BIOGAS - ITS POTENTIAL AS AN ENERGY SOURCE IN RURAL HOUSEHOLDS WITH PARTICULAR EMPHASIS ON CHINA?

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Declaration

I, (Ping ZHANG), declare that this thesis is a result of my research investigations and findings. Sources of information other than my own have been acknowledged and a reference list has been appended. This work has not been previously submitted to any other university for award of any type of academic degree.

Signature………………………………..

Date…………………………………………

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Abstract

This thesis is based on a literature review to analyze various aspects of biogas technology and address resource requirements and multiple values of biogas technology for rural household in developing countries. Biogas technology has been developed and widely used to produce a renewable, high-quality fuel, biogas. However, the development of biogas technology significantly differs over the world, particularly between developing countries and developed countries. In rural areas of developing countries, biogas is normally used for cooking, lighting, heating, etc, and feedstock for biogas production derives from agricultural resources, such as manure and harvest remains. In addition, biogas technology also contributes to GHGs emission reduction and produces a valuable and improved fertilizer. According to the calculations on the case from China, it shows if one household builds a $12m^3$ digester to produce $1.46m^3$biogas per day, it could cover their daily energy demand. It replaces straw, firewood, coal, kerosene and LPG for lighting, cooking, heating water, etc. Moreover, because of the higher effective using rate of biogas than other fuels (straw, firewood, coal and kerosene), it saves 5,558,840kcal energy consumption yearly compared to the energy consumption without biogas digesters. The feedstock requires 49kg pig manure and 61kg water per day. In practice, it could be substituted by 24.5kg pig manure (from 4-5 pigs) with the same amount of straw/crop residues. These resources are readily available under the local conditions. In addition to energy (biogas) output, the digester also produces 39ton organic fertilizer yearly recycled in the farmland of the household, which is at least sufficient to 0.48 hectare farmland for rice cultivation. With regard to environmental benefit, it reduces GHGs emissions of 2.596 tonCO_{2e} yearly. The capita reduction of CO_{2e} accounts for 14.2% of total capita CO_{2e} emissions in China. The governmental subsidies are large, which accounts for about 64% of capital costs. The result of calculations shows a relatively ideal model. Biogas technology represents a sustainable way to produce energy for household, particularly in developing countries.

List of Abbreviations

AD	Anaerobic Digestion
BSP	Biogas Support Program
CAD	Centralized Anaerobic Digestion
CDM	Clean Development Mechanism
CERs	Certified Emission Reduction
CHP	Combined Heat and Power Production
EUETS	EU Greenhouse Gas Emissions Trading System
GHGs	Greenhouse Gases
GRP	Glass Fiber Reinforced Plastics
GWP	Global Warming Potential
IPCC	Intergovernmental Panel on Climate Change
IRR	Internal Rate of Return
LPG	Liquefied Petroleum Gas
MDGs	Millennium Development Goals
REEG	Renewable Energy Sources Act
VS	Volatile Solids

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Chapter 1 Introduction, Research Purposes, Methods and Thesis Outline

Biogas is a renewable, high-quality fuel, which can be produced from a lot of different organic raw materials and used for various energy services. Biogas technology has been developed and widely used over the world, because it has a lot of advantages, including reduce of the dependence on non-renewable resources, high energy-efficiency, environmental benefits, available and cheap resources to feedstock, relatively easy and cheap technology for production, extra values of digestate as a fertilizer, etc. But the current status of biogas production and utilization largely varies among the different continents.

Biogas is produced when microorganisms degrade organic materials in the absence of oxygen. This process is also named anaerobic digestion (AD). The feedstock can derive from the agricultural, industrial or municipal sources. To date, in order to obtain a higher biogas yield, a lot of agricultural biogas plants digest manure with some additional co-substrates for increasing the content of organic materials. Besides input materials, biogas yield and AD process are affected by several other factors. There are a lot of different types of biogas plants over the world, and they are accepted and widely used by different countries. For example, floating drum and fixed dome biogas plants are two major types of small to medium scale biogas digesters used in African countries.

The implementation of biogas technology provides benefits in terms of positive environmental impacts and additional values of digestate used as fertilizer if considering current energy consumption, waste handling and agricultural production practices. In addition, biogas itself can be used in several ways: either raw or upgraded, such as production of heat or steam (the lowest value chain utilization), electricity production with combined heat and power production (CHP), upgraded and utilization as vehicle fuel, upgrading and injection in the natural gas grid. There are big differences of biogas utilization among various countries, in particular between developing countries and developed countries. In spite of the multiple benefits of biogas systems, present biogas production only uses a small part of the potential.

In this thesis, I will study various aspects of biogas technology, including its production, feedstock, different types of digesters, etc; the benefits of biogas technology, including the energy value (biogas utilization), environmental benefits, and the values of digestate; its installation costs and economic performance. These studies will show an overview of biogas technology in the world. Then I will calculate in rural China what the resource requirements and multiple benefits of one household biogas plant, considering the feedstock, water, greenhouse gases (GHGs) emissions and digestate. The simply economic analysis will also be included. According to the studies mentioned above, I intend to address: how biogas technology could influence the energy consumption and utilization; what the resource requirements in term of the feedstock supply are; what its environment benefits in term of reduction of GHGs emissions are; what the value of by-product (digestate) is? Biogas technology may represent one sustainable way to produce energy for rural household, particularly in developing countries.

This thesis will be based on a literature review and I will also do my own synthesis based on the existing literature. The relevant qualitative or quantitative data could be collected from multiple sources such as published articles, papers, documents, etc. Some analysis or discussions will be based on case studies. Some relevant data for calculations could be collected from Chinese resources.

Thesis outlines:

Chapter 1 will be the introduction part, including the thesis purpose, methods and thesis outline.

In chapter 2, I will study the background of biogas technology, and state the status of biogas technology over the different continents.

In chapter 3, I will do some studies of biogas technology based on the literature review, including comparison among different types of biogas plants, analysis of the factors affecting biogas yield and AD process in terms of feedstock and working conditions, analysis of the multiple benefits of biogas technology in terms of energy (biogas) values and applications, additional environmental benefits and by-product (digestate) values, analysis of the economic performance of biogas projects under high capital costs and the opportunities of the improvement. These studies will refer to various aspects of biogas technology and show an overview of biogas technology in the world. Parts of the findings are important to the following calculations and analysis.

In chapter 4, I will calculate in rural China how much biogas could cover the energy demand of one family for lighting, cooking, heating water, etc? How much feedstock (manure, straw, etc) is needed to produce this amount of biogas? How much water is needed? How much CO_{2e} emissions are reduced? How much organic fertilizer could be produced? How much farmland could be cultivated by this amount of organic fertilizer for crop production? How is its economic performance? According to the calculations, I intend to address: how biogas technology could influence the energy consumption and utilization; what the resource requirements in term of the feedstock supply are; what its environment benefits in term of reduction of GHGs emissions are, what the value of by-product (digestate) is?

Chapter 5 will be the conclusion part.

Chapter 2 Background

The global energy demand is increasing rapidly, and about 88% of this demand relies upon fossil fuels to date (Weiland, 2010). The energy demand will continue to grow during this century. However, GHGs emissions have become one of the most severe environmental problems. Use of fossil fuels is one of the main reasons for these emissions. According to the report of Intergovernmental Panel on Climate Change (IPCC), GHG emissions must be reduced to less than half of global emission levels of 1990 in order to minimize climate change impacts and global warming. Besides, the energy supply is another important global challenge, because some continents such as Africa are already faced with an energy crisis but most of the known conventional oil and gas resources are concentrated in politically unstable regions.

Today, there is a lot of research focusing on renewable energy resources. The development of renewable energy technology can help to reduce the dependence on the non-renewable resources and the problems of environmental degradation related to fossil fuels (Parawira, 2009). Biogas which is a renewable energy resource from wastes, residues, and energy crops will play an important role in future. The production of biogas from anaerobic digesters has significant advantages compared with other forms of bio-energy production. Firstly, biogas production has been considered as one of the most energy-efficient and environmentally beneficial ways to produce renewable energy. Secondly, it can use locally available and cheap resources to produce biogas, and it drastically reduces GHGs emissions compared to fossil fuels. Thirdly, the digestate associated with the biogas production is considered as an improved fertilizer that could partly substitute for mineral fertilizers.

In this chapter, I will state the status of biogas technology in different continents. The development of biogas technology in terms of biogas production and utilization could significantly differ over the world.

2.1 Biogas Technology Status in Africa

The African continent has already encountered an energy crisis, including both commercial (petroleum products, natural gas, coal, and electricity) and traditional energy sources (wood and other biomass) (Parawira, 2009). However, the energy consumption and demand of the African continent is estimated to grow continuously, at rates even faster than developed countries. The factors contribute to this increase include the growth in population, energy demands from various domestic sectors and the demand for improving quality of life. In order to meet the Millennium Development Goals (MDGs), especially MDG1—reducing by half the percentage of people living in poverty by 2015, it is required to improve the quality and magnitude of energy services in developing countries (Parawira, 2009). In eastern and southern Africa it is estimated that energy use significantly relies on traditional biomass energy technologies but hardly takes modern, sustainable energy technologies. Due to the current economic situation in most African countries and the shortage of commercial modern energy, it is almost unlikely that the fossil fuels substitute for biomass (Parawira, 2009). The fossil energy resources distribute on the African continent unevenly, which leads 70% of countries in Africa rely on imported energy resources (Parawira, 2009). Certainly, biomass is an inexpensive and abundant resource, but if used in an inappropriate and unplanned way it will limit regenerative utilization and cause significantly environmental consequences. So it may be helpful to change the energy situation in Africa in ways of upgrading the biomass to higher-quality energy carriers.

The problems of traditional biomass fuels and non-sustainable fossil fuels have caused widespread research on the production and application of new and renewable energy resources, such as biogas, bio-fuels, and biodiesel. It is necessary to develop the renewable energy technologies, in particular biogas technology, because it helps to reduce the dependence on non-sustainable resources and the environmental degradation problems caused by the fossil fuel. Compared with other renewable energy production systems such as biodiesel and bio-ethanol, biogas production systems are not complicated and can be built and operated at both small and large scales in urban and rural areas. Moreover, the biogas technology does not compete with food production but biodiesel and bio-ethanol technologies do (Parawira, 2009). According to global experience, biogas technology is a relatively simple technology in term of the requirements of construction and management. It has been considered as a appropriate, adaptable and locally acceptable technology in Africa (Parawira, 2009).

Various international organizations and foreign aid agencies have made a lot of efforts through their publications, meetings and visits to promote the biogas technology and stimulate the interest of biogas technology in Africa. To date, some digesters have been constructed in several sub-Saharan countries. Various wastes are used as feedstock for biogas production, such as wasters from slaughterhouses, agricultural wastes, industrial wastes, animal dung and human excreta. The exact number of plants installed in Africa is unknown but most plants were installed in Tanzania and Kenya. In other African countries only a few up to hundreds biogas plants have been installed (Van Nes and Nhete, 2007). However, most of biogas plants installed in the African continent are small-scale plants, and the development of large-scale AD technology in Africa is still embryonic. Unfortunately, it is estimated that 60% of plants installed in Africa failed to stay in operation, although other plants show the success in providing benefits to the users over a number of years and the evidence on the reliability of the technology if properly operated (Van Nes and Nhete, 2007). In most cases, in order to promote the biogas technology some demonstration projects were introduced usually free of cost by governmental structures. It is assumed that the demonstrated benefits of running the biogas plants would stimulate people to adopt this technology automatically. However, it seems that this approach has not caused widespread promotion and the market of biogas technology failed to develop. Moreover, most of the installed plants are abandoned eventually. Generally speaking, the government expects to disseminate the biogas technology over Africa based on a market-oriented approach, but it has not achieved to date. An only exception may be Tanzania, where most of the plants have been installed on a semi-commercial basis, but a large-scale dissemination is still not achieved (Van Nes and Nhete, 2007).

There are a number of constraints that affect the implementation of the biogas technology on large scale in Africa, including (Parawira, 2009):

-Inexperienced contractors and consultants leading to poor-quality biogas plants and poor choice of materials;

-Lack of reliable information on the potential benefits of the biogas technology;

-Lack of academic, legislation and commercial infrastructure in the region;

-Lack of knowledge on the biogas system in practice;

-Poor ownership responsibility by users;

-Lack of pilot studies and full-scale experience;

-Lack of properly educated operators and technical knowledge on maintenance and repair;

-Poorly informed authorities and policy makers;

-Failure to support biogas technology through the energy policy by government;

-Research at universities is sometimes considered to be too academic in practice.

2.2 Biogas Technology Status in Some Asian Countries

Biogas technology was introduced into developing countries as a low-cost alternative energy resource, which could partly mitigate the problem of energy shortage for households. The household biogas plants are designed at small-scale to digest the agricultural wasters, such as cattle, pig and poultry excreta, crop residues, etc. Biogas is produced from the reactors which are known as biogas digesters to provide energy mainly for lighting and cooking in rural areas. Millions of people, in particular farmers, have benefited from the biogas technology. Nevertheless, the overall use of biogas technology in practice is still not high. The poor acceptability of the biogas digesters is considered as the high capital costs of the digesters, lack of related knowledge to operate in practice, difficulty in getting spare parts for requires, etc.

There are several countries in Asia, especially China and India, have popularized the biogas technology massively. China has the highest number of household biogas plants in rural areas over the world. 26.5 million biogas plants haven been installed by 2007, whose biogas yield reached 10.5 billion m^3 (equivalent to more than 100 million tons of standard coal) (Chen et al., 2010). Household biogas digesters spread throughout the country, mainly distributed in the Yangtze River Basin. Sichuan province owns the largest number, 2.94 million plants roughly (Chen et al., 2010). Nevertheless, some studies show that out of seven million household biogas plants founded during 1970s, roughly half were abandoned by 1980 (Bond and Templeton, 2011). It is believed that there are around 60% of biogas digesters in rural China running normally by 2007(Chen et al., 2010). There are various technical issues related to the failure, including gas leakage, blockage, short of maintenance, etc. The major reason for failure is considered to be lack of attention paid to plant maintenance and lack of technical support (Bond and Templeton, 2011). This shows that more attentions should be paid to operation of digesters, maintenance and repairs on the biogas plant. In addition to household biogas plants, China has made efforts to promote the large-scale biogas plant. By 1998, 742 large-scale biogas plants were installed, giving an output of 164million m^3/year roughly (Source: http://finance.sina.com.cn/roll/20100514/18507939107.shtml). It has been estimated that 2500 large-scale plants will be installed by 2015, for treating industrial organic waste water, and 4100 large-scale plants which use agriculture waste as input materials will be installed, producing biogas of 4 billion m^3/year and 0.45 billion m^3/year respectively (Source: http://finance.sina.com.cn/roll/20100514/18507939107.shtml).

Then we take a glance at the status of Nepal. Actually, Nepal shares a lot of socioeconomic and geographic similarities with India, so the development of the biogas sector in Nepal was largely influenced by the situation of India. It is estimated that more than 111,000 biogas plants have been installed in Nepal (Gautam et al., 2009). There are various organizations that contribute to the development of the biogas sector in Nepal. For instance, Biogas Support Program (BSP) which is an independent non-profit organization plays a significant role in this regard, and it obtains the financial assistance provided by Netherlands (Gautam et al., 2009).

2.3 Biogas Technology Status in Some Industrial Countries

Generally speaking, the biogas technology has been developed much more sophisticatedly in developed counties than developing countries, in terms of biogas production as well as biogas utilization. For example, the biogas plants in Europe have higher efficiency, whose biogas output per m^3 digester volume could be double of ones in developing countries (Plochl and Heiermann, 2006). Compared to developing countries, there are more efficient ways of biogas utilization in developed countries. Biogas can be upgraded and then used as car fuel or injected into natural gas grid. In addition, it could also be used in CHP to produce electricity and heat.

In the EU-countries, the biogas sectors are usually linked with agriculture. The agricultural biogas plants are most developed in Germany, Denmark, Austria and Sweden (Holm-Nielsen et al., 2009). In addition, the technology is also developed at a certain level in Netherlands, France, Spain, Italy, United Kingdom and Belgium (Holm-Nielsen et al., 2009). But in countries like Portugal, Greece and some Eastern European countries, the biogas technology is currently under development (Holm-Nielsen et al., 2009). It is estimated that over 3500 farm-based digesters are running in Europe and North America today (PERSSON et al., 2007). However, there are the different requirements of using AD process to produce energy among European countries, because of the differences in the agricultural organizations, in the energy distribution systems (gas, electricity or heat) and in the environmental and energy policies (Batzias et al., 2005).

Denmark is one of the countries that have significantly developed the agricultural biogas plants in Europe. In Denmark, there are a relatively large number of biogas plants currently for manure and organic waste processing: in 2002, there were 20 centralized biogas plants (also known as community plants) and over 35 farm-scale plants in operation, producing roughly 2.6 PJ renewable energy and processing about 3% of all manure in Denmark (Raven and Gregersen, 2007). The type of digesters applied in Denmark is the Completely Stirred Tank Reactor (CSTR), which is suited for treating the liquid animal manure and organic industrial wastes. There are approximately 50–500 tons manure mixed with 10–30% organic waste mainly from industries supplying to the plants every day(Batzias et al., 2005). The biogas yield from each plant is usually between 1000 and 15,000 m^3 per day (Batzias et al., 2005).

Governmental subsidy is one of reasons that Germany has succeeded in developing biogas plants. The application of biogas technology has significantly increased in Germany since the Renewable Energy Sources Act (REEG) was enforced in 2000 (Weiland, 2003), which guarantees a fixed compensation paid for the electricity production for a period of 20 years. The compensation paid in 2002 is between 10.1 and 8.6 Euro-Cent per kilowatt-hour depending on the installed electrical capacity (Weiland, 2003). It partly stimulates the interests of biogas production, because the compensation becomes a source of extra income for many farmers. In the agricultural sector, there are different types of biogas plants applied in Germany in terms of different sizes, reactor designs, operation conditions and the feed stocks for biogas production. At the end of 2001, roughly 1650 agricultural biogas plants associated with installed electrical capacity of 140 MW stayed in operation (Weiland, 2003). In Germany, approximately 95% of all biogas plants are at farm, while only the rest of 5% are large centralized plants which use animal manure from a group of suppliers together with non-agricultural co-substrates (Weiland, 2003).

Chapter 3 Findings Based On the Literature Review

3.1 Comparisons of Different Types of Biogas Plants

There are numerous types of biogas plants over the world, categorized according to the type of digested substrates, according to the technology applied or according to the plant scale, etc. I will select various types widely applied in different countries typically as well as analyze and compare these different biogas plants in this part.

3.1.1 Different Types of Biogas Plant in Africa

Briefly, a biogas plant has to consist of two components: a digester (or fermentation tank) and a gas holder. Usually the digester is a cube shaped or cylindrical waterproof container including an inlet which introduces the fermentable mixture in the form of slurry into the digester. And the gas holder is an air tight steel container which cuts off air from the digester and collects the gas produced and it normally floats like a ball on the fermentable mixture. There are different types of small to medium scale biogas digesters which have been developed in African countries, including the floating drum, fixed dome, and plastic bag design. The former two have been applied widely in Africa. The fixed dome digester and the floating drum digester are shown in Fig1. The major differences between the two digesters are the gas collection method, which the gas holder of the fixed dome type is equipped with a gas outlet and its digester has an overflow pipe to lead the sludge out into drainage, but the digestion processes of the both two digesters are the same (Amigun and Blottnitz, 2007). Table 1 shows the comparison of constructed material, capital investment, output, life time and advantages/disadvantages between these two types of biogas plants.

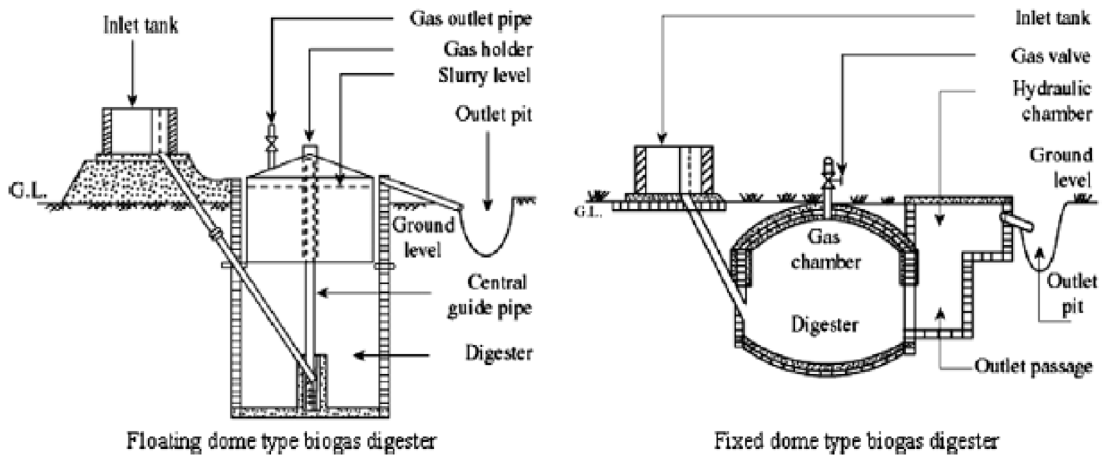

Fig.1. Typical biogas plants of floating drum and fixed dome (Amigun and Blottnitz, 2007)

Depending on the text, any type of biogas plant may be used. Nevertheless, most of the plants installed so far are the fixed dome type in Africa because of its advantages. There are no moving parts designed for the fixed dome type and also no rusting steel parts existing so a long life of the plant, 20 years or more, can be expected (Amigun and Blottnitz, 2010). The biogas plant is constructed underground which can protect it from physical damage and save space. Maintenance is required as occasional inspections, and if necessary, repairing the pipes and fittings. But the installation itself needs limited maintenance if operated properly.

A lot of studies have shown the technical and economic feasibility of fixed dome biogas plants. For instance, the fixed dome biogas plants are considered as technically suitable in Nigeria because they are easy to be constructed and the maintenance costs lowly(Amigun and Blottnitz, 2010). The economics of family size biogas plants of floating drum and fixed dome type in Punjab, India, with capacity between 1 and 6 m^3, were compared by a research, and found that the fixed dome biogas design was the cheapest model as far as the cost of installation, annual operational cost, and payback period is concerned (Amigun and Blottnitz, 2010).

Table.1. comparison between fixed dome and floating drum biogas plant

Type of Biogas Plants	Constructed Material	Capital Investment	Output	Life Time	Advantages/Disadvantages
Fixed Dome	Locally available materials, which even could be bricks	low	low	long	A longer life(20 years or more); Easier to construct; Lower costs of installation, annual operation, maintenance
Floating Drum	Concrete and steel	high	low	short	Changeable space of gas storage; Less risk of uncontrolled gas outflow due to steel gas cover

3.1.2 Different Eco-agricultural Models of Household Biogas in China

There are three different eco-agricultural models popular in the various regions of China. They all combine the biogas digester with other utilities as an integrated system in order to save and efficiently use resource and energy as well as provide additional benefits when producing biogas. However, every model is suitable for different conditions because of its own characteristics. I will analyze and discuss the differences among these models. Table 2 shows the comparison among these three different eco-agricultural models of biogas plants

'Three in One' eco-agricultural model

The 'Three in One' eco-agricultural model is widely used in southern China. It combines the biogas digester with a pigpen and a toilet. Usually the biogas digester is constructed underground, with a pigpen on the top. A toilet is constructed next to the pigpen. The combined system saves the land and manpower. This model has benefits such as providing the renewable energy source and improving the household hygiene of the rural environment simultaneously (Chen et al., 2010). Biogas can be use for lighting and cooking while the digestate generated with biogas can be used as a fertilizer for growing fruit trees, vegetables and grain. And the green food can be developed from this model. Another benefit is to eliminate the spread of disease caused by mosquito breeding because of connecting the toilet to the biogas plant. This 'Three in One' model construction requires less capital investment than other models and is quite effective, which extends value in the poor economic conditions of the area.

'Four in One' eco-agricultural model

The 'Four in One' eco-agricultural model is suitable to develop in northern China. It combines the biogas digester, pigpen, solar greenhouse, and toile as an integrated system (Chen et al., 2010). The additional solar greenhouse in this model can be used to increase the temperature of the biogas digester, which improves the efficiency of biogas production in cold area. While biogas produced in this model can be used to increase the temperature of greenhouse, which helps the vegetables grow well and pigs are well-fed. However, solar greenhouse construction requires a large investment of capital and the growth of greenhouse vegetables need more water, so this model is suitable in the north where solar energy is abundant; the economic conditions is relatively good and the water resources are available (Chen et al., 2010).

'Five in One' eco-agricultural orchard model

The 'Five in One' eco-agricultural orchard model is suitable to develop in northwest China. It combines the biogas digester with solar-powered barns, water-saving irrigation system, water cellar, and toilet as an integrated system (Chen et al., 2010). Biogas fertilizer can be used to grow fruit trees. Water resources collected in a water cellar can be introduced to the biogas production, orchard spraying and irrigation. The introduction of water-saving devices greatly helps to relieve the pressure on water resources, which makes this model is suitable for regions of Northwest where severe water shortages exist (Chen et al., 2010).

Table.2. comparison among three different eco-agricultural models of biogas plants

Model of Biogas Plants	**Combined Units**	**Suitable Regions**	**Capital Investment**	**Benefits**
"Three in One"	Biogas digest, Pigpen, Toilet	Southern China	low	Producing biogas as a energy source, Improving the household hygiene, Saving land, working time, manpower, Improving the efficiency of resource utilization,
"Four in One"	Biogas digester, Pigpen, Toilet, Solar greenhouse	Northern China(cold area, solar energy and water available)	Higher than "Three in One" model	Solving the problem of biogas production over winter in cold region, Good for vegetables growing in the greenhouse, Other benefits mentioned in first model
"Five in One"	Biogas digester, toilet Solar-powered	Northwest China(lack of water resource)	--	Saving water resource, Good for fruit trees growing,

	barn, Water-saving irrigation system, Water cellar			Other benefits mentioned in first model

3.1.3 Different Types of AD of Animal Wastes in USA

Due to energy prices rising, broader regulatory requirements and increased competition in the market, American agriculture's livestock sector has considered AD of animal wastes (Balsam, 2006). There are several types of AD used widely in America. Balsam (2006) analyzes four different types of AD which I will present in the following part. Table 3 shows comparison among these different types of biogas digester in U.S.A.

Covered lagoons

It is a pool of liquid manure topped by a pontoon or other floating cover, and there are seal plates extended down the sides of the pontoon into the liquid to prevent exposure of the accumulated gas out of the atmosphere (Balsam, 2006). Because this type of digester only uses manure with up to two percent solid content, it requires high throughput for the bacteria which is able to work on enough solid to produce gas. Covered lagoons are usually used in warmer southern regions, where the warm weather can help maintain the digester temperatures. The size of covered lagoon digesters is usually large and retention time is long (30-45 days or longer) (Source: http://www.biogas.psu.edu/). This type is the least expensive of all digesters to install and operate. And roughly 18% of all digesters used in the U.S.A nowadays are covered lagoon system (Balsam, 2006).

Complete mix

It is a silo-like tank which could handle manure with between two and ten percent solids and the manure in it could be heated and mixed (Balsam, 2006). The retention time of complete mix digester is usually 10 to 20 days (Source: http://www.biogas.psu.edu). This type of digesters is the most expensive system to install and operate. And 28% of all digesters used in the U.S.A nowadays are complete mix system (Balsam, 2006).

Plug flow

It is a cylindrical tank which could handle eleven to thirteen percent solids and the gas and other by-products from this digester could be pushed out one end by new manure fed into the other end (Balsam, 2006). This system has hot water piping through the tank to maintain the necessary temperature for the digester running. Retention time of this type of digesters is usually 15 to 20 days (Source: http://www.biogas.psu.edu). And more than half of all digesters used in the U.S.A presently are plug flow system (Balsam, 2006).

Fixed film

It is a tank filled with a plastic medium which supports a thin film of bacteria named a bio-film (Balsam, 2006). This system could handle one to two percent solids, and requires a shorter retention time (two to six days). Fixed film digesters have small reactor and must be loaded with a feedstock that could flow through the medium without clogging (Source: http://www.biogas.psu.edu). Only about one percent of all digesters currently used in the U.S. A are fixed film system (Balsam, 2006).

Table.3. comparison among four different types of biogas digester in U.S.A

Type of Biogas Plants	**Handling Ability in term of Solid Content**	**Capital and Operation Investment**	**Advantages/Disadvantages**	**Shares of Digesters Used in U.S.A**
Covered Lagoons	Up to 2%	lowest	No heating system, only used in the warm regions; long retention time	18%
Complete Mix	2%-10%	highest	Very expensive system	28%
Plug Flow	11%-13%	medium	Good design, used widely	More than 50%
Fixed Film	1%-2%	medium	Short retention time(2-6 days)	1%

3.1.4 Different Types of Biogas Plant in Europe

In Europe the first biogas plants were developed and constructed to remove the odour of animal waste as well as to provide electric energy and heat to farms. Along with the development of biogas technology, today more biogas plants are installed to produce the electricity or generated other energy forms for sale. There are many types of biogas plants in Europe. They can be categorized as the type of digested substrates, the technology used or their size, etc. However, the agricultural biogas plants usually are classified as two categories: the large scale, joint co-digestion plants and the farm scale plants (Holm-Nielsen et al., 2009). There is no big difference between these two categories in technologies. And the technologies are applied in one category are common to the other.

Digester Technology

In Europe most of biogas digesters are made of concrete with a steel skeleton or of steel

(Plochl and Heiermann, 2006). They usually have a cylindrical form standing upright. The digester tanks are equipped with insulations and heating systems in order to control temperature conditions inside. They are also equipped with systems to agitate or to stir the slurry. The biogas is collected in an external plastic bag or in the space above the slurry covered with a foli (Plochl and Heiermann, 2006). Fig.2 shows a typical digester of European examples for wet AD process. The average retention time is usually about 28 days (Plochl and Heiermann, 2006). However, it could increase to 90 days if corps or corps residues are added(Plochl and Heiermann, 2006). So a lot of biogas plants work with a post digester or a slurry storage tank covered with a foil as gas storage space.

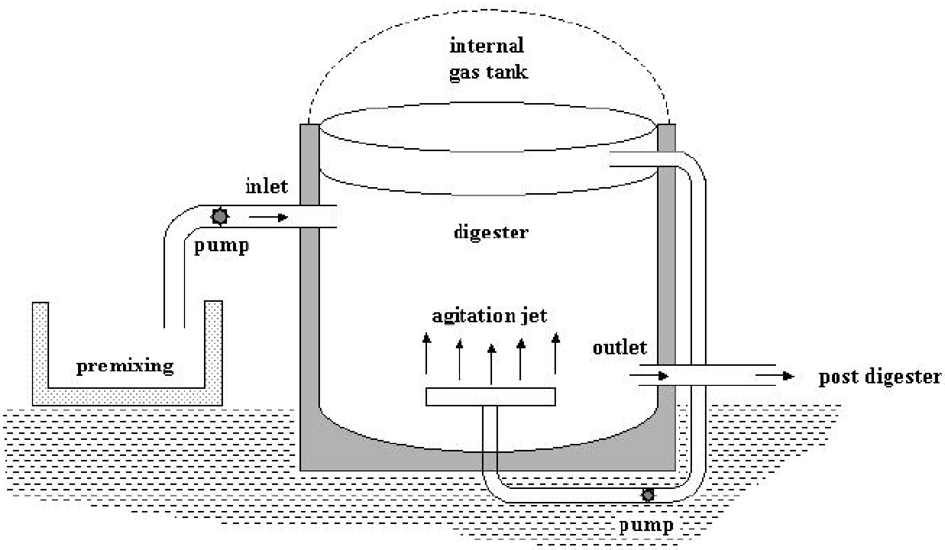

Fig.2. Digester for wet AD process: the input materials are added to the premixing pit; the feedstock is pumped from the premixing pit into the digester tank; the slurry in the tank is agitated by pressurized biogas; then digested slurry is pumped out for post digesting or storage(Plochl and Heiermann, 2006).

Besides wet AD technology mentioned above, dry AD technology is also used in Europe. The wet technology works with slurry of less than 12% dry matter content, while dry technology usually works with slurry of more than 30% dry matter content(Plochl and Heiermann, 2006). Therefore, dry AD process could handle mainly crops and crop residues as feedstock.

The joint co-digestion biogas plants

These plants co-digest animal manure from a number of farms, with suitable organic residues from the food and feed industries. The joint biogas plants have the digester capacities from few hundreds m^3 up to several thousands m^3.

Denmark is one of the pioneer countries to develop agricultural biogas plants for manure and organic residues co-digestion, which developed the joint biogas plant concept over the last two decades and represents an integrated system of manure and organic waste treatment, nutrient recycling and renewable energy production, generating combined agricultural with environmental benefits (Holm-Nielsen et al., 2009). Fresh animal manure and slurry need to be collected from the pre-storage tanks at the farms, transported to the biogas plant then mixed and co-digested with suitable organic wastes. In order to inactivate pathogens and to break their propagation cycles, specific substrates and animal by-products need to be submitted to a controlled pre-sanitation before entering the reactor content. The digested biomass is transferred to the storage tanks, usually covered with a gas proof membrane in order to recover the remaining biogas production(Holm-Nielsen et al., 2009). When the digested biomass is transported back to the farms, it is free of pathogen and nutritionally defined as liquid fertilizer and integrated in the crop fertilizer plan at each farm. Actually, the farms only receive back the digested biomass which allowed by the law to use on their fields, based on the regulation on nutrient loading per ha (Holm-Nielsen et al., 2009). The biogas plant sells the excess of digested biomass to the crop farms.

The farm scale biogas plants

These plants co-digest animal manure and slurry from one single farm, or only two or three smaller neighboring farms (Holm-Nielsen et al., 2009). The applied technology in the farm scale plants is similar to the joint biogas plants. Pre-treatment, post-treatment and separation technologies are also applied in the farm scale biogas plants.

In Denmark, there are two types of farm scale plants implemented. The first type is named the Smedemester (Blacksmith) biogas plant (Raven and Gregersen, 2007). Due to local testing and experimenting as well as supports from the German biogas industry, the Folkecenter has developed two standardized Blacksmith plants. The first plant is a horizontal steel tank, with the size between 50 and 300 m^3 (Raven and Gregersen, 2007). The manure takes 15-25 days transporting from one side where it is added to the other side of the tank by a horizontal stirrer (Raven and Gregersen, 2007). The second Blacksmith plant type is a vertical tank, with the size from 400 m^3 and upwards(Raven and Gregersen, 2007).

A second type of farm scale biogas plants was developed by the Bigadan company during the 1970s and 1980s, which consisted of low concrete digesters. During 1990s, based on conventional slurry storage tanks covered with membranes, some new concepts were developed (Raven and Gregersen, 2007). One of these plants is the Soft Cover Plant, which has a small concrete digester inside a storage tank. When the digester is full, the manure will overflow into the storage tank. (See Fig.3)

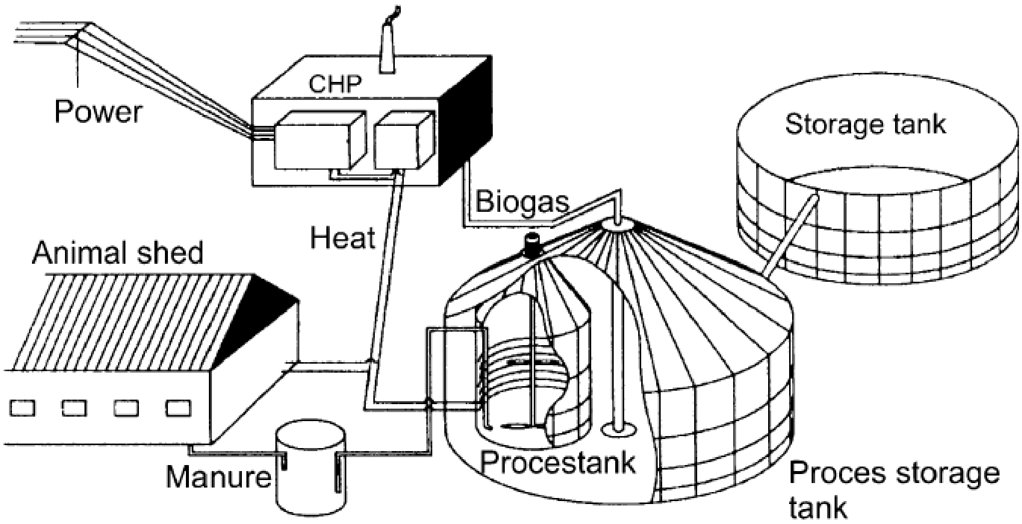

Fig.3. Layout of the soft Cover digester type: manure is added from the animal shed into the process-tank; then digested manure overflows into the process storage tank; an external storage tank provides the extra storage; when Biogas is produced from the digestion process,

it will be transported to a CHP unit for the production of power and heat; the power is fed back into the grid while the heat could be used for maintaining the digester temperature and heating the animal shed (Raven and Gregersen, 2007).

3.1.5 Other Types of Biogas Digester

Polyethylene tubular film bio-digester in Vietnam

In Vietnam, the polyethylene tubular film bio-digester technology is used widely as it is a cheap and simple way to produce gas for small-scale farms (An et al., 1997). Rural people are interested in this technology due to the low investment, fast payback, simple technology, positive effects on the environment, etc (An et al., 1997). More than 4,000 polyethylene digesters were installed in Vietnam which is paid by famers up to 1997 (An et al., 1997).

The high cost of biogas plants is the most important problem in biogas programs in developing countries. For instance, the price of a concrete digester plant installed in Vietnam is between 180 and 340 US$ (An et al., 1997). But this investment is unaffordable by average farm families. Then Chinese designers developed the red-mud digesters which cost 25-30 US$/$m^3$ but it was still expensive compared to the polyethylene digesters (5 US$/$m^3$) (An et al., 1997). Obviously the low price makes the polyethylene digesters attractive. However, the big problem of this type is the short productive life which is considered as approximate two years (Lam and Watanabe, 2000). It may be necessary to develop not only cheap but also durable digester for dissemination in rural areas.

GPR digester in China

In 2000, the biogas digesters made of glass fiber reinforced plastics (GRP) entered the market in China (Chen et al., 2010). The GRP digester has volume range from 6 to 10 m^3, with a thickness of 6 to 8 mm, a tensile strength of 93.5MPa and a bending strength of 109MPa

(Chen et al., 2010). GRP digester has a number of advantages compared to the concrete digesters, including a lower coefficient thermal conductivity, a longer operational life, lower maintenance costs, and a shorter construction cycle, etc(Chen et al., 2010). But there is no big difference in construction costs between GPR and the concrete digesters (Chen et al., 2010). To date, this type of biogas digester has been widely used by rural household in China. Figure 4 shows the pictures of a typical GPR digester.

Fig.4.The pictures of GPR digester

(Source: http://wenku.baidu.com/view/d23a5b4be518964bcf847cdb.html)

3.2 Biogas Production Process, Feedstock, Working Conditions

In this part, I will explain the processes of biogas production including three main reactions and the different digestions occur in different range of temperature, analyze the feedstock types for AD and how the input materials affecting the biogas production; analyze various factors affecting the biogas yield and AD process as well as optimum working conditions for AD process.

3.2.1 Biogas Production Process

Biogas is produced by biological processes which occur under anaerobic conditions. Biodegradable organic materials are mainly converted into methane (CH_4), carbon dioxide (CO_2) and small amounts of hydrogen sulphide (H_2S), moisture and siloxanes by anaerobic microorganisms. The process typically runs in a closed reactor at elevated temperatures or digester without heat system in the absence of oxygen. Nevertheless, it also could occur naturally in soils or old landfills at ambient temperatures (Omer and Fadalla, 2003). The degradation is a complex process, which requires some certain conditions and participation of different bacteria populations. The anaerobic fermentation processes are briefly shown in Fig.5.

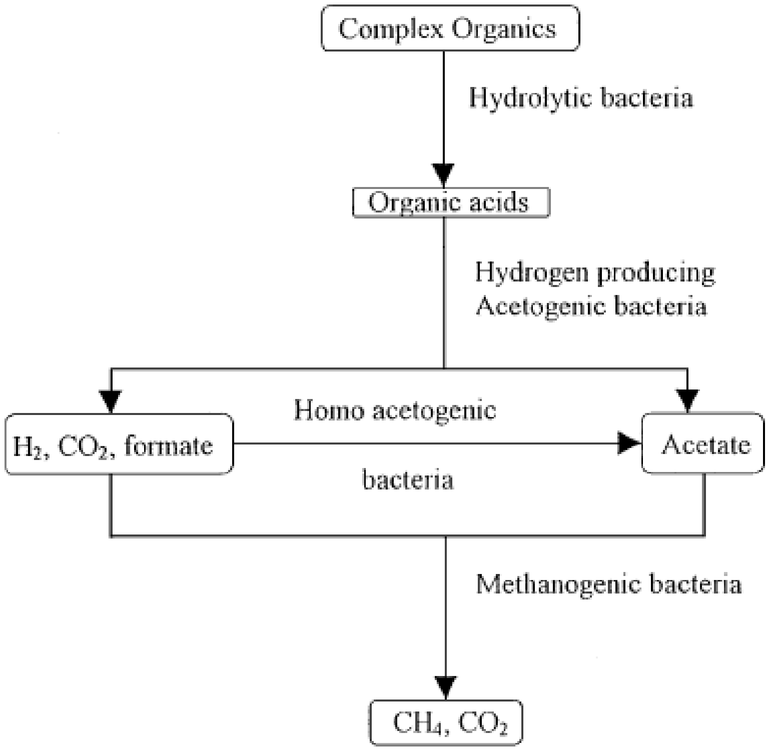

Fig.5. Biogas production process (Omer and Fadalla, 2003)

The mixed bacterial populations degrade organic compounds and produce a valuable mixture of gases (biogas). The organic compounds undergo three main reactions which are hydrolysis, acetic acid formation and production of methane.

Hydrolysis

Hydrolysis is a process that organic macromolecules such as carbohydrates, proteins and fats are de-polymerized by extra-cellular enzymes, then producing the acetic acid, long chain fatty acids and CO_2 (Lastella et al., 2002).

Acetic acid formation

Different bacteria degrade long chain fatty acids, then producing acetic acid, molecular hydrogen and CO_2 (Lastella et al., 2002). Acetic acid can be produced from CO_2 and H_2, fatty acids, alcohols and carbohydrates(Lastella et al., 2002). Enzymes for such reactions are named acetogens.

Production of methane

Acetic acid is finally degraded, then producing methane by the so-called methanogenic bacteria or methanogens, which are highly sensitive to the O_2 content in the system (Lastella et al., 2002). Their inactivity depends on an increasing fatty and acetic acids concentration within the environment, which leads to reducing pH value. In a well-balanced system, pH is measured range between 7 and 8(Lastella et al., 2002).

AD usually occurs under the temperature in range of 10-60 ℃ roughly (Source: http://nongyj.fuyang.gov.cn). There are three AD technologies in terms of different temperature requirement. The production processes in these three AD technologies are basically the same. However, the temperature affects the activity of bacteria participated in the biogas production process, which could influence the retention time and biogas yield. The first one is the digestion occurred under ambient temperature. This AD technology is widely used in rural areas of the developing countries. The digester applied this AD technology does not require a heating system, so it is easy to operate but the biogas output is unstable. For example, in rural China the digester has a lower biogas yield in winter compared to summer. In northern area the digester usually increase the temperature from a combined greenhouse as mentioned before. Along with the development of biogas technology, mesophilic digestion is widely used in developed countries and some developing countries. Recently, thermophilic digestion has also been develop and used in some joint or large-scale biogas plants due to its advantages. Table 4 compares the differences between mesophilic digestion and thermophilic digestion.

Table.4. comparison between mesophilic digestion and thermophilic digestion

AD Process	Requirement of Temperature	Retention Time	Advantages/ Disadvantages	Source
Mesophilic Digestion	30-40℃	15-30 days	More robust and tolerant, Less gas production	http://www.adnett.org/
Thermophilic Digestion	53-58℃	12-14 days	Higher gas production, Better pathogen and virus elimination, More expensive and complicated technology, More energy input	

3.2.2 Feedstock for AD Process

Biogas can be produced from nearly all kinds of biological feedstock types, which are from the primary agricultural sector and different organic waste streams overall society. Feedstock for AD derives from different agricultural, industrial and municipal sources. Agricultural resources include manure (cattle, pig, poultry, etc), energy crops, algal biomass, harvest remains, etc. Industrial resources are from food or beverage processing, dairy, starch industry, sugar industry, biochemical industry, etc.

The largest resource is considered as animal manure and slurries. For instance, more than 1500 million tones of animal manure are produced per year in the EU-27 alone, and more than 65% of these manure are handled as slurry which a liquid mixture of urine, feces, water and bedding material (Holm-Nielsen et al., 2009). Energy crops are another agricultural resource could be used for AD, including grain crops, grass crops and maize, etc, and maize silage is believed to be one of the most promising energy crops for biogas production (Holm-Nielsen et al., 2009). Biomass also can be used for biogas production if containing carbohydrates, proteins, fats, cellulose, and hemicelluloses as main components (Weiland, 2010). Generally, the feedstock type and the digestion system could influence the composition of biogas and biogas yield. Nowadays, in order to obtain a higher biogas yield, most of the agricultural biogas plants digest manure with some additional co-substrates for increasing the content of organic material, particularly in some developed countries. Typical co-substrates are harvest residues such as top and leaves of sugar beets, organic wastes from industries, municipal bio-waste from household, and so on(Weiland, 2010).

The biogas yield of every single substrate differs and depends on its origin, content of organic substance and substrate composition. Fig.6 shows the mean biogas yield of different substrates.

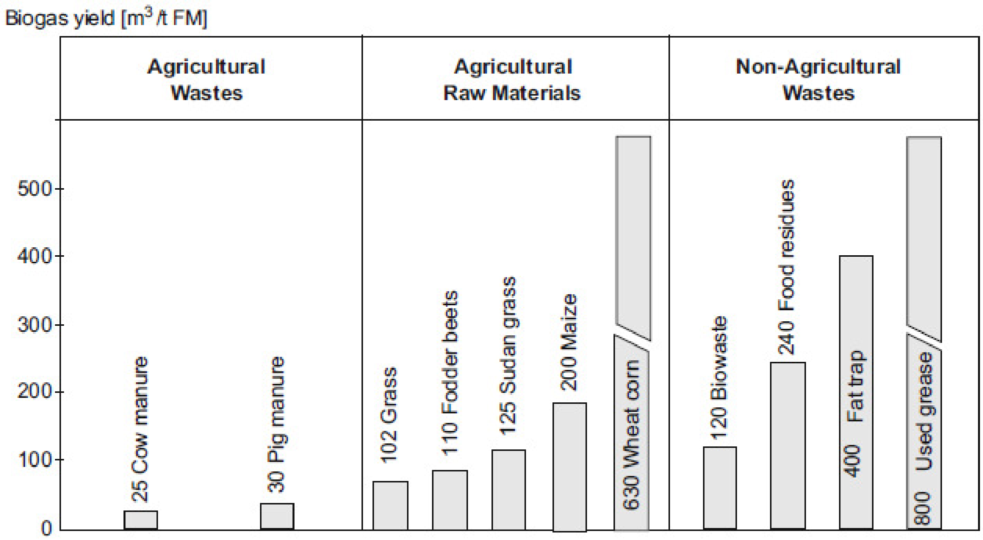

Fig.6.Mean biogas yield of various substrates (Weiland, 2010)

In the animal farming, the excrements are usually collected as slurry. Pig and cow slurries contain dry matter contents of 3 to 12%, while chicken slurry contain dry matter contents of 10 to 30% (Steffen et al., 1998). The dry matter content of other agricultural wastes differs widely. Some wasters may contain the dry matter less than 1%, but others may contain the dry matter more than 20% (Steffen et al., 1998). Besides dry matter content, the overall nutrient ratio of the waste materials is another important factor which influence the production processes, in particular the microbial biodegradation process(Steffen et al., 1998). And C/N/P ration of 100/5/1 is considered as the value for optimum degradation (Steffen et al., 1998).

There are some components, such as inorganic matter like sand, glass, metals, existing in the wasters could cause process failures, like phase separation, sedimentation, flotation etc (Weiland, 2010). Hence the attention must be paid on avoidance of these unwanted components upstream of the digesters. When these components enter the digester, the digestion process will be difficult to control properly. One example is sand. It may exist in the chicken slurry and could cause a reduction of the digester volume because of its rapid sedimentation, then leads to process failure(Steffen et al., 1998). Usually the co-substrates contain some disturbing components. It has to be considered carefully if the wastes contain large amounts of these components, and it could be pre-sorted if possible (Steffen et al., 1998).

The degradation rates of wastes could vary widely because of the different substrate composition. Generally, fats provide the highest biogas yields but require longest retention time because of their poor bioavailability, while carbohydrates and proteins have the faster conversion rates but lower biogas yield (Weiland, 2010). For instance, pig slurry shows a higher biogas yields and methane contents than cow slurry, because pig slurry has a slightly higher fat content (Steffen et al., 1998).

3.2.3 Working Conditions for AD Process

AD is a microbial process that occurs in the absence of oxygen. And in this process, several groups of microbial species degrade the complex organic materials, the producing methane and carbon dioxide ultimately. There are a lot of factors that could affect the amount of biogas produced from a specific digester, such as the substrates (particulate, soluble, biodegradable, etc), the biogas technology (wet or dry fermentation, completely mixed or fixed-bed fermentation), the temperature (mesophilic, thermophilic range), the retention time in the reactor and so on (Gallert and Winter, 2002). Balsam (2006) states that the factors related to working conditions including temperature, loading rate, mixing action, nutrients and management are extremely important to the biogas production.

Temperature

Temperature within the digester is a very important factor affecting the biogas process. In conventional mesophilic digesters, maximum conversion is considered to occur at about 35℃. When temperature decreases 11℃, the biogas production will fall by about 50%. Moreover, keeping the temperature steady is even more important. Variations of as little as 2.8℃ could cause the imbalance of the process by inhibiting methane formation and further cause system failure.

Loading rate

According to the experience, it shows that loading of manure with 6 to 10 percent solids usually works best on a daily basis. The retention time in the digester is in the range of 15 to 30 days.

Mixing action

The mixing action is necessary for the loaded manure to prevent settling and to keep the manure contacting with the bacteria. It can also prevent the scum formation and improve release of the biogas. Mixing the contents of the digester could help to maximize gas production. It can be operated by a mechanical mixer, a compressor, or a closed-circuit manure pump.

Nutrients

The process runs best with C/N ratio between 15:1 and 30:1(optimally 20:1). And most fresh animal manures meet this requirement and require no additional adjustment. When excessive amounts of exposed feedlot manure become a part of loaded manure, the nutrient imbalance could happen. And crop residues or leaves which both contain high carbon can be added to improve the digester performance.

Management

The digesters need regular and frequent monitoring in order to maintain a steady desired temperature and to prevent the system flow from clogging. If there is no proper management of the digester, a significant decline in gas production could occur and it will require months to correct the problem.

AD process could happen in a wide range of environmental conditions, but the ranges required for optimum condition are narrow. Table.5 shows the optimum condition for AD process.

Table.5. Opitimun operating condition for AD process (Engler et al., 1999)

Operating Parameter	**Typical Value**
Temperature	
-Mesophilic	35℃
-Thermophilic	55℃
pH	7-8
Alkalinigy	2500 mg/L minimum
Retention Time	15-30 days
Loading Rate	0.15-0.35 lb VS/ft^3/d

As mentioned, temperature could affect significantly the digestion rate. Although biogas production could also occur at temperatures as low as 10℃, the rate is very slow (Engler et al., 1999). Mesophilic digestion works best under the temperatures of approximate 35℃, while thermophilic digestion works best at approximate55℃.

The values of pH and alkalinity are required in the range of 7-8 and more than 2500mg/L respectively for optimum operation.

AD is a quite slow process which typically needs retention time of 15-30 days for mesophilic digestion. And thermophilic digestion is more rapid but more energy is required to heat the digester as mentioned before.

Loading rate is based on volatile solids (VS) content of the feed and is usually between 0.15 and 0.35 lb VS/ft3/d for mesophilic digestion.

3.3 Multiple Benefits of Biogas Technology

The goal of AD technology is to convert organic wasters into two categories of valuable products which are biogas and the digested substrate, commonly named digestate (Holm-Nielsen et al., 2009). The former is a renewable fuel could be further used to produce green electricity, heat or as vehicle fuel, etc. The latter can be used as an organic fertilizer or be further refined into concentrated fertilizers, fiber products, etc. In this part, I will state and discuss the benefits of AD technology, including the environmental benefits of biogas production, the benefits of digestate used as a fertilizer and the benefits of biogas used as energy source.

3.3.1 Environmental Benefits of Biogas Production

In most of the developing countries, biogas produced from anaerobic digesters is used as fuel substitute for kerosene oil, cattle dung cake, agricultural residues, and firewood (Pathak et al., 2009). Burning of those fuels causes the environmental pollution. Biogas technology is considered to provide the benefits of reducing the emission of GHGs and then mitigating global warming in ways of replacing firewood for cooking, replacing kerosene for lighting and cooking, replacing chemical fertilizers and saving trees from deforestation (Pathak et al., 2009). For example, based on the research performed by Pathak et al. (2009) in India, a family size biogas plant substitutes 316 L of kerosene, 5,535 kg firewood and 4,400 kg cattle dung cake as fuels every year. It means a family size biogas plant reduces NOx of 16.4 kg, SO_2 of 11.3 kg, CO of 987.0 kg and volatile organic compounds of 69.7 kg per year.

Methane is a major GHGs in the world, with a global warming potential (GWP) of 25 times higher than CO_2. Methane emissions could happen in any anaerobic processes with organic materials. Current disposal practices for manure slurry and food residues lead to methane released through natural processes(Klingler, 2000). It has been estimated that emission from agriculture accounts for 33% of the global greenhouse effect (Klingler, 2000). About 7% is from animal excrement which roughly equals to 20-30 million tones of methane every year

(Klingler, 2000). Through AD technology for treatment of animal excrement these gases can be used as a fuel and a well-managed AD scheme could maximize methane generation, but not release any gas to the atmosphere. Moreover, AD technology provides the environmental benefits by using renewable energy instead of fossil fuel to reduce CO_2 emissions and mitigate other environmental degradations. For instance, in developing countries the small agricultural biogas plants contribute to reduce the use of forest resources for household energy purposes, thereby slowing down deforestation, soil degradation and easing the problems like flooding or desertification.

Nitrous oxide emissions are significantly harmful to the climate change due to its high GWP of 320. Recent research states that AD of animal waste largely reduces nitrous oxide emissions because it helps to avoid emissions from storage of animal waste, reduce application of inorganic nitrogen fertilizer and avoid emissions from production of nitrogen fertilizer, etc (Klingler, 2000).

Besides the effects mentioned above, there are numbers of additional environmental benefits provided by AD technology (Source: http://www.adnett.org/).

Energy balance

A well designed and operated AD plant can achieve a better energy balance if taking emissions from transport operations into account than many other forms of energy production. The energy balance depends on the amount of energy consumed for producing energy.

Wastewater treatment

In some countries, in particular southern European countries, biogas technology has been considered as a wastewater treatment system because their manure contains very low dry matter contents and is treated similarly to wastewater. It has several environmental impacts. Firstly, anaerobic system needs much less land compared with aerobic systems for wastewater treatment. So AD could contribute to preserving valuable land resources. Secondly, it has positive energy balance because anaerobic system needs little process energy compared to generated energy.

Recycling nutrients

The products for AD plants, including liquid fertilizer and fibre, can reduce the demands for synthetic fertilizers within an overall fertilizer program if properly applied.

Reducing land and water pollution

Inappropriate disposal of animal slurries could result in land and ground water pollution. AD technology creates an integrated management system which reduces the possibility of this problem happening.

Supporting Organic Farming

AD has the potential to support Organic Farming when used as part of a closed loop. Generally organic fertilizer contains weed seeds and microorganisms resulting in pests. They cause the use of herbicides and pesticides in farming system. However, AD process could reduce the ability of seeds to germinate and minimizes the survival of microorganisms. So the use of digestate from AD as a fertilizer could contribute to organic farming due to this effect.

Reducing odour

For many farmers solving the problem of odour is an important reason to install a biogas plant. AD for manure treatment allows farmers to remove manure which causes the odour complains. It is reported that AD could reduce the odour from farm slurries and food residues by up to 80%.

3.3.2 The Benefits of Digestate Used as Fertilizer

Along with the biogas produced, AD also transforms the added feedstock into digestate that can be used as a fertilizer which is high in nitrogen, potassium and phosphorus contents. The digestate can be stored then used in farmlands for crop production at an appropriate time without further treatment. Besides, it can be separated to produce fibre and liquor. The fibre can be sold or used as a good fertilizer or a soil conditioner, while the liquor contains various nutrients and could be used as a liquid fertilizer which could be sold or used on-site. Fig.7 shows mass balance for AD process. Usually 7-25% of Fibre and 75-95% of Liquor are produced

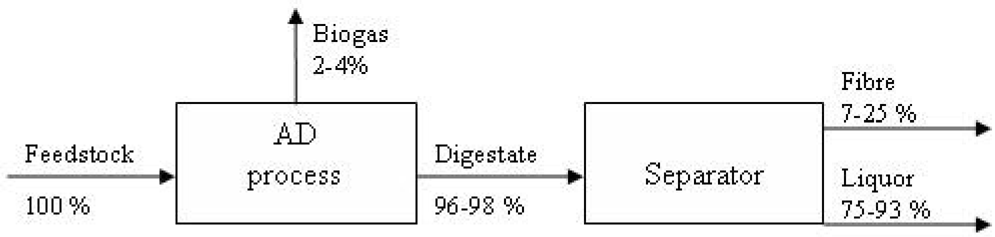

Fig.7. Simplified mass balance for AD (AGROBIOGAS, 2006)

The digestate almost remains all the non-degradable substances from the original feedstock as well as all plant nutrients. The nutrient content of digested slurry depends on which type of feedstock (manure, co-substrates, etc) is digested. Moreover, AD process of manure or other organic biomass could transform part of organic bound nutrients to a mineral form(Ørtenblad, 2000). This effect is very important for nitrogen. In AD process, part of the organic nitrogen such as proteins is released as ammonium(Ørtenblad, 2000). Ammonium is readily available for the crops when it is applied to the fields(Ørtenblad, 2000). It also helps to reduce the need for using additional mineral nitrogen fertilizers. So the digestate from anaerobic fermentation is considered as an improved and valuable fertilizer which could substitute mineral fertilizer due to the increased availability of nitrogen to crops. In addition, anaerobic treatment minimizes the survival of pathogens from the feedstock, which is important for the digestate used as a fertilizer(Ørtenblad, 2000).

Table 6 shows the differences of average content of dry matter and various nutrients among pig, cattle and digested slurries from two different biogas plants. Digested slurry 1 is from a Danish CAD plant. Digested slurry 2 is from a digested mixture of 50% pig slurry, 25% cattle slurry and 25% organic industrial waste (Birkmose 2007).

Table.6. Average content of dry matter and nutrients in pig, cattle and two different digested slurries

	Dry Matter	**Total-N**	**Amm-N**	**P**	**K**	**A-N/T-N**	**Source**
	Percent	**Kg/ton**					
Pig Slurry	3.8	4.8	3.6	1.1	2.5	0.7	(Ørtenblad, 2000)
Cattle Slurry	7.0	4.3	2.6	0.8	3.4	0.6	
Digested Slurry 1	4.9	4.6	3.3	1.0	2.8	0.7	
Digested Slurry 2	4.8	4.4	3.5	1.0	2.3	0.8	(Birkmose, 2007)

For example, Nepal usually has to import mineral fertilizers. Due to the installation of biogas digesters, it has been estimated that every year 4329 tons nitrogen, 2109 tons phosphorous and 4329 kg potassium could be saved (Gautam et al., 2009). This means almost US$300,000 could be saved every year (Gautam et al., 2009).

The reuse of the digestate from AD as fertilizer presents a sustainable way to control and direct nutrients in society. If it is implemented widely, it will be possible to recover the broken nutrient cycle between the productive soils of the countryside and the consuming people of the cities nowadays, which could facilitate the reduction of the use of mineral fertilizers (Lantz et al., 2007).

3.3.3 The Utilization of Biogas

Biogas is an ideal energy source and suitable for practically all the various fuel requirements in the household, agriculture and industrial sectors. However, the different standards of gas quality are required by the individual gas utilization, which make purification and upgrading of the gas necessary.

There are various biogas utilization purposes, including: production of heat or steam (the lowest value chain utilization); industrial energy source for heat, steam, electricity, cooling, etc; electricity production with CHP; upgraded and used as vehicle fuel; upgrading and injection into the natural gas grids; fuel for fuel cells, etc.

In the developing countries the most common utilization of biogas from small-scale plants is on-farm application, including cooking, lighting, heating (space heating, water heating, and grain drying), cooling, etc. In most cases, the equipment designed for burning natural gas requires slightly modifications to fit the different burn characteristics of biogas (Balsam, 2006).

In a number of industrial applications, biogas can be used in small-scale industrial operations for direct heating applications such as in scalding tanks, drying rooms and in the running of internal combustion engines for shaft power needs (J.-F.K. Akinbami, 2001). It could also be used for steam production.

Biogas produced by co-substrates of manure with energy crops or harvesting residues may contain H_2S whose level is in the range of 100-3,000ppm (Weiland, 2010). However, the CHP station for biogas utilization requires level of H_2S below 250ppm, in order to avoid excessive corrosion and expensive deterioration of lubrication oil (Weiland, 2010). Today biological desulfurization is a main method for removal of H_2S. Small-scale biogas plants are widely used for CHP in decentralized on-farm units. Typical output from CHP station based on biogas is about 2/3 thermal and 1/3 electricity at 80-90% efficiency (Poeschl et al., 2010).The generated heat is commonly used for heating of digesters and the local residential houses and animal stalls, but it also could be used for heat transmission to public buildings, grain drying, production of animal feed, and drying of wood fuel. Nevertheless, heat transmission causes heat losses in the range of 3.5-20% dependent on the transmission distance (Poeschl et al., 2010). Electricity generated from CHP could be sold to independent energy supplies.

In some EU countries, biogas is scrubbed of carbon dioxide and other impurities to generate a CH_4-enriched biogas which is 95–98% CH_4 (Murphya et al., 2004). This CH_4-enriched biogas could be used as vehicle fuel. For example, Volvo has developed a bi-fuel car, which runs on petrol and biogas (Murphya et al., 2004).This offers flexibility to the consumer and could maximize utilization of the biogas. A remarkable example of biogas utilization as vehicle fuel is Sweden. It is reported that the market for such biogas utilization has been increasing rapidly in the last decade, and today there are 15,000 vehicles based on upgraded biogas in Sweden (PERSSON et al., 2007). It is predicted there will be 70,000 vehicles running on biogas supplied from 500 stations, by the year of 2010-2012 (PERSSON et al., 2007).

In addition, CH_4-enriched biogas could also be introduced into the natural gas-grid to support a series of biogas service stations. In some EU countries like Germany, Sweden and Switzerland have developed the quality standards for biogas injection into the natural gas-grid (Weiland, 2010). Upgrading and injecting biogas into the natural gas-grid is an efficient way of integrating the biogas into the energy sector. Since biogas cannot always be used nearby the production plants, injecting upgraded biogas into the natural gas-grid offers the opportunities to transport and use biogas in the larger energy consumption areas, where the population is intensive (Holm-Nielsen et al., 2009).

These two applications of biogas which are utilization as vehicle fuel and injection into the gas-grid have become more and more important because the gas can be used in a relatively energy efficient way.

Table.7. summary of the benefits of AD technology concerning environmental impacts, digestate values and biogas utilization

Scope	Benefits/Values
Environmental Impacts	1. reducing the environmental pollution by replacing kerosene oil, cattle dung cake, agricultural residues, firewood, etc in rural area of developing countries 2. partly contributing to save forest resources(e.g. trees) from deforestation in some developing countries 3. benefits of reducing GHGs emissions then mitigating global warming - reducing CO_2 emissions by replacing the fossil fuel - reducing methane emissions from organic materials(e.g. animal excrement) - reducing N_2O emissions in ways of avoiding emissions from storage of animal waste, reducing application of nitrogen fertilizer, etc. 4. achieving a better energy balance 5. used as wastewater treatment system in some countries 6. recycling nutrients 7. preventing land and water pollution from inappropriate disposal of animal slurries 8. having potential to support organic farming 9. reducing odour caused by manure etc.
Digestate Values	1. The digestate can be used on-site for crop production at an appropriate time without further treatment. 2. The digestate can be separated to produce fibre and liquor. 3. The digestate could substitute chemical fertilizer due to the good availability of nitrogen to crops. 4. The reuse of digestate represents a sustainable way to control

	nutrients between productive soils and consuming people. etc.
Values of biogas itself	1. as a fuel for cooking, lighting, heating, etc (on-farm application) 2. used in small-scale industrial operations, such as heating, drying rooms, running the internal combustion engines, etc 3. electricity production with CHP 4. upgraded and used as vehicle fuel 5. upgrading and injection into the natural gas grid 6. as a fuel for fuel cells etc.

3.4 Installation Costs and Economic Performance of Biogas Plants

The economy of a biogas plant includes the investments cost, the operation and maintenance costs, the costs of raw materials and the income from the sale of biogas as generated electricity, heat, vehicle fuel, etc. Sometimes, there are other values could be added, such as value of digestate as a fertilizer. The installation costs of a typical biogas plant is large and site specific which depends on the location of the plant, the biogas technology applied in the plant, labor cost at the site location, community participation, etc. The economic performance of a biogas plant could also be site specific which depends on the current markets for the input and outputs, the policies related to the biogas production or utilization, the supports or subsidies from the government, etc. In this part, I will discuss the installation cost and economic performance of the biogas plants briefly.

3.4.1 Installation Costs of the Biogas Plant

The costs for installing a biogas plant are usually high and largely differ among various countries. For example, in EU countries, Switzerland and Austria have the highest costs for the farm-scale plant, while Italy and Germany have the lowest costs (Higham, 1998). However, the differences are largely caused by different technical approaches. In Germany, a lot of plants are installed with readily available parts by farmers(Higham, 1998). Therefore, such biogas plants may have higher maintenance costs, poorer performance and shorter lifecycle. The Italian plant has the low costs because it usually uses a relatively simple tank covered with a plastic membrane as the reactor(Higham, 1998). However, the Swiss and Austrian plants appear to be commercially supplied equipment. Capital grants may be a factor driving these different approaches to the technology applied by the biogas plants (Higham, 1998). Switzerland and Austria have capital grants from public funds while Italy and Germany do not (Higham, 1998). So it is important to consider if the funding is available, which technology is suitable for the context, etc, when assessing the installation costs of a biogas plant.

Balsam (2006) states that the installation costs of AD system for animal manures could significantly vary, depending on its size, intended purposes and sophistication. For example, covered lagoon system costs as low as US$25,000 for 150 animals of swine and as high as US$1.3 million for 5,000 animals of dairy cows. Plug flow system costs in the range of US$200,000 for 100 dairy cows to US$1.8 million for 7,000 dairy cows.

In the developing countries, the high installation costs may inhibit the initiation of a biogas project. For example, a recent studies in Nigeria shows that a family-scale biogas digester of 6.0 m^3 produces 2.7 m^3 biogas per day in order to meet the cooking requirement of a household of 9 persons (J.-F.K. Akinbami, 2001). This project has been predicted to have a capital cost of US$500, annual expenditure of US $70 and annual benefit of US$160, which appear to have a good economic potential (J.-F.K. Akinbami, 2001). However, the users who are the poor urban and rural households could not afford such high first costs. Since biogas technology has the long term both economical and environmental benefits, it may be worth introducing some financial incentives into Nigerian biogas industry, especially in the rural areas. The incentives could include soft loans as well as direct or indirect subsidies on the biogas technology. Some organizations such as the Poverty Alleviation Program, Community Banks, State and Local Governments, Commercial Banks and even private bodies could help to found these incentives under the government regulations and policies (J.-F.K. Akinbami, 2001).

3.4.2 Economic Performances of the Biogas Plant

Firstly, I selected two large-scale biogas projects from China and intent to simply analyze their economic performances.

Table.8. simply economic analysis of two cases of biogas projects from China

	Project 1	**Project 2**
Input Materials	Domestic wastes and manures	Organic waters from the combined units of the plant(feed factory, slaughterhouse, fishery, etc)
Output	10,000 m^3/day biogas (9000 m^3 for generating electricity with CHP), 110 tons/day fertilizer,	500 m^3/day biogas (470 m^3 for generating electricity with CHP), 2.8 tons/day fertilizer
Capital Investment	100.3 million Yuan	2.8 million Yuan
Operation Costs	70.83 million Yuan/year	0.22 million Yuan/year
Revenue	89 million Yuan/year	0.66 million Yuan/year
Payback Periods	5.5 years	6.4 years
Source	http://www.biogas.cn/Z_Show.asp?ArticleID=1142&ParentClassName=%B9%A4%B3%CC%CA%B5%C0%FD (in Chinese)	http://www.doc88.com/p-382735419832.html (in Chinese)

According to the calculations in the above table 8, it shows that these two projects have the payback periods of 5.5 years and 6.4 years, respectively. Without governmental financial supports, the enterprise may not be interested in investing in the project like those two cases due to such high capital costs and quite low revenues.

Higham (1998) made economic analysis of the generic biogas plants based on the data available from the real plants. The result of that analysis shows the biogas plants have long payback periods and low internal rate of return (IRR). All these cases show the biogas project may not be strongly economically attractive.

However, there is still opportunity to improve the economic performance of biogas plants, such as using the digester with lower costs, improving gas yield, obtaining the gate fees from digesting feedstock like kitchen wastes or food processing wastes, etc(Higham, 1998). Economics of a biogas plant could be influenced by the conceptual design of the system due to the effect on capital and operation costs as well as plant revenue. For instance, commonly agricultural wastes require no disposal fees but other agro-industrial wastes do. Digestate as a fertilizer from biogas plant could be sold if the market developed. Sometimes the digestate could be returned to farmers who provide feedstock free of charge, if the farmers have some financial stake in the biogas plant (Higham, 1998). In order to improve the economic performance it is important to analyze the particular situation of a biogas plant in terms of feedstock, AD technology, digestate application, integrating with related industries, available subsidy or supports from government, etc.

In addition, if the environmental benefits of the biogas plant are considered, the economic performance could be further improved. Apparently, the plant can contribute to reduce GHGs emissions, reduce water pollution and odour pollution, etc. If these benefits are added to the economic value, they could become a further income stream to the plant. For example, China has financially benefited from the Clean Development Mechanism (CDM) projects based on biogas technology. There is a report(Yapp and Rijk, 2005) shows a lot of developing countries having large potential to develop CDM projects of biogas technology, which could contribute to reduction of GHGs emissions as well as obtain economic returns. In some EU countries, in order to meet targets of the Kyoto protocol, the large power plants (>20MW thermal capacity) have the limitations for maximum CO_2 emissions, but additional emissions are allowed to be purchased from a dedicated stock markets under the EU Greenhouse Gas Emissions Trading System (EUETS) (Poeschl et al., 2010). Currently the market price is roughly €20/tonCO_2, which could add value of roughly €8.3/MWH for energy supply from biogas (Poeschl et al., 2010).

Chapter 4 Resource Requirements and Multiple Values of the Household Biogas Plant in China

As mentioned, China owns a large number of household biogas plants in rural areas. In this chapter, firstly, I will do the calculations based on a particular area of China as representative. I will calculate the biogas demand, energy saving, biogas digester size, feedstock demand, water demand, reduction of CO_{2e}, digestate yield as a fertilizer, the economic performance, etc, from a biogas digester which is installed to produce biogas for covering the energy demand of one household. Then I will discuss how biogas technology could influence the energy consumption and utilization; what the resource requirements for biogas production in term of the feedstock supply are; what its environment benefits in term of reduction of GHGs emissions are, what the values of by-product (digestate) is. In addition, the reasons why China has partly made a success in implementing the biogas technology will also be discussed.

4.1 Analysis and Calculations on a Household Biogas Digester in Rural China

In this part, I intend to calculate and analyze the following questions in rural China. How much energy demand is required by one household for cooking, lighting, breeding, heating water, etc. How much biogas is required to be produced to cover one household energy demand? How much energy is saved through biogas replacing other fuels? How much feedstock for biogas production is needed? How much water is needed? What is its environmental benefit (How much CO_{2e} emissions are reduced)? What is the value of digestate used as organic fertilizer (How much fertilizer is produced? How much farmland is supported)? I will also do the simply economic analysis according to some calculations.

The structure for this analysis is shown in Fig.8. Some data related to this calculation or analysis is collected from Chinese sources.

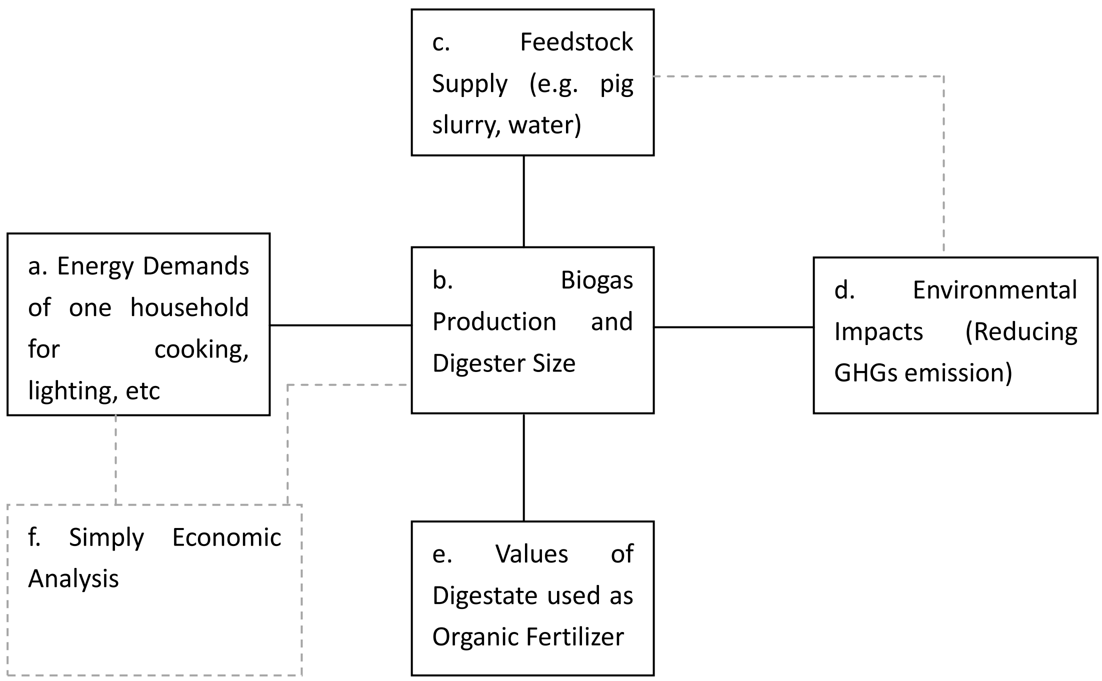

Fig.8. structure of the analysis

In this study, I take the situation of family energy consumption in Lianshui as a representative to do the calculations and analysis. Lianshui County, located in the east of Xu Huai plateau, Jiangsu Province, is an under-developed area whose economic structure is based on agriculture. Most families have four or five people. (Wang and LI, 2005).

a. Energy Demands of one household for cooking, lighting, etc

Table 9 shows the energy consumption and effective using part (energy demand) of various energy resources for lighting, cooking, breeding, heating water, etc per capita in Lianshui County in 2003. It does not include the consumption of electricity. This table also shows straw, firewood, coal have relatively low effective using rates. However, the effective using rate of burning biogas could approach to 60% (Wang et al., 2007).

Table 9. Per capita rural household energy consumption and energy demand in Lianshui County in 2003. (Wang et al., 2007) (**unit: kgce**)

*The unit of **kgce** is widely used in Energy Industry of China.*

1kgce= 7000kcal= 29307.6KJ (Source: http://baike.baidu.com/view/683337.htm)

In order to simplify calculations, I will remain this unit in this chapter.

	Straw	**Firewood**	**Coal**	**Kerosene**	**LPG**	**Total**
Lighting	-	-	-	0.07	-	0.07
Cooking	80.20	138.42	27.95	-	4.96	251.53
Breeding	11.12	4.58	0.50	-	-	16.20
Heating water	20.55	-	2.75	-	0.33	23.63
Remainder	0.40	-	-	-	-	0.40
Total of Energy Consumption	112.27	143.0	31.2	0.07	5.29	**291.83**
Total of Effective Consumption (Energy Demand)	25.74	20.21	6.86	-	3.17	**55.98**

Effective Using Rate	23%	14%	22%	-	60%	**19%**

According to table 9,

Total Energy Consumption (TEC) = 291.83 kgce.Capita^{-1} .Year^{-1} (=2,042,810kcal.Capita^{-1} .Year^{-1})

Energy Demand (DE) = 55.98 kgce.Capita^{-1} .Year^{-1} (=391,860kcal.Capita^{-1} .Year^{-1})

The effective using rate of burning biogas is approximate 60% (burning biogas could loss 40% thermal value) as mentioned, so:

ED (Biogas) = 55.98/60% =93.3 kgce. Capita^{-1} .Year^{-1} (=653,100 kcal.Capita^{-1} .Year^{-1})

Every household has 4-5 people (pick 4 people/ household), so:

ED (Biogas) =93.3×4 =373.2 kgce. Household^{-1} .Year^{-1} (=2,612,400kcal.Household^{-1} .Year^{-1})

TEC=291.83×4 =1167.32 kgce.Household^{-1} .Year^{-1} (=8,171,240kcal.Household^{-1} .Year^{-1})

Energy Save by Biogas (ES) = TEC – ED (Biogas) =1167.32-373.2 =794.12kgce.Household^{-1} .Year^{-1} (=5,558,840 kcal.Household^{-1} .Year^{-1})

b. Biogas Production and Digester Size

T*hermal value of biogas ≈ 0.7 kgce/ m^3 (one m^3 biogas producing 0.7 kgce energy) (Source: http://baike.baidu.com/view/683337.htm), so:*

Biogas Demand (BD) =ED (Biogas) /0.7 = 373.2/0.7= 533.1 m^3.Household^{-1} .Year^{-1} =533.1/365 (day/year) =1.46 m^3.Household^{-1} .day^{-1}

Past experience shows in Lianshui County the biogas output from a 8 m^3 digester is 370 m^3/ year (Wang et al., 2007), so:

Biogas Output (BO) = 370/8/365 (day/year) = 0.127 (m^3biogas). (m^3digester)$^{-1}$. Day^{-1}

In order to meet the Biogas Demand for a household, a digester should be designed as:

Biogas Digester Volume (BDV) = 1.46/ 0.127= 11.5 $m^3 \approx$ 12 m^3

c. Feedstock Supply

The investigation(Wang and LI, 2005) shows one farmer in Lianshui County raise 4-5 pigs and the plenty of straw is available. In rural China, most of families own farmland to cultivate some crops. So pig manure (excreta) with straw/crop residues could be fed to feedstock to produce biogas. In order to simplify the calculations, the pig manure is assumed to be only input material of the feedstock.

According to the data from Fig.6, the biogas yield from pig manure is 30 m^3/ ton, so:

Pig Manure Demand (PMD) = 1.46 /30 = 0.049 tons.Household^{-1}. Day^{-1} = 49 kg.Household^{-1}. Day^{-1}

Some data shows in China one pig produces 2.1 ton manure per year. (Source: http://www.biogas.cn/). So one pig could produce 5.8kg manure per day.

It means one household needs to raise 8~9 pigs for biogas production. In practice, straw or crop residues could also be fed into feedstock with manure. Based on some experience in rural China, 50% manure with 50% straw is considered to work well as a feedstock (Source: http://www.biogas.cn/). Therefore one household needs to raise 4~5 pigs for biogas production, while in fact one household indeed raises 4-5 pigs in Lianshui country as mentioned.

As mentioned in chapter 3, the loading rate of AD process should be in range of 6%-10% (mean value 8%). Some reports show in rural China, the dry matter content in pig manure is 18% (Source: http://baike.baidu.com/view/43456.htm). It means 1ton pig manure requires 1.25 ton water. So, Water Demand(WD)= $49 \times 1.25 = 61$ kg. Household^{-1}. Day^{-1}

Therefore, one household needs 49kg pig manure with 61kg water as feedstock to produce biogas per day. In practice, 49kg pig manure could be substituted by 24.5kg pig manure with the same amount straw/crop residues.

d. Environmental Impacts (Reducing GHGs emission)

E =E1-E2

E: total reduction of CO_{2e} on this biogas project

E1: reduction of CO_{2e} due to reducing GHGs emission from all other fuels

E2: increase of CO_{2e} due to GHGs emission from using biogas as fuel (biogas combustion)

(1) E1

According to IPCC reports (2006, Vol2, Table 1.4 and 2.5), Default Emission Factors of various fuels for stationary combustion in the residential categories are shown in Table 10.

Table10. Default Emission Factors (DEF) of various fuels for combustion

(Source: https://www.ipcc.ch/meetings/session25/doc4a4b/vol2.pdf)

Unit: kg/TJ (1TJ=10^{12}J=10^9KJ)

	Straw	Firewood	Coal(anthracite)	Kerosene	LPG
CO_2	100000	112000	98300	71900	63100
CH_4	30	30	1	3	1
N_2O	4	4	1.5	0.6	0.1

According to Table 9, the Energy Consumption (EC) of various fuels per capita per year is:

As mentioned, 1kgce=7000kcal=29307.6KJ

EC (straw)= 112.27 kgce.Capita^{-1}.Year^{-1} = 3.29×10^6 KJ.Capita^{-1}.Year^{-1}

EC (firewood)= 143 kgce.Capita^{-1}.Year^{-1} = 4.19×10^6 KJ.Capita^{-1}.Year^{-1}

EC(coal)= 31.2 kgce.Capita^{-1}.Year^{-1} = 0.91×10^{6} KJ.Capita^{-1}.Year^{-1}

EC (kerosene)= 0.07 kgce.Capita^{-1}.Year^{-1} = 0.002×10^{6} KJ.Capita^{-1}.Year^{-1}

EC (LPG)= 5.29 kgce.Capita^{-1}.Year^{-1} = 0.16×10^{6} KJ.Capita^{-1}.Year^{-1}

The Default Emission Factors of CH_4 and N_2O are significantly smaller than Default Emission Factor of CO_2 for every fuel in Table 10. Therefore, in order to simplify the calculations, the effects of CH_4 and N_2O will not be included in the following calculations. It will hardly influence the results of calculations although GWP of CH_4 is 25 times higher than CO_2 and GWP of N_2O is 320 times higher than CO_2.

CO_2 Emission (straw) = EC (straw) ×DEF (CO_2, straw) =3.29×10^{6}×100000×10^{-9} = 329kg. Capita^{-1}.Year^{-1}

CO_2 Emission (firewood) = EC (firewood) ×DEF (CO_2, firewood) =4.19×10^{6}×112000×10^{-9} = 469kg. Capita^{-1}.Year^{-1}

CO_2 Emission (coal) = EC (coal) × DEF (CO_2, coal) =0.91 × 10^{6} × 98300 × 10^{-9} =89kg.Capita^{-1}.Year^{-1}

CO_2 Emission (kerosene) = EC (kerosene) ×DEF (CO_2, kerosene) =0.002×10^{6}×71900×10^{-9} = 0.14kg. Capita^{-1}.Year^{-1}

CO_2 Emission (LPG) = EC (LPG) ×DEF (CO_2, LPG) =0.16×10^{6}×63100×10^{-9} = 10kg. Capita^{-1}.Year^{-1}

So:

E1 = CO_2 Emission (straw) + CO_2 Emission (firewood) + CO_2 Emission (coal) + CO_2 Emission (kerosene) + CO_2 Emission (LPG) = 897.14 (kgCO_{2e}).Capita^{-1}.Year^{-1} =0.897(tonCO_{2e}). Capita^{-1} .Year^{-1}

(2) E2

E2= CO_2 emission from CH_4 combustion + CO_2 release from biogas

Normally biogas contains 60% CH_4 and 35% CO_2 (Source: http://www.biogas.cn);

CH_4 combustion: $CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$

CO_2 density= 1.96kg/m^3,

So:

E2= 1.46/4 × 365(day/year) × 60% (CH_4/biogas) × 1.96 + 1.46/4 × 365(day/year) × 35% (CO_2/biogas) × 1.96 = 248.1 (kg CO_{2e}). Capita^{-1}.Year^{-1} =0.248(tonCO_{2e}).Capita^{-1}.Year^{-1}

(3) E

E= E1-E2 =0.897-0.248=0.649 (tonCO_{2e}).Capita^{-1}.Year^{-1}

In China, CO_{2e} emissions from fuel consumption is 4.57 ton.Capita^{-1}.Year^{-1}

(Source: http://www.carbonplanet.com/country_emissions), so:

E/4.57 =0.649 /4.57 = 14.2%

The reduction of CO_{2e} emissions per capita from this project accounts for 14.2% of total CO_{2e} emissions per capita in China.

Therefore, if one household installs a biogas digester to produce 1.46m^3 biogas per day for meeting their own demands, it could contribute to reducing GHG_S emission of 2.596 ton CO_{2e} yearly. The reduction per capita accounts for 14.2% of total capita CO_{2e} emissions in China.

e. Values of digestate used as Organic Fertilizer

According to Fig.7, 96-98% (mean value 97%) feedstock could be converted into digestate, so:

Digestate Yield (DY) =(49+61) × 365(day/year) × 97%= 38,946kg.Household^{-1}.Year^{-1} =39 ton. Household^{-1}.Year^{-1}

Digestate almost remains all nutrients from feedstock by AD process, and it could be used as a valuable organic fertilizer. *Total amount of various nutrients (N, P, K) could be figured according to Table 6:*

39 ton digestate contains 406.0kg N (Nitrogen), 93.0kg P (Phosphorus) and 211.0kg K (potassium).

In China, double-cropping systems (wheat-maize, rice-wheat and rice-rice) receive at least 500kg.hectare^{-1}.year^{-1} nitrogen fertilizer.

(Source: http://www.beluga.is/default.asp?Page=472)

Fertilizer application rates of N:P:K for rice cropping is 1 : 0.39 : 0.48 (Tan et al., 2003). So:

In rice-rice double-cropping system, 406kg N (Nitrogen) is sufficient for 0.81 hectare land per year; 93kg P (Phosphorus) is sufficient for 0.48 hectare land per year; 211kg K (potassium) is sufficient for 0.88 hectare land per year. Therefore, 39 ton digestate used as organic fertilizer could at least support for rice cultivation in 0.48 hectare farmland.

f. Simply Economic Analysis:

(1) Capital Costs

The capital costs are site specific because there are varieties in building materials and labor costs among different areas. Due to lack of the related economic data of Lianshui Country, I collect the data from Wencheng County, Zhejiang Province, whose condition of economic development is quite similar with Jiangsu Province.

It is estimated that the capital costs (building materials and labor) of one 8m^3 concrete biogas digester is about 1884yuan.

(Source: http://www.wzagri.gov.cn/html/main/nydtView/9570.html)

So:

Capital Costs of 12m^3 digester = 1884/ 8×12 =2826 yuan. Household^{-1}

(2) Governmental Subsidies

According to the related rules, the governmental subsidies for biogas digesters are also site specific. The following data is collected from the same source above (Source; http://www.wzagri.gov.cn/html/main/nydtView/9570.html).

In Wencheng County, the subsidies for one household biogas digester are from central *government finance (800 yuan), provincial government finance (200 yuan), city government finance (700 yuan) and county government finance (100 yuan).*

So:

Governmental Subsidies for one household biogas digester= 800+200+700+100 =1800 yuan. $Household^{-1}$

(3) Economic Benefits

It is difficult to evaluate the real economic benefits of using biogas. Since the input materials are free of cost and the digestate is returned to the household free of charge, here I will only calculate the direct economic benefits of biogas replacing the non-free fuels. Straw and firewood are free of cost. The amount of kerosene utilization is very small. So the economic benefits are mainly from biogas replacing coal and LPG.

Energy Demand of coal = 31.2 $kgce.Capita^{-1}.year^{-1}$

Energy Demand of LPG =5.29 $kgce.Capita^{-1}.year^{-1}$

T*hermal value of coal = 0.7143 kgce/kg(1kg coal producing 0.7143 kgce energy)(Source: http://www.coalchina.org.cn/page/info.jsp?id=20937)*

T*hermal value of LPG= 1.7143 kgce/kg (1kg LPG producing 1.7143 kgce energy) (Source: http://www.coalchina.org.cn/page/info.jsp?id=20937)*

So:

Coal Demand=31.2/0.7143 = 43.7 $kg.Capita^{-1}.year^{-1}$= 174.8 $kg.Household^{-1}.year^{-1}$

LPG Demand =5.29/1.7143 = 3.1 kg. $Capita^{-1}$ $.year^{-1}$=12.4 $kg.Household^{-1}.year^{-1}$

The mean price of Coal for household utilization is about 900 yuan/ton (Source: http://www.sxcoal.com/wym/index.html)

The mean price of LPG in Lianshui is about 4.6 yuan/kg (Wang et al., 2007)

So:

Coal Costs=174.8×900/1000 = 157.3 $yuan.Household^{-1}.year^{-1}$

LPG Costs = 12.4×4.6= 57 yuan. $Household^{-1}.year^{-1}$

Economic Benefits = Coal Costs + LPG Costs = 214 yuan. $Household^{-1}.year^{-1}$

(4) Payback Periods = (Capital Costs – Governmental Subsidies) /Economic Benefits = (2826-1800) / 214 = 4.8 year

4.2 Discussion Based On Calculations and Findings

According to the calculations and analysis above, Fig.9 shows the calculation results which are resource requirements and multiple values of one household biogas digester in rural China.

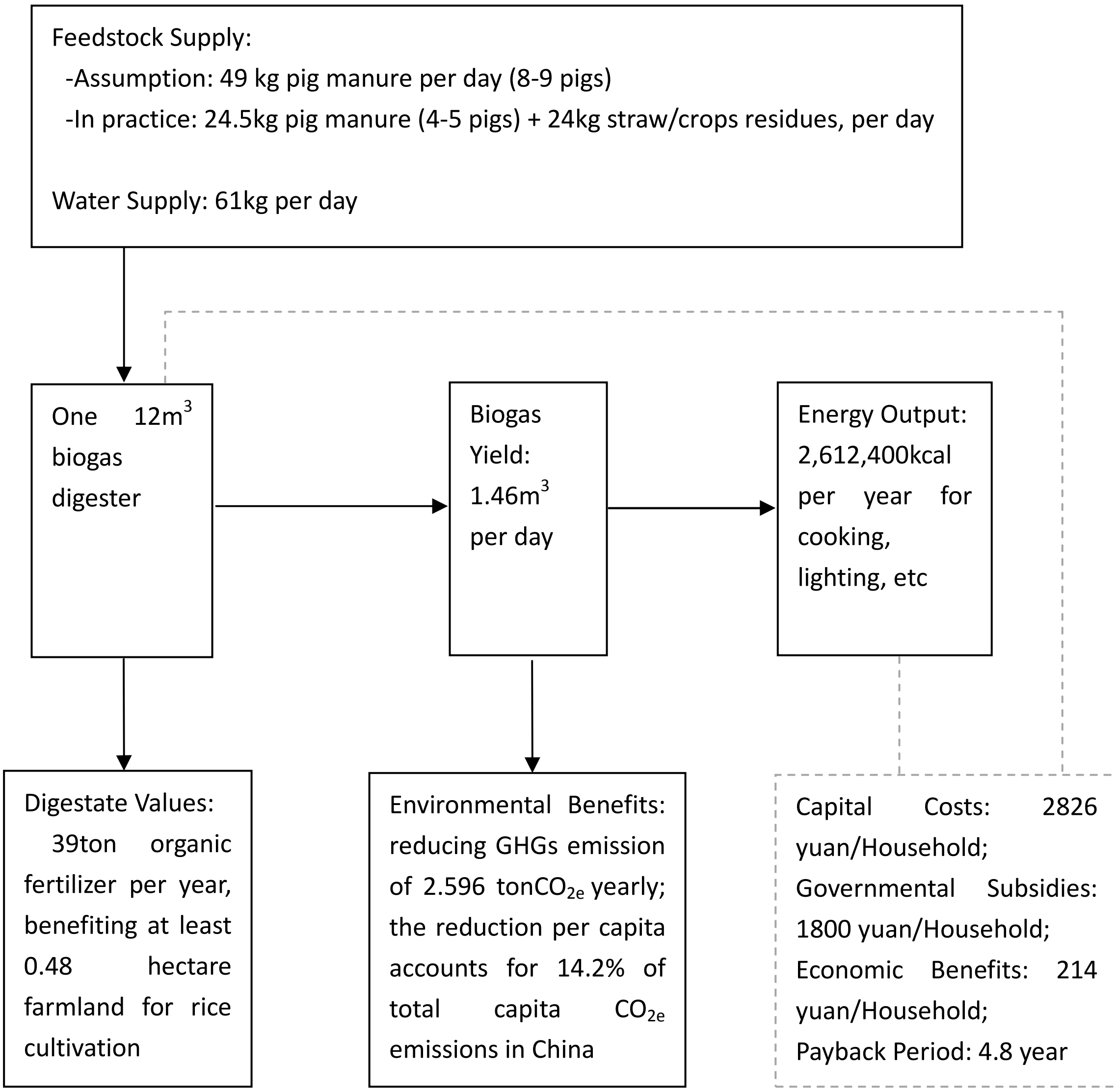

Fig.9 summary of the calculation results

As mentioned, the global energy demand will continue to grow during this century. However, the energy supply has become an important challenge because large proportion of it relies upon non-renewable resources. Biogas is considered as one of substitutes since biogas technology is relatively simple and cheap. According to the calculation above, it shows installing a $12m^3$ digester by one household could cover 2,612,400kcal energy demand yearly. Moreover, it could replace the fuels of straw, firewood, coal, kerosene and LPG in rural areas. Because the effective using rates of straw, firewood, coal and kerosene are relatively low, biogas could not only replace them but also save the energy consumption which is 5,558,840kcal per year in this case. In most of developing countries, particularly in rural areas, biogas is used in the lowest value chain such as providing heat or steam. However, it has more widely utilization purposes, particularly in the developed countries, such as providing electricity (with CHP), using as vehicle fuel, injecting into the natural gas grids, producing fuel cells, etc. However, it certainly requires more advanced post-treatment technologies of biogas as well as coordination with other industries. Biogas technology has influenced the energy consumption and utilization by replacing various fuels and saving large energy consumption in this case. It has potential to benefit energy utilization more efficiently and more widely based on the related technology development.

In the previous chapter, I have compared some different types of biogas plant. All of them have their own characteristics, advantages and disadvantages. Different types are suitable for different situations, including available input materials, available biogas technology, climate conditions, economic conditions, plant scale, etc. Each factor need to be considered for the plant design. In this case, fixed dome digester could be one of suitable types based on past experience of rural China. So in this case one household could build a $12m^3$ fixed dome digester to produce $1.46m^3$ biogas for daily utilization. In addition, China has developed and widely used different plant types of eco-agricultural model. They show a lot of advantages and benefits when combining a few units with biogas digester into an integrated system, which other rural area could refer to. In order to produce biogas successfully, the working conditions should be considered, such as temperature, PH value, loading rate, C/N ratio, etc. Because of warm climate, the digester without heating system could be applied in this area. However, in northern rural areas of China, the biogas yield could be very low or even none in winter without additional heat supply. The eco-agricultural model could help to solve this problem as mentioned. So the requirement of temperature could affect the plant design. In addition, the requirement of loading rate could affect the feedstock and water supply. In rural areas, most people lack of practical knowledge, so they have to rely on the educations and technology supports from contractors or consultants. This is also very important for biogas production in rural areas.

Feedstock for biogas production could derive from different agricultural, industrial and municipal sources. In this case the feedstock for biogas production could be pig manure with straw/crop residues. As mentioned, in order to simplify the calculations, I only used pig manure as the feedstock. However, in practice, the manure from 4-5 pigs with about same amount (24.5kg) of straw/crop residues as feedstock is sufficient for the biogas production per day. These input materials are readily available under currently local conditions in this case. In addition, 61kg water per day also needs to be added into feedstock in order to meet the requirement of loading rate for biogas production, and this amount of water is available in this area. However, in a lot of rural areas, the insufficient input materials and water resource could be the limits to produce biogas. While for different purposes, the feedstock could derive from other resources. In some cases, biogas plants are installed not only to produce biogas but also to treat the wastes or the waste water, particularly large-scale biogas plants in developed countries. Some large-scale biogas plants usually link with the particular industry for feedstock supply. In addition, the feedstock types could significantly influence the biogas yield. Therefore, a lot of factors should be considered when choosing the feedstock for biogas production, such as locally available input materials, the composition of feedstock, the plant purpose and scale, the available biogas technology, etc.

As mentioned, biogas technology provides a lot of environmental benefits. According to Fig.9, it shows in this case one digester could contribute to reduce GHGs emissions of 2.596 tonCO_{2e} yearly. The capita reduction of CO_{2e} accounts for 14.2% of total capita CO_{2e} emissions in China. The proportion is not large, but the contribution could be great because of large populations in China as long as the biogas technology is widely disseminated over the rural households. Moreover, this part of calculations does not contain the reduction of CH_4 emissions from animal manure. A small part of CH_4 could emit from storage of animal manures. Removing the manure as feedstock for biogas production contributes to reducing CH_4 emissions. However, the amount of this part of emissions is difficult to estimate due to limited information. The effect of this part of CH_4 is therefore not factored in. Another environmental benefit is the reduction of straw and firewood consumption. Saving trees and firewood from deforestation could contribute to mitigate the environmental degradations. Through CDM projects based on biogas technology, environmental benefits could partly convert to economic benefits of the biogas projects. CDM arranged under the Kyoto Protocal helps industrialized countries reducing GHGs emissions in a cheaper way by investing in projects to reduce GHGs emissions in developing countries. A lot of developing countries have benefited from CDM biogas projects. In addition, it also shows that there is a large potential to develop CDM projects based on biogas. Usually a biogas project shows relatively poor economic performance due to high installation costs. So without subsidy or other supports the biogas projects are not economically viable, particularly in developing countries. The benefits from CDM projects could partly help to improve the economic performance of biogas projects, which is important to start a biogas project. Moreover, the cooperation between developed countries and developing countries through CDM projects may transfer the advanced biogas technology from developed countries to developing countries, which could help developing countries obtain new biogas technology and experience.

In addition to environmental benefits, the fertilizer value of the digestate is another benefit. In this case, one biogas digester produces 39ton organic fertilizer yearly from pig manure and water. It is sufficient for at least 0.48 hectare farmland for rice cultivation based on remained nutrients in digestate. In this case, the digestate could be transported to the farmland of the household since usually the rural household in this area owns relatively large farmland for crop cultivation. However, the large amount of digestate from the medium or large scale biogas plants could be separated with further treatment to produce fibre and liquor. They could be sold or used in more ways. Moreover, a lot of research shows the digestate from anaerobic fermentation is an improved and valuable fertilizer compared to the original input materials such as pig manure in this case.

According to simple economic analysis, it shows for one household the capital costs (2826yuan) are quite large compared to their income (about 9120yuan/year (Wang et al., 2007)). The payback period is 4.8 years roughly. The governmental subsidies are 1800yuan, which accounts for about 64% of capital costs. In this case the financial support is important for household to start a biogas plant. Without the subsidy, the household could be reluctant to build biogas plants because of the capital costs. More subsidies could help to reduce the payback period and then increase the willingness of households to install the biogas plants.

The result of calculations shows a relatively ideal model. Based on this model, biogas technology shows a lot of benefits for rural household. It reduces the energy costs and only requires locally available input materials. According to this model, biogas technology represents a sustainable way to produce energy for rural household, particularly in developing countries. However, this model is based on the particular condition of one rural area in China. When these analysis and calculations are made in different areas, there are other factors that need to be considered, such as biogas digester type (if requiring additional energy input), feedstock type, water resource supply and storage tank for digestate (if household has not farmland).

China has made a big achievement in developing and implementing biogas technology in both rural household and large-scale biogas plants. Discussion of the reasons or advantages of China may provide some experience to other developing countries.

(1) Input material availability -link with agriculture and livestock industry

    The main resources for household biogas digesters in rural China are livestock and poultry manure which is mainly from pigs, cattle and chicken as well as agricultural residues. Along with the development of livestock industry, more manure could be collected as the input material for biogas production. The amount of agricultural residues used as the input material mainly depends on the output of crops. The plentiful crop yield ensures the supply for biogas production.

(2) State financial subsidy

The Chinese government started to focus on supporting rural biogas projects by this century. Large numbers of financial subsidies from various governmental institutions or sectors has been directly invested to install the biogas plants. For example, the Ministry of Agriculture Development and Reform Commission set up a project of Rural Household Biogas State Debt then invested 840 million RMB to construct the household biogas plants in 22 provinces (Chen et al., 2010). This subsidy helps to solve the problem that the high capital costs inhibit the biogas projects which often happens in Africa.

(3) Development of biogas digesters

Unlike most African countries, China has developed several different types of biogas digester which have lower construction cycle and costs, less requirements for maintenance, etc compared to traditional concrete digester. GPR digester is one type of them and it has been widely used in rural areas as mentioned.

(4) Eco-agricultural models replacing single household biogas plant

Eco-agricultural models of biogas plants are used widely in rural China today. They have multiple benefits in terms of agricultural production, energy use and hygiene issue from an integrated system. They also could help to build biogas digester in cold areas or build biogas digester in areas that lack of water resource. It has been discussed in previous chapter. But the benefits from these new models have become an important reason that Chinese government and rural people intend to develop and promote the biogas technology.

(5) Clean Development Mechanism(CDM) projects based on biogas technology

As mentioned CDM projects based on biogas technology in China have developed rapidly. The first large project in Shandong province shows the revenue of 6.3 million Yuan/year from the sale of Certified Emission Reduction (CERs) (Source: http://www.sdny.gov.cn/). The large economic benefits could help to stimulate development of biogas projects, in particular large scale biogas plants in China. To date, there are 120 projects based on biogas technology have been registered and 42 projects have been issued in China (Source: http://cdm.ccchina.gov.cn/). A report has estimated that China has potential to generate 109 Mt CO2e/year worth US$439 million from 23 million digesters (Yapp and Rijk, 2005).

Chapter 5 Conclusion

Biogas is widely in use all over the world, but the status varies among the different continents. In Africa most of biogas plants are small-scale but the large-scale AD technology is still under developed. The dissemination of biogas plants is still difficult in Africa. Some Asian countries such as China and India have built a large number of biogas plants. Millions of people, in particular farmers, have benefited from the biogas technology. More sophisticated plants are found in developed countries.

The literature review and following synthesis show the important aspects of the biogas technology. Generally speaking, (a) Different types of biogas installation are suitable for different situations, including available input materials, available biogas technology, climate conditions, economic conditions, plant scale, etc; (b) Feedstock for biogas production could derive from different agricultural, industrial and municipal sources. For different purposes, the feedstock type could be different, and it significantly influences the biogas yield. In order to produce biogas successfully, the working conditions should be considered, such as temperature, PH value, loading rate, C/N ratio, etc; (c) Biogas technology provides multiple benefits including energy value, environmental benefits and fertilizer values. Biogas could be used as heat, steam, producing electricity, vehicle fuel, etc. There are large differences of biogas utilization between developing countries and developed countries. Biogas technology shows a lot of environmental benefits. One of the most important benefits is to reduce the GHGs emissions. With regards to fertilizer values, the digestate from AD almost remains all contents of various nutrients, and it is considered as a valuable and improved fertilizer compared to the original input materials; (d) Usually the biogas plants do not show strongly economically attractive due to high capital costs without additional subsidies. But there are still opportunities to improve it, such as developing CDM projects based on biogas technology in developing countries, increasing its fertilizer values of digestate, etc.

In order to discuss the effect of biogas technology on the energy consumption, the resource requirements of biogas technology and the multiple values of biogas technology including energy, environmental and agricultural benefits, I do the calculations on a household biogas plant in rural China. When one household build one $12m^3$ biogas digester to produce $1.46m^3$ biogas per day, it could cover their daily energy demand. It replaces the fuels of straw, firewood, coal, kerosene and LPG. Moreover, because of the higher effective using rate of biogas than straw, firewood, coal and kerosene, it also saves 5,558,840kcal energy consumption yearly. The feedstock requires 49kg pig manure and 61kg water per day. In practice, it could be substituted by 24.5kg pig manure (from 4-5 pigs) with the same amount of straw/crop residues. These resources are locally available. In addition to energy (biogas) output, the digester also produces 39ton organic fertilizer yearly could be returned to the farmland of the household, which is at least sufficient to 0.48 hectare farmland for rice cultivation. With regard to environmental benefits, it reduces GHGs emissions of 2.596 tonCO_{2e} per household yearly. The capita reduction of CO_{2e} accounts for 14.2% of total capita CO_{2e} emissions in China. The proportion is not large, but the contribution could be great because of large populations in China. In addition to CO_{2e} reduction, it also saves straw and trees (firewood) from deforestation, which partly mitigates the environment degradations. The economic analysis shows that the governmental subsidies accounts for about 64% of capital costs. More subsidies could help to reduce the payback period and then increase the willingness of households to install the biogas plants under high capital investment.

According to this case, biogas technology influences the energy consumption and utilization by replacing various fuels and saving energy consumption. It produces renewable energy by using local input. It significantly benefits the environment in term of reduction of GHGs emissions, and it benefits the agricultural practice. Biogas technology represents a sustainable way to produce energy for rural household, particularly in developing countries. However, these calculations and analysis are based on the particular condition of one area in rural China. Other factors need to be considered, such as biogas digester type (if requiring additional energy input), feedstock type, water resource supply and storage tank for digestate (if household has not farmland) when doing analysis and calculations in other rural area. China has made a big achievement in developing and implementing biogas technology in both rural household and large-scale biogas plants. The reasons include (a).plenty of feedstock. Along with the development of livestock industry, more manure could be collected as feedstock for biogas production. In addition, the plentiful crop yield also ensures the supply of agricultural residues for biogas production. (b).strong state financial subsidy. The Chinese government started to focus on supporting rural biogas projects by this century. Large numbers of financial subsidies from various governmental institutions or sectors has been directly invested to install the biogas plants. (c). development of biogas digesters. Unlike most African countries, China has developed several different types of biogas digester which have lower construction cycle and costs, less requirements for maintenance, etc compared to traditional concrete digester. (d).eco-agricultural models replacing the single household plant. Eco-agricultural models of biogas plants are used widely in rural China today. The multiple benefits from these models stimulate Chinese government and rural people to promote the biogas technology. (e).developing CDM projects based on biogas technology. CDM projects based on biogas technology in China have been developed rapidly and the potential is great. The large economic benefits from these projects could help to stimulate development of biogas projects, in particular large scale biogas plants in China. These reasons may provide some experience to other developing countries. Certainly, the developed countries have more advanced biogas technologies in terms of biogas production and utilization, and these technologies can also become relevant in developing countries.

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