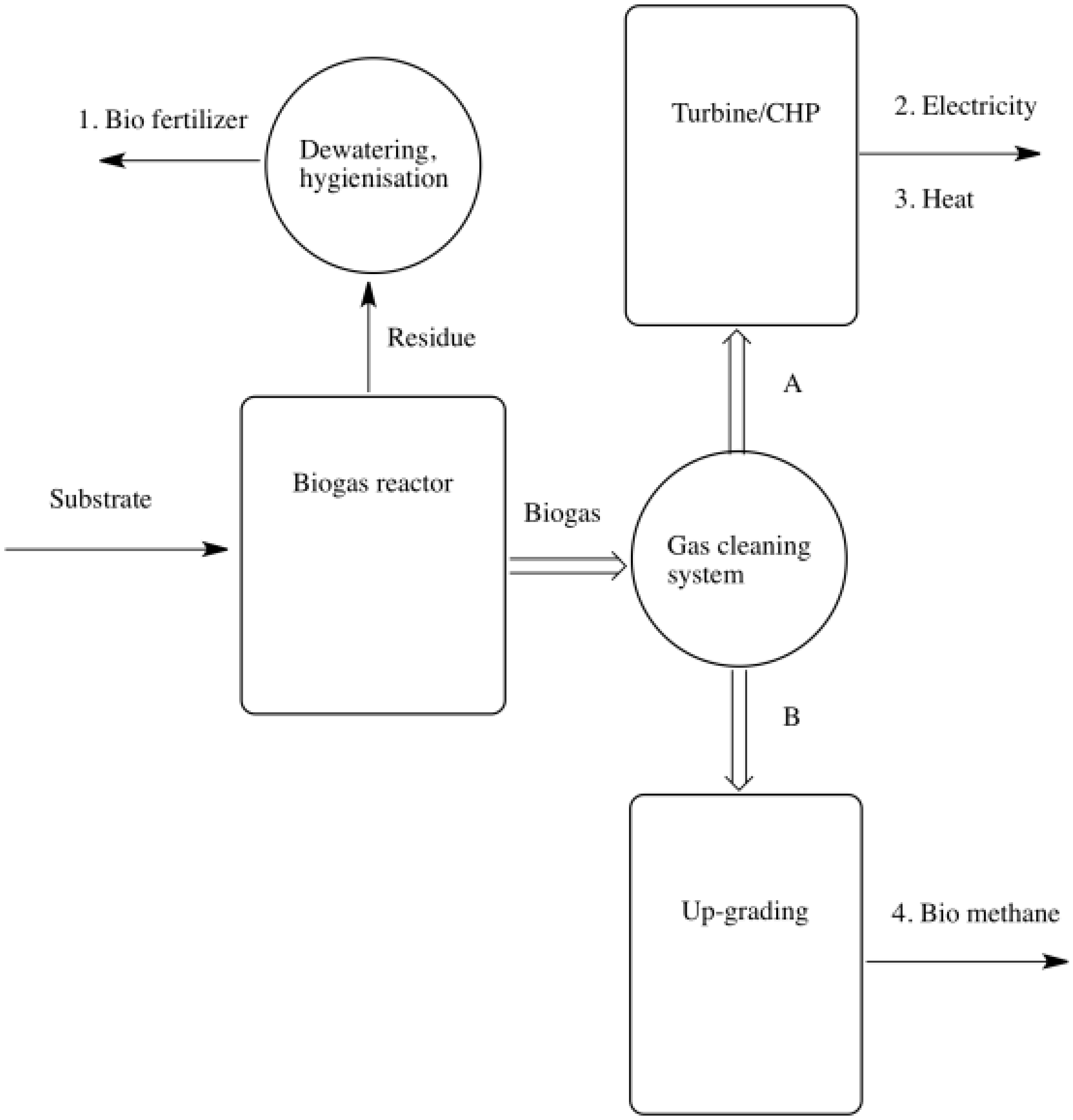


Figure 2.1, products from anaerobic digestion (AD)

After biogas is produced there are two pathways that the gas can follow, A or B in figure 2.1. Producing electricity and heat in a Combined Heat and Power plant (CHP) is the easiest alternative to utilize the energy in biogas. The heat to power ratio is around 1.2-1.8:1, thus if a plant produces 5 MW electricity it also produces 6-9 MW of usable heat (DECC, 2012 and UNFCCC, 2011e). This alternative omits pathway B. If the gas is to be sold as fuel gas for cars or injected to the natural gas grid, the biogas has to be upgraded to meet certain criteria from the purchaser of the gas, such as methane and water content (see chapter *5.5.3 Demands on Gas Producers*), and has to follow pathway B. The quality of the bio fertilizer has to be guaranteed and depend on the quality of the substrate. If municipal solid waste (MSW) is used as substrate, the bio-manure might contain heavy metals and other contaminants that makes it unsuitable as a fertilizer.

3. Biogas Production in China - Status to Date

The Chinese State has for a long time supported biogas in small scale for farmers in rural areas and only 2% of the total capital invested in biogas from 2003-2005 was invested in large and medium-sized biogas projects. (Li & Ma et. al., 2009) This is probably due to the lack of product orientation.

A co-operation between the German federally owned Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH and the Foreign Economic Cooperation Center (FECC) of China Ministry of Agriculture (MOA) is currently evaluating biogas production in China. GIZ's project Sino-German Project for Optimization of Biomass Utilization (SGPOBU) has identified five tasks that have to be dealt with to make biogas profitable in China (Raninger, 2012)

1. Increase the scale of the reactors, to gain scale benefits
2. Expand the substrate to include also non-breeding industries, today only breeding industries are included in investment subsidies
3. Improve gas yield, today mostly <0.5 m^3/m^3 reactor,day compared to Germany 1.2-1.8 mostly due to digestion at ambient temperature
4. The end product must be subsidized, this includes subsidizing purification of biogas, fertilizer use and so on
5. Build a quality control system and punish poorly operated biogas projects

SGPOBU are running seven demo biogas plants to try different concepts and technologies, and covers different climate conditions. Most of the investments are provided by the owner themselves through loans from Asian Development Bank, and by the Chinese government through investment subsidies.

The project clearly emphasizes that the biogas market must move to a performance-based system of subsidies from the given situation with investment subsidies. Increasing the feed-in tariff for electricity produced by biogas, subsidizing bottled compressed biogas and bio-fertilizer is a better way to increase the biogas production. (SGPOBU, 2011)

Table 3.1, key-projects run by SGPOBU

Province/place	**Substrate**	**Investment Cost (million RMB)**	**Scope of Innovation**
Heilongjiang/Longneng	Bio-organic Municipal Waste, manure	73	Extreme cold, dry fermentation, co-digestion, grid injection
Jiangxi/Jiayu	Swine Manure	8	Upgrading of existing technology
Beijing/Deqingyuan	Straw and liquid effluent from another AD-reactor	150	Co-digestion with straw, fuel gas production
Shandong/Lunan	Chicken manure and sewage sludge	24	Centralized co-digestion
Henan/Beixu	Swine manure and flush water	34	Connection to e-grid, heat utilization by industry
Sichuan/Xingmu	Yak manure	30	Use of effluent to fertilize over used grasslands, centralized large-scale with 10 km collection radius
Inner Mongolia/Hulunbeier	-	72	-

A conclusion from the investigations made by SGPOBU is that projects without CDM-support are very sensitive to changes in prices of the products. A way to secure return on investment could be to use feed-in tariffs for biogas and ensure grid connection possibilities. This should be done by lowering the existing limit of 500 kW for connection to the electricity grid, to 150 kW. Support via CDM-credits is available until 2013 for China. (Raninger, 2012)

4. Investment Costs of Biogas Plants

To calculate the capital cost of a biogas plant in Sweden Roth et. al. (2009) used the Equivalent Annual Cost (EAC) with a discount rate of 6% and gave the year of depreciation to 15 years. In this report this will be called the "Swedish Scenario". Swedish biogas companies are faced with this reality and when looking to expand internationally they will compare an investment in China with this scenario.

In China a discount rate of 8% and 10 years life span for a biogas plant, which is used by several sources, have been used as benchmark values. (UNFCCC, 2011a) (UNFCCC, 2011b)

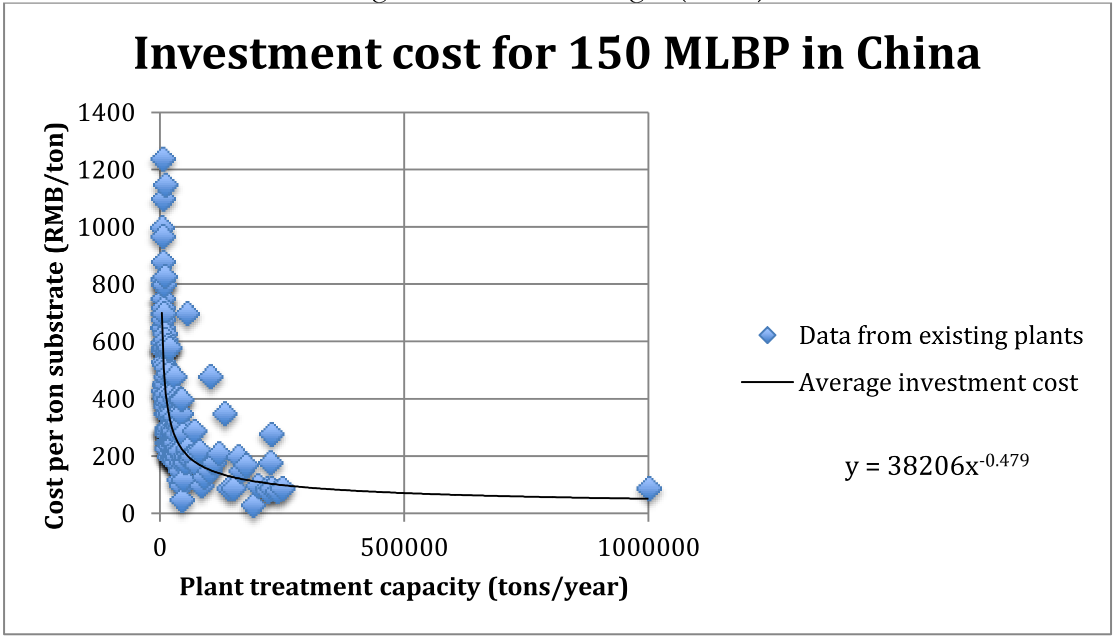
4.1 China

The investment cost per treatment capacity in China is clearly decreasing with increasing size of the plant and can be taken to be €30-€60 per metric ton of feedstock to the digester for a CSTR (Continuous Stirred-Tank Reactor). For additional electricity production the total cost of the plant can be taken as €1600/kW-€3300/kW installed electricity production capacity (Raninger et. al., 2012).

Per plant the central government of China subsidies between 25%-45% and usually 15% is the company's own responsibility (Raninger et. al., 2012).

The investment cost from 150 biogas plants is shown in figure 4.2. The cost varies a lot but the trend is clearly lower cost per treated substrate with larger treatment capacity.

Figure 4.2, from Raninger (2011a)



Six biogas plants have been used as case-plants using the investment costs given above and are presented in table 4.1.

Table 4.1, investment cost in China

Name	Investment biogas (only plant) [MRMB]	Installed power el. needed [MW]*	Electricity generation [MWh/ year]*	Heat generation [MWh/ year]*	Treatment capacity [tons/year]
Linköping	10.15	3.364	26640	31968	45000
Deqingyuan	13.46	1.732	13720	16464	77380
Tieling	9.02	1.062	8408	10090	35864
Bjuv	9.48	1.061	8400	10080	39500
Boxing	12.39	2.273	18000	21600	66000
Mengniu	11.87	1.360	10771	12925	60749

*Estimation based on the biogas production from the plant and not actual installed effect.

The CHP-unit constitutes 47-72% of the total investment in these cases.

4.1.1 Case Study - Beijing Deqingyuan Chicken Farm

The biogas plant in Beijing Deqingyuan (DQY) is one of few grid-connected biogas projects in China. This plant has two combined heat and power generators with 1064 kW electricity and 1200 kW heat installed. The plant delivers 14 000 MWh electricity annually. The reactor is of CSTR type and treats 212 tons of manure from 3 million chickens, and wastewater. The investment cost was expected to be 19 million RMB for the digester and 23 million for the power generation equipment, and the installation cost 7.745 million in 2008. The actual total investment cost for the project was a little higher than expected, 58.34 million RMB. The maintenance cost for the plant is 1.391 million RMB and other costs such as salaries, operation cost etc. is 2.666 million. (UNFCCC, 2011a) The biogas residue is used as liquid organic fertilizer for the farmers nearby who plant organic apple and organic grapes, covering an area of about 6.67 km^2. (Li, 2011)

Table 4.2, process items at DQY biogas plant

Items	Values
Process temperature	35°C-41°C
Reactor volume	2150 m^3
TS in feed	8.0%
HRT	17 days
OLR	4.0~4.5kg TS/m^3,day
Gas production rate	1.0 m^3/ m^3,day
Biogas output	18000 m^3/day

Table 4.3, data from the CHP Unit at DQY biogas plant

Name	Model	Biogas consum. (m^3/day)	Power electricity (kW)	Power heat (kW)	Electric efficiency	Heat eff-iciency	Total eff-iciency
Jen-bacher	JMS320 GS-B.L	10960 (60% CH_4)	1064	1200	40.8%	46.0%	86.8%

4.2 Sweden

Investment costs in Sweden vary a lot with location and substrate treated.

Figure 4.3 suggests that the CHP unit constitutes 35% (the green line) of the total investment cost for a biogas plant with electricity production of 500 kW electricity (the blue line). The pink line is the investment cost for the biogas facility and the blues line the total cost including 10% planning cost.

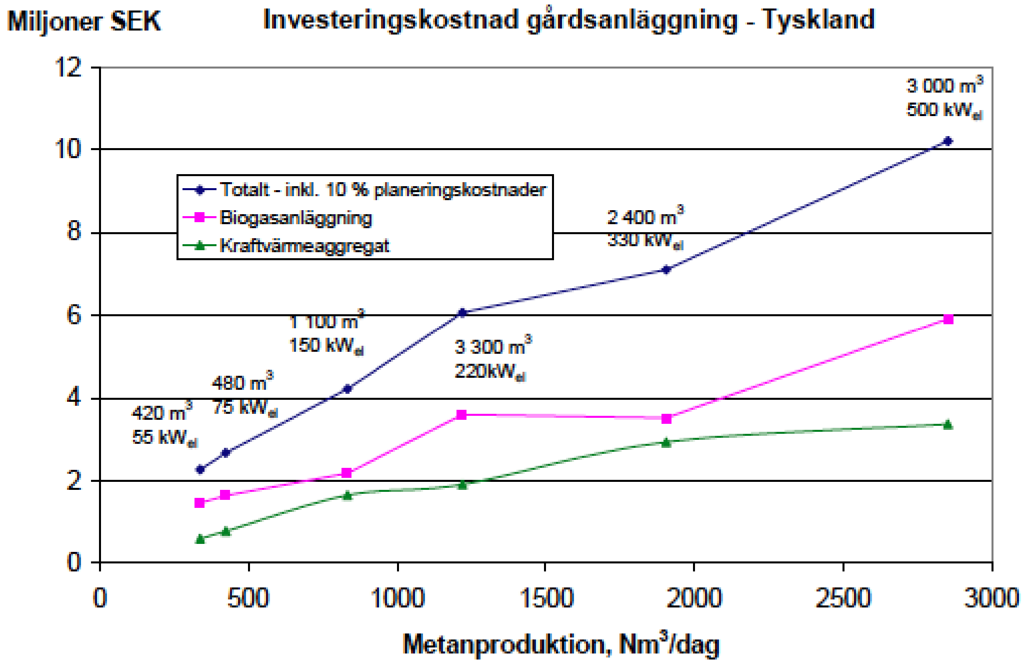


Figure 4.3, investment cost for farm based biogas plants in Germany (Held et. al., 2008)

5. Investment Areas for Biogas in China

5.1 Introduction

A report on successful cleantech cooperation in China found that Chinese companies want to see practical proofs that the product works in China. The decision makers in Chinese companies ranks "Cost breakthrough", "Technology innovation" and "Team/Management" highest when asked: How do you rate the importance of the following criteria when you assess potential western cleantech companies (The criteria are not shown). (Mahoney, 2012)

After investigations of the feasibility studies executed on CDM-credit (clean development mechanism) receiving projects with biogas production in China, it was found that fluctuation in sale revenues of the biogas has the largest impact on the internal rate of return (IRR) for the project. (UNFCCC, 2011a) (UNFCCC, 2011b) Raninger (2012) found that only 2 of 11 medium and large biogas plants are economically viable without support of CDM-credits, with the applied benchmark value for IRR of 8%. When performing a sensitivity analysis with the 3 scenarios: 10% cost increase (e. g. cost of technology), 10% benefit decrease (e. g. revenue of fertilizers), 10% cost increase + 10% benefit decrease, Raninger (2012) found that none of the projects investigated could reach 8% IRR. According to Raninger (2012), biogas production in China is not economically viable without CDM-credits with the existing situation.

According to Dicke (2010), the lack of economically feasible biogas projects in China is due to the low feed-in tariffs for biofuel projects. Dicke (2010) expects 200 MW installed biogas-to-electricity in 2015, from just a 12 MW 2009 (SGPOBU, 2010). However, in China's 'Medium and Long Term Program of Renewable Energy Development Plan 2006-2020' it is anticipated that 3 GW electricity produced by 16 000 medium to large biogas plants will be installed by 2020. So even though biogas is not economically viable, there are great plans of investing in plants.

Table 5.1, comparing the biogas markets. Partly from Dicke (2010)

Germany	China
Market driven biogas sector, energy and fertilizers are profitable	Environmental driven biogas sector, reduce smell and water pollution
Guaranteed payback due to feed-in tariffs and reliable technology	Governmental subsidies covers capital demand
99% of 4600 plants are grid connected, also small plants are connected	Less than 10 plants are grid connected, <500kW not grid permitted
6-7 years ROI for good plants	No ROI
1.6 RMB/kWh	0.75-0.518 RMB/kWh (0.631 mean value for all provinces) if feed-in tariff
Re-circular system and good yield leads to small transport cost	No circle system, feedstock is transported far. Low yield leads to large volumes of residue → even more transport
1740 MW electricity installed (2009)	12 MW electricity installed (2009)

This chapter is further divided into three parts to investigate how biogas production can be used to produce the four products in China:

1. **Bio-fertilizer**
2. **Electricity**
3. **Heat**
4. **Bio methane**

5.2 Bio-fertilizer

If hygiene requirements of the residue can be met, a bio-fertilizer with high amounts of nutrients can be produced. The fertilizer can be used on the farm or sold to nearby farms. Proper use of the residue has been found to be one of the keys to successful development of the biogas sector in China. (SGPOBU, 2010)

Bio-fertilizer can be sold at a price of 100-430 RMB/ton in China. (UNFCC, 2011a) (UNFCC, 2011c)

During the visit to the small-scale biogas plants around the Yuqiao-reservoir in Tianjin (as described in part 1, chapter *2.7 Rural Biogas Production - Yuqiao-reservoir*), China, it was found that the farmers use industrial-fertilizers out of convenience. Proper methods need to be applied to produce a high standard dewatered fertilizer from the biogas residue (SGPOBU, 2010). The small-scale farm reactors are not suitable for this kind of production, as dewatering takes a lot of energy.

5.2.1 Demands on Bio-fertilizer Producers

"Discharge standard of pollutants for livestock and poultry breeding (GB18596)" regulates the discharge of wastewater from animal farms but according to UNFCCC (2011d) there are no laws and regulations for the use of biogas residues as bio-fertilizer.

5.3 Electricity

5.3.1 Technology for Electricity Generation

When generating electricity from methane, methane is burnt to generate heat and this heat can be utilized in a gas turbine to produce electricity, or both electricity and hot water in a combined heat and power unit (CHP). The heat can also heat steam and power a steam engine. The chemical energy in methane can also be utilized in a fuel cell and this will give a much higher efficiency. By going through the literature (see UNFCCC, 2011a-c) it was found that the standard technology for producing electricity from biogas in China is a CHP-unit and therefore this technology will be used for further calculations.

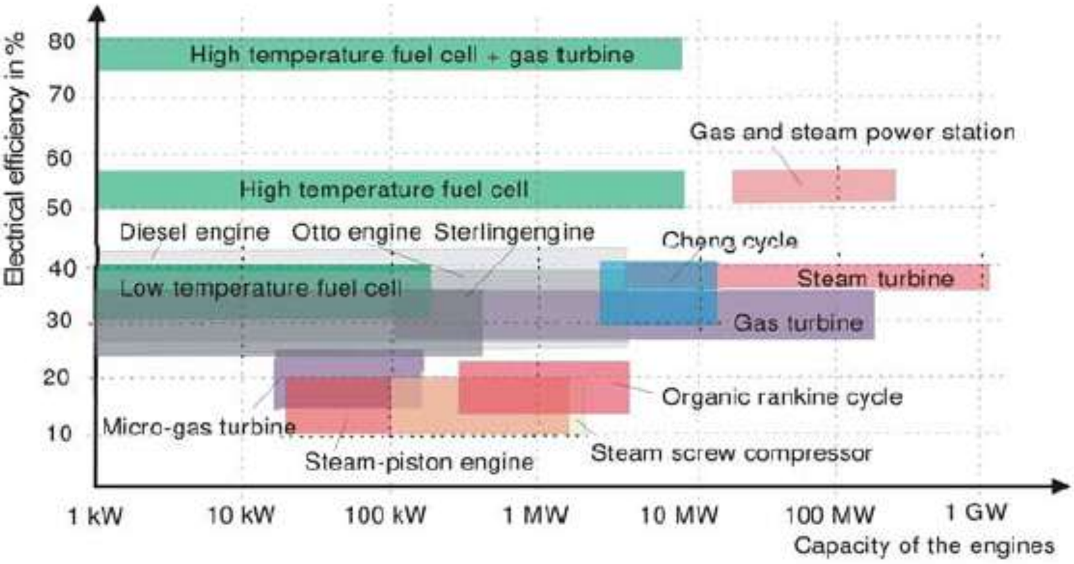


Figure 5.1 Efficiency of engines used for electricity production,
from Deublein & Steinhauser (2008)

5.3.2 Feed-in Tariffs and Tax Privileges

China's power industry has suffered a lot lately due to high coal prices. The electricity prices have not risen the same way the coal prices sky-highed in 2008 and this has reduced the profits for electricity production. An extra feed-in tariff for desulfurized coal has made installation of desulfurization technology beneficial and the recently applied feed-in tariff for electricity generated from renewable fuel has made use of solar power, wind power and biomass more beneficial. (Ma, 2011)

There were only three grid-connected biogas plants in China in 2010, with 1, 2 and 3 MW installed generation capacity respectively. Electricity generation from biogas is not popular in China due to that the power generated must be at least 500 kW to guarantee grid connection. (Raninger et. al., 2012) Furthermore, a feed-in tariff of 1 RMB/kWh is needed to gain viability in biogas production according to one estimation (SGPOBU, 2010).

The electricity prices in China are set after province and based on the "average social cost of power generation". The cheapest electricity is produced in Ningxia and the most expensive electricity in Guangdong province. (Ma, 2011)

Table 5.2 provincial electricity price, from Ma (2011)

Region	Province	2009 Nov [RMB]
West	Shaanxi	0.342
	Gansu	0.281
	Ningxia	0.268
	Qinghai	0.294
South	Guangdong	0.496
	Guangxi	0.436
	Guizhou	0.332
	Yunnan	0.33
	Hainan	0.44
Central	Hubei	0.425
	Hunan	0.44
	Jiangxi	0.422
	Henan	0.391
	Sichuan	0.394
	Chongqing	0.388
East	Shanghai	0.457
	Zhejiang	0.457
	Jiangsu	0.43
	Anhui	0.398
	Fujian	0.414
North	Beijing	0.381
	Tianjing	0.382
	Hebei (North)	0.386
	Hebei (South)	0.387
	Inner Mongolia (West)	0.285
	Shanxi	0.325
	Shandong	0.397
Northeast	Liaoning	0.39
	Jilin	0.376
	Heilongjiang	0.38
	Inner Mongolia (East)	0.299

By burning biogas directly in a Combined Heat and Power unit (CHP) electricity can be generated and sold. The heat generated can be used to keep the anaerobic process at a constant temperature, especially in the wintertime and to heat nearby buildings.

If the electricity is renewable an on-grid electricity tariff is applicable which has the following mechanisms (Ma, 2011):

- **Mandatory grid-connection**
  This mechanism requires grid companies to buy all electricity generated by renewable fuels. Article 14 in the Renewable Energy Law obligates grid enterprises to buy renewable energy from companies that have legally obtained

administrative license. They shall also provide grid-connection service for the generation of power with renewable energy. (PRC, 2006)

- **On-grid pricing**
  On top of the benchmark on-grid electricity tariff for coal-fired power plants a fixed amount is added to the price for renewable electricity that is connected to the grid, this applies for 15 years after the start of the project. For biogas this is 0.25 RMB/kWh first year and then decreasing with 2% per year if the substrate is manure (around 0.7 RMB/kWh in total depending on province) or a total of 0.75 RMB/kWh if the substrate is agro- and forestry-biomass waste (Raninger et. al., 2012). Another 0.1 RMB/kWh is received if the substrate is straw (Wang et. al. 2012).
- **Cost sharing**
  The additional cost for renewable electricity is shared by the end user through the feed-in tariff
- **Financial incentives**
  Tax concession consisting of three years without income-tax plus three years of taxation at 50% of the full income-tax

Table 5.3 Grid feed-in tariff and tax privilege for biogas power, from (Raninger et. al., 2012)

Substrate	**Power benchmark tariff**	**Power subsidy obligatory price for grid companies to pay if >500 kWh**	**Tax concession**
Livestock- and poultry waste	Provincial price of desulfurized coal (see table 5.2)	$0.25*0.98^x$ (x=0 for year 1, x=1 for year 2 etc.) RMB/kWh, for 15 years	No income tax year 1-3 50% income tax year 4-6
Agro- and forestry-biomass	a. 0.75 RMB/kWh b. For the approved project, the feed-in tariff requires approval c. Extra 0.1 RMB/kWh for straw*		If 70% of the feedstock is crop straw, husk and/or corn crop, 10% income is tax free

* Wang et. al. (2012)

The amendments to the Renewable Energy Law, effective since April 1 2010, further strengthens the obligations for grid companies to buy electricity produced by renewable energy sources.

5.3.3 Calculating the Income from Electricity Generation

To calculate the net present value of the income from biogas production equation [5.1] can be used

$$NPV_{el} = \sum_{t=0}^{N} \frac{R_{t,}}{(1+i)^t} \quad [5.1]$$

NPV_{el} – total income from electricity

R_t – Net income at time t

t – time in years

i – discount rate

The net income for a facility producing electricity from biofuel is based on the feed-in tariff for desulfurized coal. To this feed-in tariff an additional feed-in tariff applies, the feed-in tariff due to the use of biofuels and the total NPV_{el} is therefore

$$NPV_{el} = NPV_{coal} + FiT \quad [5.2]$$

NPV_{coal} – Total income from electricity produced from desulfurized coal

FiT – Feed-in tariff for electricity produced with biofuel

FiT decreases with 2% every year for 15 years,

$$FiT = \sum_{t=0}^{N} \frac{R_{t,FiT}}{(1+i)^t} \cdot 0.98^t \quad [5.3]$$

$R_{t,FiT}$ – Additional net income from feed-in tariff due to use of biofuel

and thus [5.2] becomes

$$NPV_{el} = NPV_{coal} + FiT = \sum_{t=0}^{N} \frac{R_{t,coal}}{(1+i)^t} + \sum_{t=0}^{N} \frac{R_{t,FiT}}{(1+i)^t} \cdot 0.98^t$$

$$= \sum_{t=0}^{N} \frac{R_{t,coal} + R_{t,FiT} \cdot 0.98^t}{(1+i)^t} \quad [5.4]$$

$R_{t,coal}$ – Net income from electricity production on basis of desulfurized coal

Equation [5.4] can be used to calculate the NPV of the income from electricity and be compared with the investment cost to investigate the profitability of the investment.

5.3.4 Desulfurization of Biogas

The H_2S in the biogas can cause problems in the turbine producing electricity and must therefore be reduced to 100-500 mg/m^3. H_2S forms SO_2 when combusted and corrodes metallic parts and can acidify the engine oil. The operating cost for a desulfurization tower is around 13 USD/1000 Nm^3 biogas. (Deublein & Steinhauser, 2008)

5.3.5 Demands on Electricity Producers

500 kW is the minimum power needed to sell the electricity generated to the grid.

The grid companies are required to buy electricity generated from renewable fuels.

5.4 Heat

When electricity is generated in a CHP-unit heat is cogenerated with a heat to power ratio of about 1.2-8:1, thus if a plant generates 5 MW electricity it also generates 6-9 MW of usable heat (DECC, 2012). This heat can be used to keep the biogas reactor at a constant temperature, this is essential when the ambient temperature drops in the winter or the low temperature will inevitably lead to process failure.

Hot water is used to heat buildings in the wintertime in China so theoretically heat can be sold as a product. However, the hot water cannot be transported long distances and this report assumes the only use for the hot water is heating of the plant.

5.5 Fuel Gas

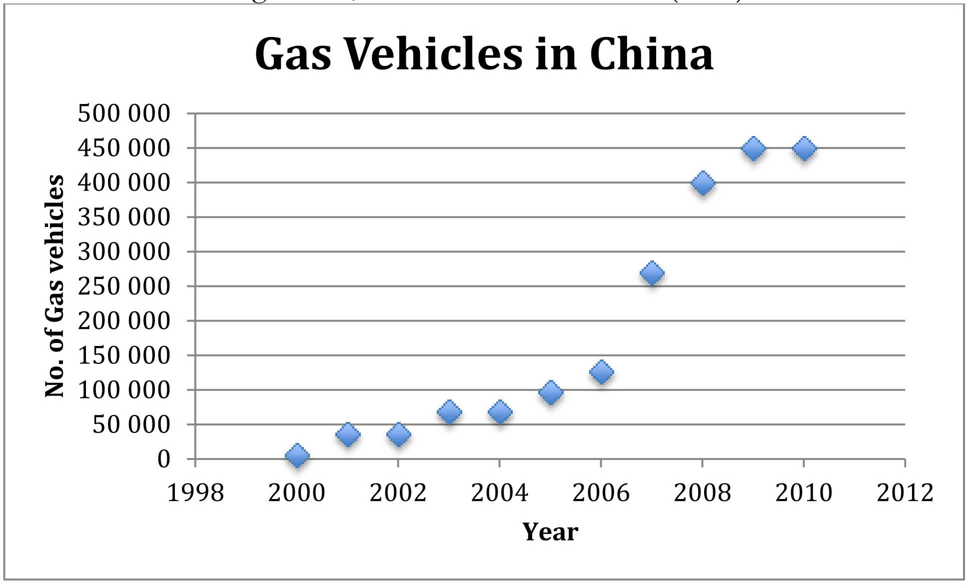
Sweden is seen as the leading country in the world when it comes to biogas powered vehicles (Cai & Tan, 2012). This would naturally give Swedish companies a good position to promote technology for upgrading biogas to fuel gas.

5.5.1 Gas Vehicle Demand

According to predictions, China's oil demand in 2020 will equal $5.6*10^8$ tons, when domestic production only reaches $1.9*10^8$ tons. The Chinese consumption of gasoline cars is predicted to stabilize in 2025 even though the car consumption increases and the increase will instead be constituted by electric and gas vehicles. (Cai & Tan, 2012)

The market for gas vehicles has grown fast in China the recent years (NGV Global, 2010).

Figure 5.2, data from NGV Global (2010)

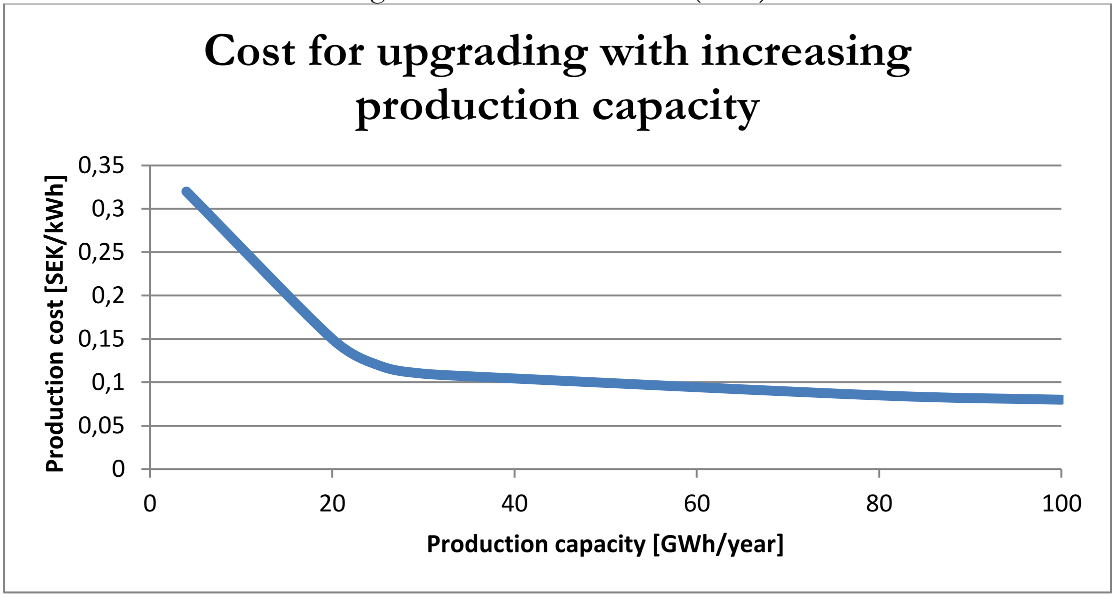


In 2010 China had 450 000 natural gas vehicles and 1350 filling stations (NGV Global, 2010). If a car can run on natural gas it is no problem to change fuel to biomethane, the upgraded biogas can be used in already existing filling stations to substitute natural gas.

5.5.2 Upgrading of Biogas

To produce fuel gas from biogas an upgrading unit is needed. This unit adds an extra investment cost to the biogas plant and this is only economically feasible if a certain production capacity is available in the biogas plant. It is true for Swedish biogas plants that if the plant produces less than 25 GWh biogas/year the production price/kWh of upgraded biogas decreases rapidly with the increase in production capacity of the plant, to stabilize and only slowly decrease after 25 GWh/year. (Roth et. al. 2009)

Figure 5.3 from Roth et. al. (2009)



The cost for the upgrading unit depends on the technology used. The operating energy demand varies from 0.12-0.25 kWh/Nm^3 upgraded gas. (Cai & Tan, 2012)

5.5.3 Demands on Gas Producers

Here the demands on biogas upgrading quality and testing methods of the gas for grid injection and vehicle fuel are presented.

Table 5.4, demands on biogas for grid injection, NSPRC (1999)

Item	Category One	Category Two	Category Three
Higher heating value [MJ/m^3]	>31.4		
Total sulfur [mg/m^3]	≤100	≤200	≤460
H_2S [mg/m^3]	≤6	≤20	≤460
CO_2 [%(V/V)]	≤3.0		-
Water dewpoint °C: Under the pressure and temperature of the natural gas dewpoint, the water dewpoint shall be 5°C lower than the lowest ambient temperature			
Note: The reference condition is P=101.325 kPa, T=20°C			
Note: The pipelines installed before the implementation of this standard, under the pressure and temperature of natural gas dew point, there shall be no free water in the natural gas, which means the natural gas could not be separated with free gas by mechanical separation.			

Table 5.5, standards regulating testing methods of gas quality, NSPRC (1999)

Item	Standard testing method reference
Higher heating value	GB/T 11062
Total gas composition	GB/T 13610
Total sulfur	GB/T 11061
H_2S	GB/T 11060.1
CO_2	GB/T 13610
Water dewpoint	GB/T 17283
Natural gas sampling*	GB/T 13609

* The sampling point shall be at the natural gas dewpoint stipulated in the contract

Table 5.6, demands on natural gas use as fuel gas, NSPRC (2000)

Item	Technical demand
Higher heating value [MJ/m^3]	>31.4
Total sulfur [mg/m^3]	≤200
H_2S [mg/m^3]	≤15
CO_2 [%V/V]	≤3.0
O_2 [%V/V]	≤0.5
Water dewpoint °C	Within a special geological area where vehicles are driven, and under the highest operating pressure, the waterdew point shall not be over -13°C; when the minimum air temperature is below -8°C, the water dewpoint shall be 5°C lower than the minimum air temperature.
Note: The reference condition is P=101.325 kPa, T=20°C	

Storage and Utilization of Gas Bottles (NSPRC, 2000):

1. The storage containers of compressed natural gas shall meet related regulations of the national existing Pressure Vessel Safety and Technical Supervision Regulations and Rules for Safety Supervision of Cylinders. The steel cylinders for compressed natural gas shall meet related regulations of GB 17258 Cylinders for Compressed Natural Gas as Vehicle Fuel. The gas can be compressed in CNG storage tanks under a pressure of 250 atm (Cai & Tan, 2012).

2. At operating pressure and temperature, compressed natural gas shall be free of liquid hydrocarbon.

3. The diameter of solid particles in compressed natural gas shall be below 5μm.

4. Compressed natural gas shall have perceptible odor. Odorless natural gas or natural gas with insufficient odor shall be odorized. The minimum quantity of odorizing agent shall meet that, when natural gas is leaked to the air and reaches 20% concentration of lower limit for explosion, the odor shall be perceptible. Odorizing agent is generally formulated with thio alcohol, thio ether or other organic compounds containing sulphur, and all of which have obvious odor.

5. When compressed natural gas as vehicle fuel is being used, its anti-explosion performance shall be taken into considerations. Appendix A in the standard *GB18047 – 2000 Compressed Natural Gas as Vehicle Fuel* presents the calculation method of Methane Number of natural gas.

6. When compressed natural gas as vehicle fuel is being used, its Wobbe index (Wobbe number) shall be taken into considerations. For compressed natural gas of each gas station of the same gas source, its type of fuel gas shall remain unchanged. Appendix B in the standard *GB18047 – 2000 Compressed Natural Gas as Vehicle Fuel* presents the fuel gas types of compressed natural gas.

Comparison with Swedish demands:

Table 5.7, Swedish demands on methane as vehicle fuel

Item	Demand, type A	Demand, type B
Wobbe index	44.7-46.4 [MJ/Nm^3]	43.9-47.3 [MJ/Nm^3]
CH_4 (Volume T=273.15K, P=101.325kPa)	97±1%	97±2%
Water dew point	At the highest operating pressure the water dew point shall be 5°C lower than the monthly mean value of the air temperature.	
Water content, max	32 [mg/m^3]	
CO_2+O_2+N_2 max volume	4.0%	5.0%
O_2, max volume	1.0%	1.0%
Total nitrogen (excluding N_2) as NH_3, max	20 [mg/m^3]	
Maximum particle size	1 μm	

6. Results and Assumptions

6.1 Basic Data

6 case-plants were introduced in chapter *4.1 China*. The case-plants are medium or large biogas plants in Sweden and China and are chosen to provide some fundamental data on treatment capacity, biogas production and installed electricity generation effect. The 6 plants form the base for the economic feasibility analysis. They are run differently and are not equally efficient, which is reflected in the different profitability.

Investment cost for the biogas plant, CHP-unit and upgrading equipment are given in the attached excel-file. In this file electricity prices and gas prices for each region in China, running cost etc. are also given. A user manual to the excel-file can be found in Appendix 3. The basic data for the 6 plants are given in table 6.1

Table 6.1, basic data from the 6 case-plants

Name	**No.**	**Treatment capacity [tons/year]**	**Electricity generation [MWh/ year]**	**Installed effect [kW]**	**Heat generation [MWh/ year]**	**Investment cost high [RMB/kW]****	**Investment cost low [RMB/kW]****	**Life span*****	**Fertilizer price [RMB/ton]**	**Fertilizer produced [ton DM/year]**	**Upgraded biogas (GWh/year)**	**Discount rate*****
Linkoping	1	45000	26640	3364	31968	27343	13257	15	100	4500	66.6	6%
DQY	2	77380	13720	1732	16464	27343	13257	15	100	7738	34.3	6%
Tieling	3	35864	8408	1062	10090	27343	13257	15	100	3586	21.0	6%
Bjuv	4	39500	8400	1061	10080	27343	13257	15	100	3950	21.0	6%
Boxing	5	66000	18000	2273	21600	27343	13257	15	100	6600	45.0	6%
Mengniu*	6	60749	10771	1360	12925	27343	13257	15	100	6075	26.9	6%

* No data for treatment capacity, so this is estimated using the DQY plant.
** Investment cost high and low is the reported investment cost for a biogas plant with a CHP-unit. Investment cost high gives the upper limit and investment cost low the lower limit.
*** The life span and discount rate are varied according to the "Swedish case" or the "Chinese case" as specified in chapter *4. Investment Costs of Biogas Plants*

6.2 Results

Using the model created in excel it is possible to compare different strategies in biogas production.

The prices vary a lot depending on the province, with the mean electricity price and gas price corresponding to the Beijing price. If this is a coincident or a political decision is beyond the author's knowledge, but it sure is interesting.

In Guangdong, a province in the south of China, the price of electricity and gas is much higher than in Beijing.

In the tables below the 6 case-plants are compared with the variables El/gas (electricity generation or gas production) and Guangdong/Beijing (the place of the plant). The Swedish scenario is used with 15 years life span and 6% discount rate.

Table 6.2, investment and running cost for the case-plants

	Running cost el. for the life span [NPV, MRMB]*	Running cost gas for the life span [NPV, MRMB]*	Investment gas [MRMB]**	Investment electricity [MRMB]**
1	163.05-123.40	102.26	28.96	91.97-44.59
2	98.80-78.38	66.17	23.29	47.37-22.97
3	63.59-51.08	42.89	15.16	29.03-14.07
4	63.53-51.03	43.28	15.62	29-14.06
5	122.18-95.4	79.5	25.2	62.14-30.13
6	80.46-64.44	54.21	19.65	37.19-18.03

* Including depreciation cost so this is the total cost for the plant's lifetime of production

** Including upgrading-unit and biogas reactor

*** Based on €3300/kW-€1600/kW installed electricity production capacity (Raninger et. al., 2012)

Table 6.3, scenario S1

Guangdong, (el.price=0.746 RMB/kWh)

	Total income	Profit	Investment	Running cost	El/gas
1	195.5	13.14-52.78	91.97-44.59	163.05-123.40	El
2	105.95	(-3.32)-17.10	47.37-22.97	98.80-78.38	El
3	64	(-6.09)-6.43	29.03-14.07	63.59-51.08	El
4	64.1	(-5.76)-6.74	29.00-14.06	63.53-51.03	El
5	135.55	(-0.02)-26.76	62.14-30.13	122.18-95.4	El
6	83.18	(-5.50)-10.52	37.19-18.03	80.46-64.44	El

Table 6.4, scenario S2

Guangdong (Gas price=4.19 RMB/Nm3)

	Total income	Profit	Investment	Running cost	El/gas
1	275.39	145.93	28.96	102.26	gas
2	147.1	66.4	23.29	66.17	gas
3	88.94	37.26	15.16	42.89	gas
4	89.29	37.19	15.62	43.28	gas
5	189.53	91.31	25.2	79.5	gas
6	115.37	49.76	19.65	54.21	gas

Table 6.5, scenario S3

Beijing (el.price=0.691 RMB/kWh)

	Total income	Profit	Investment	Running cost	El/gas
1	164.54	-14.76/24.88	91.97/44.59	163.05/123.40	El
2	90	-17.69/2.73	47.37/22.97	98.80/78.38	El
3	54.04	-14.89/-2.38	29.03/14.07	63.59/51.08	El
4	54.34	-14.55/-2.05	29/14.06	63.53/51.03	El
5	114.63	-18.87/7.91	62.14/30.13	122.18/95.4	El
6	70.66	-16.79/-0.76	37.19/18.03	80.46/64.44	El

Table 6.6, scenario S4

Beijing (gas price=2.05 RMB/Nm3)

	Total income	Profit	Investment	Running cost	El/gas
1	136.97	21.18	28.96	102.26	gas
2	75.81	2.15	23.29	66.17	gas
3	45.29	-2.07	15.16	42.89	gas
4	45.65	-2.15	15.62	43.28	gas
5	96.01	7.02	25.2	79.5	gas
6	59.46	-0.62	19.65	54.21	gas

Table 6.7, comparing the feasibility for four scenarios

Scenario	El/gas	Profit [MRMB]	Province
S1	El	(-6.09)-52.78	Guangdong
S2	gas	37.19-145.93	Guangdong
S3	El	(-18.87)-24.88	Beijing
S4	gas	(-2.15)-21.18	Beijing

6.3 Assumptions and Notes on the Excel-file

6.3.1 Assumptions

All assumptions are used in the excel-file and also explained further there.

1. A gas turbine runs 330 days per year 24 hours a day.

2. The investment cost, y, for the biogas reactor can be calculated using data for the treatment capacity, x, from 150 biogas plants and fitting a power equation to the data. The equation is:

$$y = 38206x^{-0.479} \quad [7.1]$$

3. The investment cost for the upgrading unit, y, is dependent on the gas production, x, and can be estimated using data from two existing upgrading units in China using the equation

$$y = 0.2778x + 0.3049 \quad [7.2]$$

4. The running cost, y, is related to the treatment capacity, x, and can be estimated using data from 4 CDM-projects using the equation

$$y = 2.2523ln(x) - 20.344 \quad [7.3]$$

5. The running cost, y, is related to the installed electricity generation capacity, x, and can be estimated using data from 5 CDM-projects in China and fitting the equation

$$y = 2.7619ln(x) - 15.925 \quad [7.4]$$

6. The leakage from the upgrading plant is assumed to be 2%

7. The leakage from the biogas plant is assumed to be 0%

8. Production cost for upgraded biogas, y, is dependent on the production capacity, x, and can be estimated using a linear regression after Roth et. al. (2009). The regression is

$$y = (-0.0005x + 0.1333) \cdot 0.933514 \quad [7.5]$$

9. The Swedish investors in the biogas sector are assumed to use a discount rate of 6% and a life span for the biogas reactor of 15 years. (Roth et. al., 2009 and Bohman et. al., 2011)

10. The Chinese investors in the biogas sector are assumed to use 8% discount rate and a life span of 10 years as used by the CDM-projects investigated. (UNFCCC 2011a-c)

11. All provinces have the same investment cost, production costs and taxes.

12. The heat generated in the CHP-unit cannot be sold, but is only used to heat the biogas process.

13. The fertilizer production is assumed to be 10% of the treatment capacity and sold as a dewatered organic fertilizer.

6.3.2 Notes

1. A small population of data is used to estimate the running cost, which makes this output data uncertain.

2. The investment cost for an upgrading plant is based on only two existing plants. This makes the out data regarding gas upgrading uncertain.

6.4 Discussion

The model created in Excel is used to compare different scenarios for biogas production in China. The most economically feasible scenario is scenario S2 upgrading of biogas to bio methane and injection to the gas grid in Guangdong province. This scenario was profitable for all 6 case-plants.

Linköping biogas plant in Sweden is the case-plant showing the best profits in all scenarios. This is a well-run plant with high output of biogas per treatment capacity.

Bjuv biogas plant is generally not a profitable case-plant. This plant is smaller and do not deliver as much biogas as the Linköping plant.

Guangdong province is one of the provinces where the electricity price and gas price is highest in China. It is also a province with a big fishing industry and large cities and might therefore be a prospect province for a plant co-digesting sewage sludge and fish waste.

The lack of data from upgrading plants makes the profit from gas production a bit uncertain. However, two well-documented plants form the base for the calculations and it should be possible to create bio methane to similar running cost.

The model can easily be used to compare other scenarios in the future.

7. Conclusions

For conclusions on part 1 see page 54.

Raninger (2012) reports that most of the biogas plants in China has a very low yield, <0.5 [m^3/m^3 reactor, day] compared with Germany's 1.2-1.8 [m^3/m^3 reactor, day]. One of the factors affecting the yield is the low temperature the digesters are run at. This problem has to be addressed to gain profitability in biogas production.

The threshold for feeding in electricity to the grid today is 500 kW. This threshold and the fact that receiving the feed-in tariff of 0.25 RMB/kWh electricity delivered to the grid is connected with difficulties means that 95% of the animal farms in China cannot connect a generator to the grid. It is suggested that the limit is lowered to 150 kW. Today less than 10 biogas plants in China are grid-connected. (Dicke, 2010)

Problems with insufficient training of the operators and maintenance of the biogas plants are discussed by Han et. al. (2008), but are currently being addressed by the Sino-German Project for Optimization of Biomass Utilization at their newly installed Biogas Training Centre Laboratory, at the Deqingyuan demonstration project in Yanqing county, Beijing (SGPOBU, 2012).

The biogas market in China is new and not yet mature. Stricter environmental laws on national level (e. g. CO_2-emissions) and locally (e. g. air-quality in cities), harder restriction on landfills and increased fuel prices all give biogas a bright future. Being prepared for this future by investing in biogas production in China should be a wise decision. It is important to know that Chinese investors need proof for that the technology works in China to invest.

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Appendix 1 - Biogas organizations in China

Biogas Institute of the Ministry of Agriculture (BIOMA), http://www.biogas.com.cn/

Sino-German Project for Optimization of Biomass Utilization, Biogas
http://www.biogas-china.org/

Appendix 2 - The Project Village Questionnaire

项目村问卷调查表/The Project Village Questionnaire

1.关于种植问题/Questions on cultivation：

（1）您的主要种植的作物包括什么？种植的面积分别是多少？/Which are your main crops, how big is you planted area?

Corn, wheat, 0.4 mu / person（1 mu= 666 ⅔ m^2）or 267 m^2 per person

（2）您在种植过程中是否使用有机肥料？如果使用，种植何种作物时使用，具体的用量为多少？/Do you use organic fertilizers? If yes, for what crops? How much are you using?

Use manure as fertilizer as a ground, it takes a long time for manure to release the nutrients, so use only once a year. The farmer likes the chemical fert. because it’s easier to carry, a lot of nutrients per volume. Can use motorbike easily and bring the chemical fertilizer to the fields. Manure takes a lot of work.

（3）您是否会在作物收割后回收秸秆？如果是，那么您如何利用您的秸秆？/Are you recovering the straw from the crops after harvest? If yes, what do you use the straw for?

Yes, not used for biogas. ~10 % firewood. If they have cow or sheep the animals can eat straw. Pigs do not. Dump ~90% just outside house.

2.关于养殖问题/Questions on breeding animals：

（1）您的家庭是否有畜禽养殖？养殖种类及规模为分别为多少？/Does you household have livestock? If yes, how many and what species of livestock?

Most families have 5-6 pigs. Bigger families have 40. The tendency is towards bigger farms with more animals.

（2）畜禽养殖粪便如何处理？还田，产沼气，外销，或是随意丢弃？/How do you handle the manure? Do you apply it directly on the fields, make biogas, sell it to other farms or throw it away?

If have biogas, 30-40% of the manure will be used for biogas. Some manure back to the fields. Pollution.

（3）如果产生沼气，沼渣液如何处理？If you produce biogas, how do you handle the residue?

If close to the fields they use it as a fertilizer. Good fertilizer. But hard job to bring it to the fields.

3.关于农村生活问题 /Questions on the economic situation and the rural life)：
（1）您的家庭是否以农业收入作为主要来源？/Is agriculture your family’s main income?

Yes.

（2）沼气的使用可以节约您多少化石能源费用？/Has the use of biogas saved you a lot of money due to reduced use of fossil fuels?

Use straw instead of fossil fuels. ()

4.关于沼气问题/Questions on biogas production：
（1）您多久会向反应池内投料？不同季节会有所区别么？/How often do you feed the reactor? Is there any seasonal variation?

Every 20 days in summer. Depends on gas pressure, if too high they will not add more manure, if low they will add more.

（2）沼气的产气效率如何？可以满足日常做饭所需么？Is the methane enough to meet requirement of cooking?

If the biogas production works, it will be enough. If they have a greenhouse they can cook one meal a day in wintertime as well. If they don’t have a greenhouse the indication to stop using the biogas reactor is when ice is forming, about four months per year.

（3）如果向您的沼气池内添加秸秆可以取得更好的产气效果，您是否愿意尝试？/Are you willing to add straw if this means more biogas is being produced?

They are afraid that straw might be clogging the biogas reactor and are not willing to use straw in the untreated shape.

Appendix 3 – User Manual for the Excel Model

Introduction

The model is built in Microsoft Excel and uses a few built in functions that are explained in Excel through the Formula Builder toolbox. The functions used are:

IF, SUM, SUMIF, NPV, PV, OFFSET, CELL

Cells are sometimes referred to as 'Sheet'!Cell. For example, the cell F43 in the sheet with the name Running cost is referred to as 'Running cost'!F43.

The model has been changed after this manual was written and therefore cell-references might be incorrect in some cases. It is appreciated if errors are pointed out to the author!

Contact information: alols@kth.se

Assumptions and Applications

A gas turbine runs 330 days per year 24 hours a day. This assumption is used to estimate the needed capacity (sheet 'Result' cell F7) for a given electricity production (sheet 'Result cell E7).

Investment cost can be calculated using data from 150 biogas plants and fitting a power equation to the data. The equation is (see sheet 'Investment cost' in the model)

$$y = 38206x^{-0.479}$$

The running cost is related to the treatment capacity and can be estimated using data from 5 CDM projects using the equation (see sheet 'Running cost' in the model)

$$y = 2.2523ln(x) - 20.344$$

The running cost is related to the installed electricity generation capacity and can be estimated using the equation (see sheet 'Running cost' in the model)

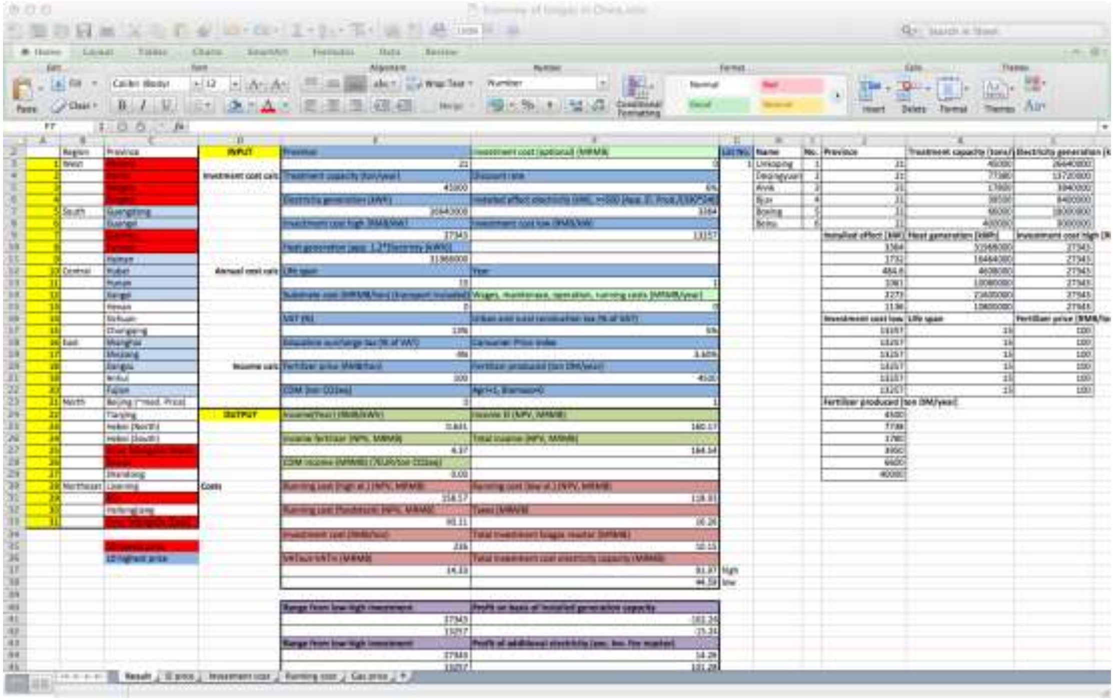
$$y = 2.7619ln(x) - 15.925$$

The Swedish scenario is assumed to have a discount rate of 6% (sheet 'Result' cell F5) and a life span for the biogas reactor of 15 years (sheet 'Result' cell E13). (Roth et. al., 2009 and Bohman et. al., 2011)

The Chinese circumstances are 8% discount rate (sheet 'Result' cell F5) and a life span of 10 years (sheet 'Result' cell E13) as used by the CDM-projects investigated. (UNFCCC 2011a-c)

‘Result’

The model is built up of several spreadsheets, where the first spreadsheet is named Result and is the input-output area. This is the spreadsheet where all the data is put in and also the spreadsheet where all the models calculation results are displayed.



Province E3 and Year F13

Typing in a province number in cell E3 and a year in cell F11 decides the actual electricity price from that specific province for a certain year. Shaanxi has number 1, Gansu number 2 and so on. The price is calculated in sheet ‘El price’ according to the formula specified in chapter ‘El Price’.

Investment cost (optional) F3

If the investment cost is known it can be specified here. Otherwise the model will calculate the investment cost as described in chapter ‘Investment cost el’.

Treatment capacity E5

Treatment capacity in tons/year calculates the investment cost according to the formula in chapter ‘Investment cost el’.

Electricity generation E7 and Installed effect electricity F7

Electricity generation is specified in cell E7. The need for installed effect can be estimated by the formula:

$$Installed\ effect \approx \frac{Generated\ electricity}{330 \cdot 24}$$

This assumes 330 days of operation with 35 days for service of the generators.

Heat generation E11

The heat generated depends on the selection of generator. If a combined heat and power (CHP) unit is selected, the efficiency of the heat exchangers will determine the heat generated. Usually around 1.2*electricity generated, but higher is not unusual.

Investment cost high E9 and Investment cost low F9

The investment cost in China for a biogas plant with electricity generation capacity is 13257-27343 RMB/kW installed capacity electricity (1600-3300 €/kW). In cell E9 the highest investment can be specified in RMB/kW and the lowest estimated can be specified in cell F9.

Life span E13

In cell E13 the life span of the reactor is specified.

Substrate cost (transportation included) E15

In cell E15 a substrate cost can be specified. If gate fees for municipal solid waste can be obtained, the substrate cost should be negative.

Wages, maintenance, operation, running costs F15

If this is known it can be specified here, otherwise the model calculates is using the sheet 'Running cost'.

Important note: Running costs should be specified if possible since it varies a lot from different projects. The lack of data available makes this estimation very rough in the model. (See further chapter 'Running cost')

VAT E17, Urban and rural construction tax F17, education surcharge tax E19 and Consumer Price Index F19

The taxes: they can vary from location to location and must be specified.

Fertilizer price E21 and Fertilizer produced F21

Income from fertilizers can be specified here. The amount of fertilizers can be estimated by this formula:

$$Fertilizer\ produced = Treatment\ capacity \cdot 0.1$$

CDM E23

If CDM-credits (Clean Development Mechanism) can be given this can be specified here.

Agri=1, Biomass=0 F23

Here it can be specified if the substrate is livestock- and poultry waste = Agri or agro- and forestry biomass waster = Biomass.

If cell F23=1 the substrate is livestock- and poultry waste and the electricity price will be calculated using sheet 'El price', and it will vary from different provinces. If cell F23=0 the substrate is biomass and 0.75 RMB/kWh will be applied as the electricity price.

Income(Year) E25, Income El F25, Income fertilizers E27, Total income F27 and CDM income E29

Income(Year) gives the actual income for a certain year in cell E25. This is based on the province E3 and the year in cell F13.

Income El gives the total income from electricity generation during the life span of the project in cell F25.

The income from fertilizers is given in cell E27.

The total income is given in cell F27

$$Total\ income = Income\ El + Income\ fertilizer + CDM\ income$$

If there are incomes from CDM-credits they can be specified in cell E29.

Gas price F29

Cell F29 gives the gas price for the province selected in cell E3.

Running cost (high el.) E31, Running cost (low el.) F31, Running cost (feedstock) E33

See chapter 'Running cost'.

Taxes F33

In cell F33 the taxes are added as =(F17+E19)*E31*E17+'Running cost'!C9.

$Total\ tax = Additional\ tax \cdot Total\ income + VAT$

F17 and E19 are taxes expressed as a fraction of VAT and then multiplied with the total income. The VAT is calculated in sheet 'Running cost' cell C9 and is already multiplied with the total income

$$VATout = Total\ income \cdot VAT$$

VATin in sheet 'Running cost' is estimated to be 33% of VATout. If it is desired to change this, it has to be changed in the 'Running cost' sheet and cannot be managed in the 'Result' sheet.

Investment cost E35

This is the investment cost per ton of substrate estimated using the 'Investment cost' sheet. See further chapter 'Investment cost'.

Total investment biogas reactor F35

This is the investment for the biogas reactor alone without additional electricity production capacity. (See further Profit in chapter 'Result')

Total investment cost electricity capacity F37

This is the total investment cost with electricity generation capacity. The note high in G37 and low in G38 indicates that this is the investment cost based on the minimum price and the maximum price. (See further Investment cost high E9 and Investment cost low F9 in chapter 'Result')

Profit

In cells F39, F40, F42 and F43 the profit is calculated in four different ways. F39 calculates the profit using the investment cost specified in cell E9 and F40 uses the investment cost in cell F7. F42 does the same as F39 and F43 the same as F40 with the difference that the sheet 'Investment cost' is used to estimate the investment for only the biogas reactor. This can be used if the investment in the biogas reactor has to be made due to environmental reasons and it could be interesting to investigate if additional electricity generation capacity would give a profit.

Profit of electricity

In 'Result'!F45 and 'Result'!F46 you see IF(F41=0, "Not Applicable", E31-E33-F37) and IF(F42=0, "Not Applicable", E31-F33-F37). This means that Not Applicable will be shown if the income from electricity is 0 and otherwise calculated as Total income-Running cost gas-Total tax.

$$Total\ profit = Total\ income - Total\ running\ cost - Total\ tax$$

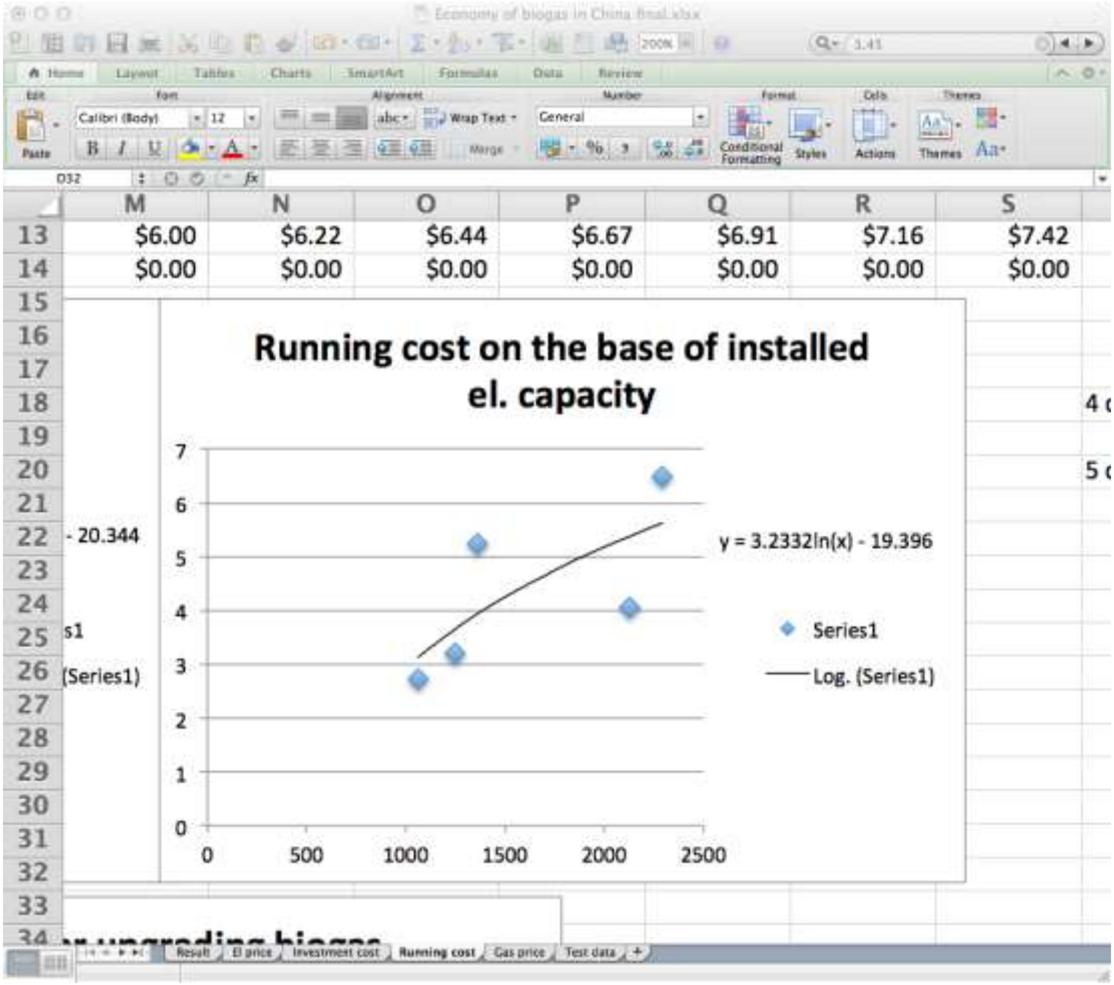
Note that it is only possible to calculate the profit from gas or from electricity due to the IF-statement.

Since either the cell 'Result'!F25=0 or 'Result'!F29=0, 'Result'!E31 is the total income from either electricity+fertilizer+CDM or from gas+fertilizer+CDM. If Income el F25=0 then there has to be an income from gas.

'Running cost'!C12 and 'Running cost'!C13 gives the running cost for the low investment cost and high investment cost respectively:

=IF(Result!$F$7=0, 0, ((3.2332*LN(Result!$F$7)-19.396)+$C$17)*(1+Result!$F$19)^C4)

This is using the equation from the fit to the 5 CDM-projects that form the base of the running cost estimation:



	M	N	O	P	Q	R	S
13	$6.00	$6.22	$6.44	$6.67	$6.91	$7.16	$7.42
14	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00

$$y = 3.2332 \cdot \ln(x) - 19.396 + DRel$$

y – running cost [MRMB]

x – installed generation capacity

DRel – Depreciation rate for the plant including generators ‘Running cost’!C17 och ‘Running cost’!18

The term (1+Result!$F$19)^C4) is the increase in costs due to CPI-increase.

In the same way the running cost based on treatment capacity is calculated:

$$y \;=\; 2.2523 \cdot ln(x) -\; 20.344 + DRfeedstock$$

DRfeedstock – the depreciation rate for the biogas plant, ‘Running cost’!C16

Profit for gas production F48

In ‘Result’!F48 you see IF(F11=0, "Not applicable", E31-F35). This means that Not applicable will be shown if the income from gas is 0 and otherwise calculated as Total income-Running cost gas-Total tax.

$$Total\ profit = Total\ income - Total\ running\ cost - Total\ tax$$

'Result'!F35 is the running cost for gas. The running cost is calculated using the long statement in 'Running cost'!C14:

=IF(Result!$F$11=0, 0, (('Gas price'!$C$38*Result!$F$11+'Gas price'!$C$39)*'Gas price'!$C$40*Result!$F$11+$C$19+$C$16)*(1+Result!$F$19)^C4)

This means that if the gas income is 0 then the running cost is 0, otherwise the running cost is given by the equation:

$$y = (-0.0005 \cdot x + 0.1333) \cdot 0.93354 + DRgas + DR\ feedstock$$

y – production cost [RMB/kWh]

x – annual production [GWh/year]

DRgas – the depreciation rate for the upgrading unit, 'Running cost'!C19

DRfeedstock – the depreciation rate for the biogas plant, 'Running cost'!C16

The equation is a linear fit to data from Sweden (Roth et. al., 2009) and is valid for an annual production of 25-100 GWh gas/year.

The running cost further includes depreciation cost for both the upgrading plant and the biogas plant:

Profit of additional electricity (excl investment for reactor)

This is an estimation of the profit for a biogas reactor that already exist but do not generate electricity. Installing generation capacity will give an additional running cost and investment cost but also additional income.

=IF(F41=0, "Not Applicable", E31+F39-E33-F37) and =IF(F42=0, "Not Applicable", E31+F39-F33-F37)

This simply subtracts the investment cost for a biogas plant by adding it to the investment cost for a biogas plant with electricity production:

$$Investment\ of\ extra\ el. = Investment\ el. - investment\ plant$$

But since the investment cost for a biogas plant with electricity generation includes the investment cost for the biogas plant, this must be added to the profit.

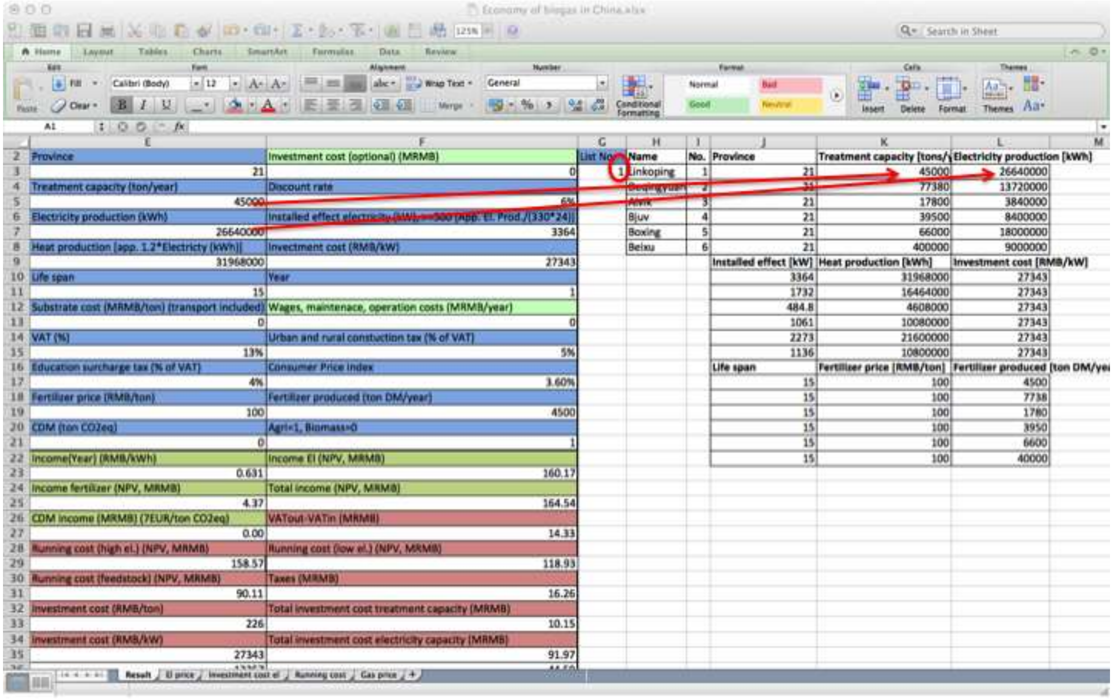
$$Profit = Total\ income + investment\ plant - running\ cost\ el. - tax$$

This will slightly under estimate the profit due to the fact that the operation and maintenance cost for the biogas plant without electricity production is taken as 0.

List Mode

Columns E and F as all the inputs and out puts. If the user wants to compare several biogas plants at the same time a SUMIF function is pre-programmed in several input cells. Using columns J, K and L for the input enables the user to compare several biogas plants or to change one or several input parameters for the same biogas plant.

For example, cells K3:K8 and L3:L8 are the input for treatment capacity and electricity generation respectively for 6 different biogas plants. Cell G3 is the specification for the set of data the user wants to investigate. In the example “Linköping” is chosen by entering 1 in cell G3, this makes the model collect the data from cell K3 and L3 for Lindköping. The treatment capacity 45000 appears in cell E5, and electricity generation 26640000 appears in cell E7, and so on with all the data. To change to the next biogas plant named Deqingyuan, simply change 1 to 2 in cell G3 and all the data that the user has specified changes and new output data appears.



	E	F
2	Province	Investment cost (optional) (MRMB)
3	21	0
4	Treatment capacity (ton/year)	Discount rate
5	45000	6%
6	Electricity production (kWh)	Installed effect electricity (kW), >=500 (App. El. Prod./(330*24))
7	26640000	3364
8	Heat production [app. 1.2*Electricty (kWh)]	Invectment cost (RMB/kW)
9	31968000	27343
10	Life span	Year
11	15	1
12	Substrate cost (MRMB/ton) (transport included)	Wages, maintenace, operation costs (MRMB/year)
13	0	0
14	VAT (%)	Urban and rural constuction tax (% of VAT)
15	13%	5%
16	Education surcharge tax (% of VAT)	Consumer Price Index
17	4%	3.60%
18	Fertilizer price (RMB/ton)	Fertilizer produced (ton DM/year)
19	100	4500
20	CDM (ton CO2eq)	Agri=1, Biomass=0
21	0	1
22	Income(Year) (RMB/kWh)	Income El (NPV, MRMB)
23	0.631	160.17
24	Income fertilizer (NPV, MRMB)	Total income (NPV, MRMB)
25	4.37	164.54
26	CDM income (MRMB) (7EUR/ton CO2eq)	VATout-VATin (MRMB)
27	0.00	14.33
28	Running cost (high el.) (NPV, MRMB)	Running cost (low el.) (NPV, MRMB)
29	158.57	118.93
30	Running cost (feedstock) (NPV, MRMB)	Taxes (MRMB)
31	90.11	16.26
32	Investment cost (RMB/ton)	Total investment cost treatment capacity (MRMB)
33	226	10.15
34	Investment cost (RMB/kW)	Total investment cost electricity capacity (MRMB)
35	27343	91.97

G	H	I	J	K	L
List No.	Name	No.	Province	Treatment capacity [tons/y	Electricity production [kWh]
1	Linkoping	1	21	45000	26640000
	Deqingyuan	2	21	77380	13720000
	Alvik	3	21	17800	3840000
	Bjuv	4	21	39500	8400000
	Boxing	5	21	66000	18000000
	Beixu	6	21	400000	9000000
			Installed effect [kW]	Heat production [kWh]	Investment cost [RMB/kW]
			3364	31968000	27343
			1732	16464000	27343
			484.8	4608000	27343
			1061	10080000	27343
			2273	21600000	27343
			1136	10800000	27343
			Life span	Fertilizer price [RMB/ton]	Fertilizer produced [ton DM/yea
			15	100	4500
			15	100	7738
			15	100	1780
			15	100	3950
			15	100	6600
			15	100	40000

Figure: Using the list in column J, K and L, enables the user to compare several sets of input data by just changing the number in cell G3 (red circle).

‘El Price’

This spreadsheet contains the electricity feed-in tariff for various places in China. The price for each year is the sum of the feed-in tariff for desulfurized coal for the given cell and the feed-in tariff for agricultural biomass which is 0.25 RMB/kWh decreasing with 2% for every year. This gives the formula to calculate the electricity feed-in tariff for a given year:

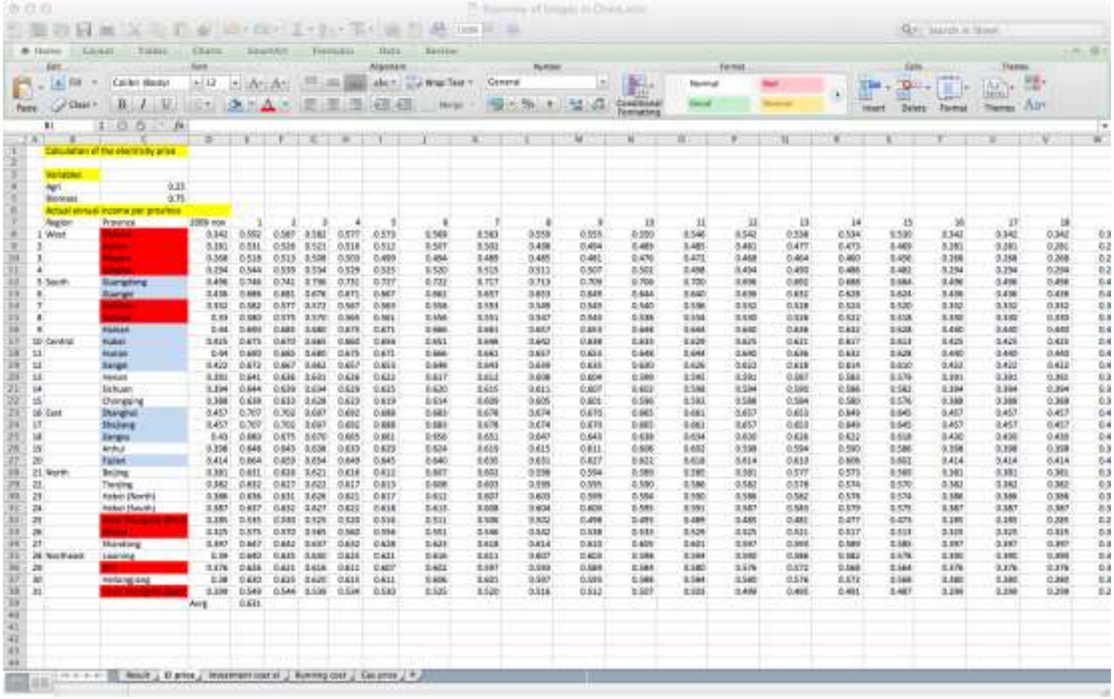
$$FiT = FiT_{coal} + 0.25 \cdot 0.98^{t}$$

FiT – Feed-in tariff for electricity produced from biogas

FiT_{coal} - Feed-in tariff for desulfurized coal by location

t – time in years from production start

The input from F5 and G15 gives the output in F27.



‘Investment cost’

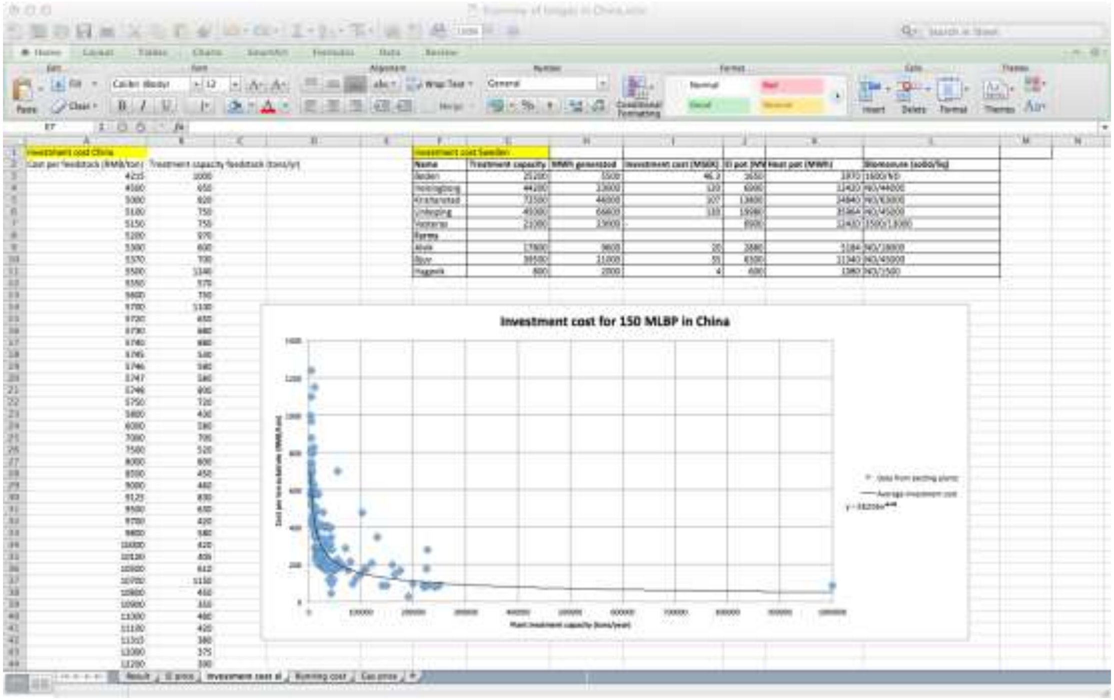
Biogas plant

This spreadsheet contains data from 150 existing biogas plants in China from Raninger (2012). The data are used to fit a formula to estimate investment cost for a biogas plant based on treatment capacity.

$$y = 38206 \cdot x^{-0.479}$$

y – Investment cost per ton treated [RMB/ton]

x – Treatment capacity [tons/year]



This only gives the investment cost for the biogas plant and not for the electricity generation equipment. This data can for example be used if the biogas reactor is a way to treat manure and would be installed anyway, and it is interesting to find out if installation of electricity generation equipment can be profitable (se Profit in chapter 'Result').

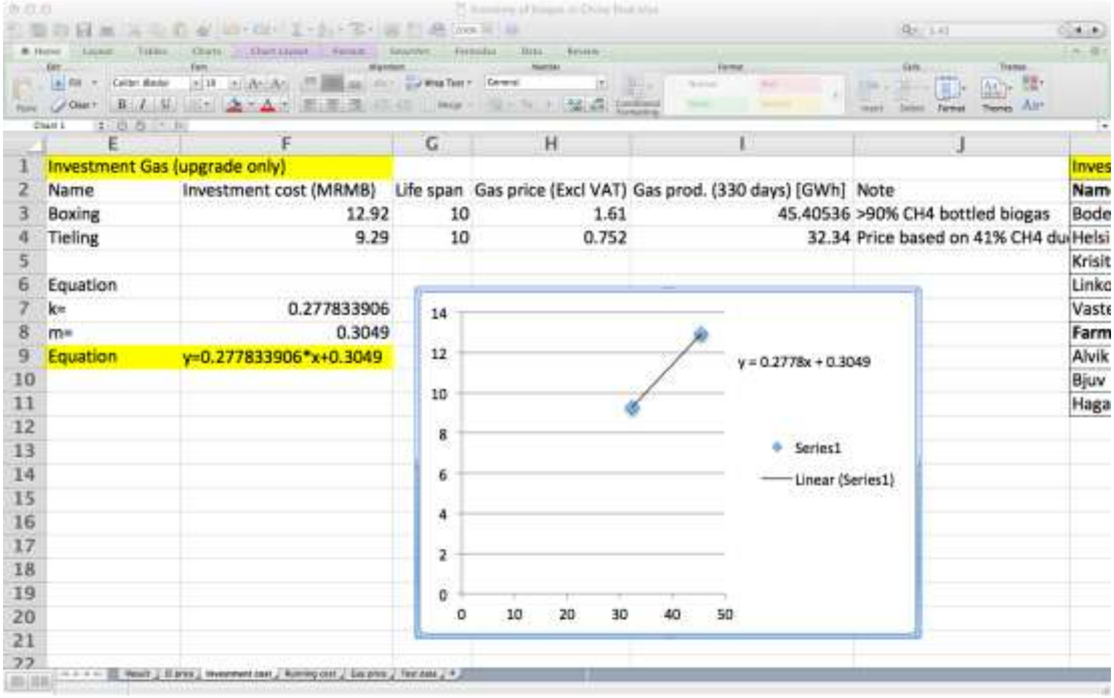
Some data from Swedish plants are presented for comparing investment costs.

Gas upgrading plant

Data from upgrading facilities in China is very limited. Two plants are found and used to estimate the investment cost for the upgrading plant. A linear equation is derived from the two data points:

$$y = 0.2778 \cdot x + 0.3049$$

and this equation is used to estimate the investment cost for the upgrading plant.

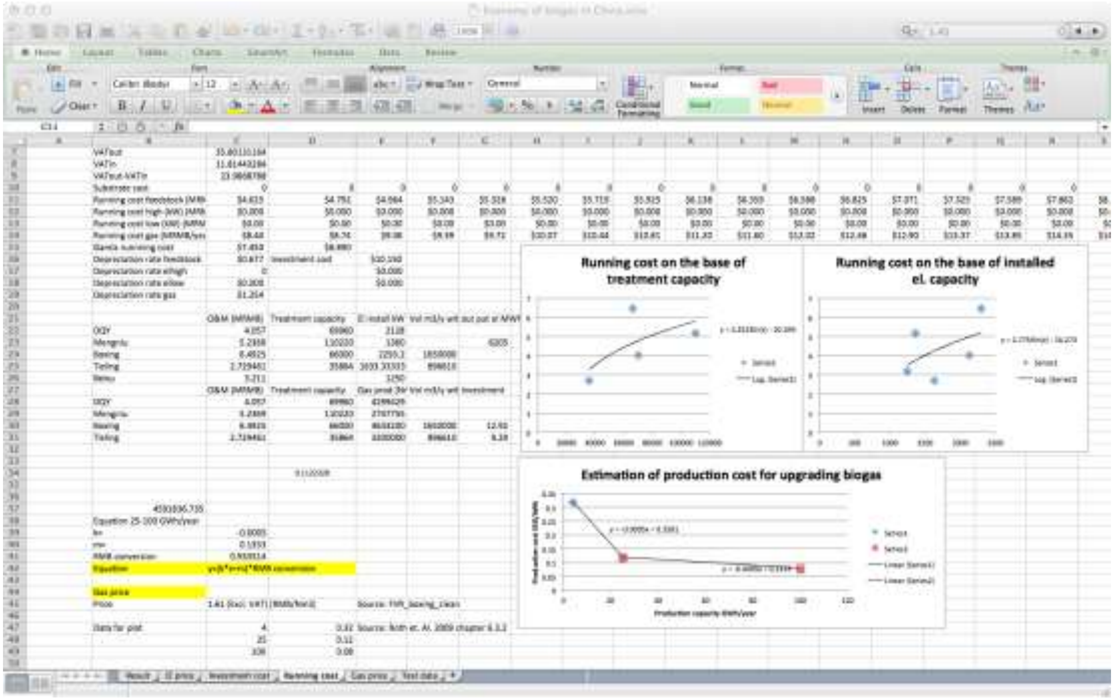


	E	F	G	H	I	J	
1	Investment Gas (upgrade only)						Inves
2	Name	Investment cost (MRMB)	Life span	Gas price (Excl VAT)	Gas prod. (330 days) [GWh]	Note	Nam
3	Boxing	12.92	10	1.61	45.40536	>90% CH4 bottled biogas	Bode
4	Tieling	9.29	10	0.752	32.34	Price based on 41% CH4 du	Helsi
5							Krisit
6	Equation						Linko
7	k=	0.277833906					Vaste
8	m=	0.3049					Farm
9	Equation	y=0.277833906*x+0.3049					Alvik
10							Bjuv
11							Haga

‘Running cost’

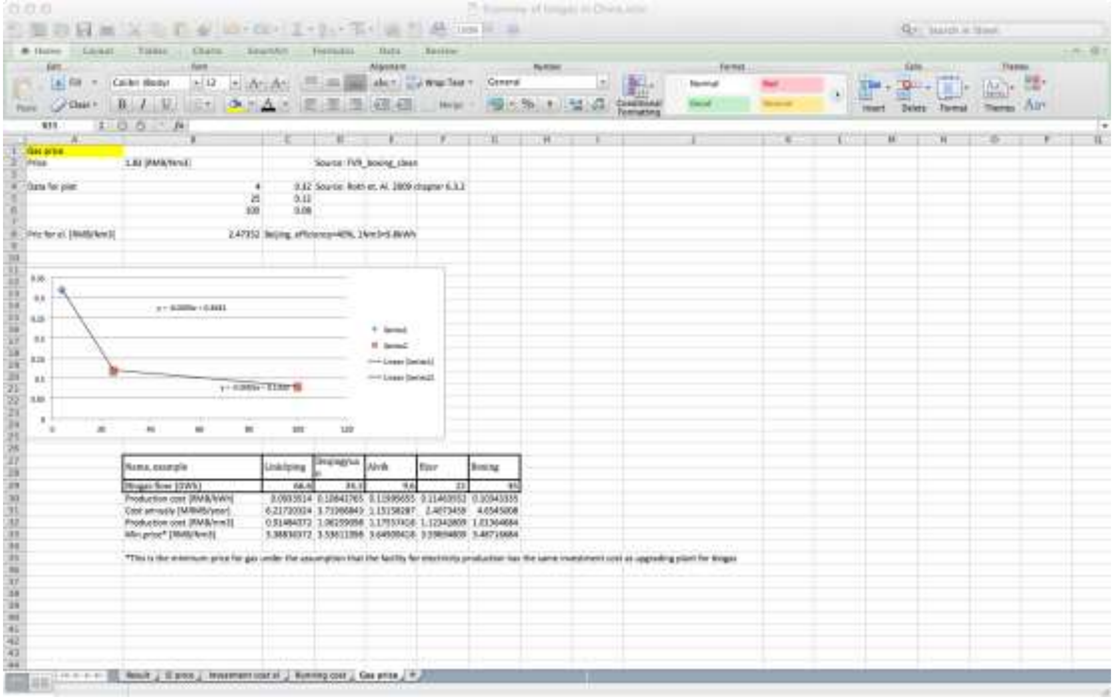
If the running cost is given in sheet ‘Result’ cell F15, the running cost will be displayed in cells C5:AA5 using CPI given in sheet ‘Result’ cell F19 to estimate the increase in running costs. If sheet ‘Result’ cell F15 is 0, the running costs are estimated using data from only four projects. The data called “Running cost on the base of installed el. capacity” is used to calculate the running cost in cells C10:AA11 and C11:AA11 and the data called “Running cost on the base of treatment capacity” is used to calculate the running cost in cells C9:AA9.

The net present value (NPV) is calculated and added given a life span in sheet ‘Result’ cell E13 and a discount rate in sheet ‘Result’ cell F5. The output shows the NPV for the total running cost of the project.



‘Gas price’

This sheet gives an estimation of the production cost of upgraded bio methane using a linear fit to two regions of the data from Roth et. al. (2009) chapter 6.3.2. The data is suited for Swedish conditions but by looking at the two cases Boxing and Tieling, it can be confirmed that the data also suits an estimation of the operating cost in China.



A calculation is made in the sheet to estimate the benefit of upgrading biogas to methane using the production cost given by the two lines:

$$Production\ cost = (-0.0005 \cdot biogas\ flow + 0.1333) \cdot 0.933514$$

0.933514 is the conversion from SEK to RMB.

Verification using the Boxing and Tieling cases:

Table 1 Comparing the actual production cost in China to data from Roth et. al. (2009)

Production cost	**Boxing**	**Tieling**
Actual	0.144	0.0844
Equation	0.103	0.109

For the Linköping biogas plant this means the following annual cost for upgrading:

$$Biogas\ flow = 66.6 \Rightarrow Total\ annual\ cost \left[\frac{MRMB}{year}\right]$$
$$= Production\ cost \left[\frac{RMB}{year}\right] \cdot Biogas\ flow[GWh]$$
$$= (-0.0005 \cdot 66.6 + 0.1333) \cdot 0.933514 \cdot 66.6 = 6.22 \left[\frac{MRMB}{year}\right]$$

Production cost for 1 Nm^3 of methane with the energy value of 9.8 kWh/Nm^3:

$$Production\ cost\ gas = (-0.0005 \cdot 66.6 + 0.1333) \cdot 0.933514 \cdot 9.8$$
$$= 0.91 \left[\frac{RMB}{Nm^3}\right]$$

The price for electricity from a generator with efficiency 0.4 and a feed-in tariff of 0.631 RMB/kWh gives the minimum price for gas:

$$Minimum\ price\ gas = 0.4 \cdot 9.8 \cdot 0.631 = 2.47\ RMB$$

adding the production cost:

$$Minimum\ price\ gas = 2.47 + 0.91 = 3.38 \left[\frac{RMB}{Nm^3}\right]$$

This can be compared with one reference where the price for natural gas is 1.83 RMB/Nm^3. Thus it is not economically feasible to upgrade the biogas.