Determination of the Potential Energy Contribution and Green House Gas Mitigation of Small and Medium Anaerobic Digester Systems in Bangladesh

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A thesis submitted in partial fulfilment of the requirements of the University of Brighton for the degree of Doctor of Philosophy

The University of Brighton

2011

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Abstract

This research is to determine the anaerobic digestion (AD) potential and green house gas mitigation of small and medium anaerobic digester systems in Bangladesh which could provide energy for the country's need. This was determined for two common feedstocks: cattle dung and poultry litter. A third potential feedstock is also investigated as a novel and significant new source: waste rice straw used in cattle markets. These three feedstocks were chosen because between them, they cover a large fraction of scenarios in the country where AD could be used. All of the data needed to determine the energy parameters of these three representative AD facility types were collected (i.e. biogas yield, biogas composition, life cycle data). Highest biogas yield of 0.099 m^3/kg feedstock and methane percentage 74.4% were found from cattle market rice straw feedstock. The relative potential contributions to energy were then calculated. Where no reliable secondary data was available, primary data was obtained, through site visits and surveys. In order to determine the potential distribution of these representative AD facility types across the country, a survey of 125 smallholdings/farms in one district was carried out. This showed that 70% of the potential energy from AD would come from the cattle feedstock (87% of energy for the cattle feedstock would come from domestic plants). The poultry feedstock contributes 16% of the potential energy (63% of energy from poultry feedstock would come from medium sized plant) and the rice straw from the cattle markets is 14% (53% large and 47% very large). The energy capacity is presented in terms of the potential development of small, medium and large AD facilities. The total potential for biogas energy from cattle farms, poultry farms and cattle market rice straw in Bangladesh is 240 $\times 10^6$ MJ (240 TJ). This energy is equivalent to 66.7 $\times 10^6$ kWh which can meet the cooking energy requirements of 30 million people in Bangladesh.

This study also contains a Life Cycle Assessment (LCA) and the result showed that the lifetime Global Warming Potential (GWP) of a 3.2 m^3 cow dung fed AD plant is 130 tonnes of CO_2 equivalent. Biogas as cooking fuel can reduce the GWP by 109 tonnes of CO_2 equivalent. It means the reduction of GWP of a domestic AD plant is of 84% to 21 tonnes CO_2 equivalent.

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Acknowledgements

For the opportunity to undertake this research I am indebted to my supervisory team, Professor Marie Harder and Dr. Ryan Woodard for providing advice and encouragement throughout. Thank you both.

I would also take this opportunity to thank Professor Callum Firth, Head of the School of the environment and Technology for the provision of the postgraduate facilities necessary to complete this research.

Thank is extended to members of the Waste and Energy Research Group past and present, Technical expert and staff of Grameen Shakti, Advance Engineering, Bangladesh Council for Scientific and Industrial Research, Bright Green Energy Foundation, Planet Finance and Barfoot Energy who made this research possible. Special thanks to M. A. Gofran, D.C. Barua, Prof. S. M. Imamul Haque, Rawshan Chowdhury, Professor Md. Yunus, Professor A. M. Akanda, Chris Cooper, Dr. A H Molla, Pascale Geslain and Dr. Elezabeth Manzanares.

Special thanks to my wife Sultana Kudrati Khoda, my parents (Khondokar Khalilur Rahman and Mrs. Mamtaz Begum), all members of family and friends for their continued support.

I would like to thank some of my well wishers who helped me during data collection from the fields and laboratories. My special thanks to Mostafizur Rahaman Shamim, Aftabur Raja, Md. Abdur Rahim, Md. Abdul Jalil, Fredrika Uppman and Nasu Miah.

Declaration

I declare that the research contained in this thesis, unless otherwise formally indicated within the text, is the original work of the author.

The thesis has not been previously submitted to this or any other university for a degree, and does not incorporate any material already submitted for a degree.

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Khondokar Mizanur Rahman **Date**

Acronym

AD	Anaerobic Digestion
BCSIR	Bangladesh Council of Scientific and Industrial Research
BOD	Biological Oxygen Demand
BSP	Biogas Support Partnership
CDM	Clean Development Mechanism
CER	Certified Emission Reduction
CML2	Centre of Environmental Science of Leiden University
COD	Chemical Oxygen Demand
DCC	Dhaka City Corporation
DEFRA	Department for Environment, Food and Rural Affairs
DLO	District Livestock Officer
DLS	Division of Livestock Services
EDIP	Environmental Design of Industrial Products, in Danish UMIP
GHG	Green House Gas
GS	Grameen Shakti
GTZ	German Development Organization
GWP	Global Warming Potential
HRT	Hydraulic Retention Time
IDCOL	Infrastructural Development Company Limited
ISO	International Standardization Organization
KVIC	Khadi and Village Industry Commission
LCA	Life Cycle Assessment
LGED	Local Government Engineering Department
MSW	Municipal Solid Waste

OLR	Organic Loading Rate
OM	Organic Matter
PAS	Publicity Available Specification
PIC	Product of Incomplete Combustion
SimaPro	System for Integrated Environment Assessment of Production
SNV	Netherland Development Organization
TS	Total Solid
UNFCCC	United Nations Framework Convention on Climate Change
VS	Volatile Solid
WRAP	Waste and Resource Action Program

Chapter 1

Introduction

This chapter presents an introduction to the thesis. The chapter starts by presenting background information on Bangladesh to set the context of the research, followed by the aims and objectives, layout of the thesis and an overview of the methodology used.

1.0 Overview leading to Aims and Objectives

Bangladesh is officially named the People's Republic of Bangladesh. It has a land area of 147,570 square kilometres and is one of the least developed and densely populated countries in the world (Islam, 2006). The population density of Bangladesh is 1,063 per square kilo meter, which is about five times higher than the UK, with an income per capita 1/100th of the UK (International Monetary Fund, 2008). Meeting all the basics in life, including provision of energy, is a challenge.

The population of over 144 million faces problems like environmental degradation, shortage of food supply, reduction of soil fertility and scarcity of energy (World Bank, 2005). The economy of Bangladesh is agriculture-based and more than 60% the workforce is engaged in agriculture (Asian Development Bank, 2001). Agriculture contributes about half of the Gross Domestic Product (GDP). Bangladesh has one of the lowest rates of energy consumption per capita in the world. In 1997, energy consumption per capita of Bangladesh was 197 kg oil equivalent (OE) which was less than the average energy consumption per capita of South Asia for the same period (443 kg OE), and far less than the averages for low income (563 kg OE) and lower middle income (1,178 kg OE) countries (World Bank, 2001).

Except for natural gas found along its eastern border, limited quantities of oil in the Bay of Bengal, coal, and some uranium, Bangladesh possesses few minerals. More than 55% of the country's energy requirement comes from traditional biomass energy sources which are crop residue, twigs, leafs, fire wood and dung cake (Netherland Development Organization-SNV, 2005). Traditional biomass energy is used mostly for cooking. Dung cake fuel is one of the important traditional uses of cow dung in Bangladesh. Excessive use of biomass energy causes deforestation and in the long run increases the propensity of environmental disasters like cyclones and floods, compromising agricultural productivity and economical development (Netherland Development Organization-SNV, 2005).

Commercial energy consumption consists around 66% natural gas, met by the country's recoverable reserves of natural gas, and 34% is supplied mostly by oil and limited amounts of hydropower and coal. The gas is used for the manufacturing of fertiliser, generation of electricity, direct use in certain industries and as cooking fuel in major urban areas. Economically, it is not feasible to supply the gas to the rural areas through pipelines. Petroleum products like high speed diesel oil and superior kerosene oil are predominantly used for transport and rural lighting (ADB, 2001).

Every day 3,500 tonnes of waste is produced in Dhaka, the capital of Bangladesh. This includes Municipal Solid Waste (MSW), agricultural waste and animal waste (cattle dung and poultry litter) which are the major sources (Sinha, 2010). Yearly disposed waste at simple controlled landfill in Dhaka is 511,000 tonnes and lost or illegally dumped waste is 509,248 tonnes per year (Choudhury, 2009). In cities, the government and City Corporation collect only 42% waste for disposal in landfill and the rest lies on roadsides, near open drains, and in the low-lying areas of the city (Figure 1.1) (Enayetullah, 1995). The dumping of this waste has led to major environmental problems like transmission of diseases, Green House Gas emissions (GHG) and pollution of ground water through leakages (Dhaka City Corporation, 2004). Open storage of cow dung in farmer's houses makes breeding grounds for mosquitoes and causes diseases (Biswas and Lucas, 1997). Inadequate collection and uncontrolled disposal of waste create a serious health hazard to inhabitants and the environment (Goyal et al., 2005). Waste management has become a major environmental problem confronting urban areas in developing countries (Pfammtter & Schertenleib, 1996). It seems evident that waste management is still in its infancy in Bangladesh. Open waste dumped in an uncontrolled manner is an important issue. It can be detrimental to the urban environment causing significant air and water pollution (Huri bin Zulkifli, 1993). Composting of household waste and anaerobic digestion of animal manure are the two major common practices of organic waste in Bangladesh.

Composting and anaerobic digestion serve to stabilise, hygienise and reduce the mass of organic waste. Furthermore, organic compounds and nutrients can be recycled to earth. Anaerobic digestion also aims to produce energy in the form of biogas. Composting and digestion can be used as complementary approaches depending on the situation and the kind of waste material, one or the other may be the preferred option. Aerobic and anaerobic steps may also be combined in one treatment facility (Körner and Visvanathan, 2006). A more recent environmental driver has been climate change, leading to a move away from landfilling biodegradable wastes (a major source of methane emissions) and to a renewed focus on energy recovery from waste (Department for Environment, Food and Rural Affairs-DEFRA and Waste and Resources Action Programme-WRAP, 2007). Due to having multiple benefits, AD has become an important option for developed and developing countries.

Figure 1.1 Roadside open dumping of city waste in Dhaka, Bangladesh (Gofran, 2009).

Anaerobic digestion (AD) is a biological process of the breakdown of organic matter by naturally occurring bacteria in the absence of air, and this produces biogas, and a solid digestate, which can be used as a bio-fertiliser. Biogas comprises of mostly methane and carbon dioxide with a small amount of hydrogen sulphide and hydrogen. Depending on the type of input material the residual solid matter or digestate can be a nutrient rich bio-fertiliser (Gofran, 2008). According to a report by the Bangladesh Centre for Advance Studies (2005), the 8.44 million households of Bangladesh have 22.29 million cattle and buffalo and 116, 000 poultry farms which produce 22,139 tonnes litter per day. Traditional use of dung and litter has a big impact on the environment and cultivable land in Bangladesh. For example, Figure 1.2 shows the dumping of poultry litter on low ground in adjoining areas of the poultry farm, the adjoining plots, some of which are dwellings, are severely affected by smell, dust and surface water pollution (Waste Concern, 2005). In many places the neighbours have lodged serious complaints. Bangladesh has nearly 40,000 domestic biogas plants, however, they use only cow dung and poultry litter. SNV (2005) estimated that Bangladesh has the potential for more than 3 million domestic AD plants.

Figure 1.2 Dumping of poultry litter on low ground in adjoining areas of the poultry farm causes surface water pollution and affects the cultivated land.

The potential for mass deployment of domestic AD plants is very promising. Government and micro-finance companies support such schemes. The use of AD rather than in fuel can supply both the much needed energy resource for domestic consumption for cooking and bio-fertiliser to enrich the farm land. It will also reduce deforestation by displacing wood fuel. These AD plants will be situated in rural farm areas where there is no realistic option for extending natural gas supply. They will benefit farm communities where 60% of the country's labour work force earns their subsistence. Despite the potential of AD no research has been undertaken to investigate the life cycle impact of widespread implementation of domestic AD plants in Bangladesh. Furthermore, for future implementation of AD and funding opportunities, carbon counting is a pre-requisite and it is an important criterion for Clean Development Mechanism (CDM).

The traditional use of biomass for cooking or the burning of renewably harvested fuel wood has often been assumed to be Greenhouse Gas neutral as eventually all the CO_2 will be recycled and taken up by vegetation in the next growing season. But this process is not emissions-neutral unless the biomass fuel is burnt efficiently and completely (UNEP, 2006).

Nevertheless, the burning of biomass fuels in stoves typically achieves only about 10 - 25% overall efficiencies and emits a significant portion of pollution in the form of products of incomplete combustion (PIC) that have higher global warming impact per carbon atom than CO_2. Thus inefficiently burned biomass fuels have a global warming contribution even if renewably harvested (Edwards, 2002). Biogas derived from AD using cow dung as feedstock when used in stoves is cleaner and the combustion efficiency is 57% which is more than biomass (22%) or the direct burning of dung cake (10%) during cooking (Smith, 2007). The current use of cow dung and poultry litter is open dumping, organic fertilizer, direct cooking fuel and AD. At present there is limited information on the contribution that each of these options has on the management of dung but the Division of Livestock Services (DLS) (2000) estimated that 68% and 32% of cow dung is used as an organic fertilizer in rural and urban areas respectively. Figure 1.3 shows the environmental consequences of traditional use of cattle dung. It shows that direct burning of dung cake as a cooking fuel causes emission and a huge loss of secondary and micronutrient elements.

As an agricultural fertilizer, according to Wu and Liu (1988), using anaerobic reactor effluent instead of chemical fertilizer increased a field's net economic yield by 30%. In general, the effluent is used as a supplement to chemical fertilizers thereby reducing chemical fertilizer requirements. Anaerobically digested fertilizer also increases yields compared to material composted aerobically presumably due to the conservation of nitrogen in an anaerobic system. Long (1992) compared the impact on fruit production of manure stored in an open top storage pit against effluent from a 6 m^3 anaerobic digester. The effluent from the anaerobic digester increased annual tree fruit production by 300 kg.

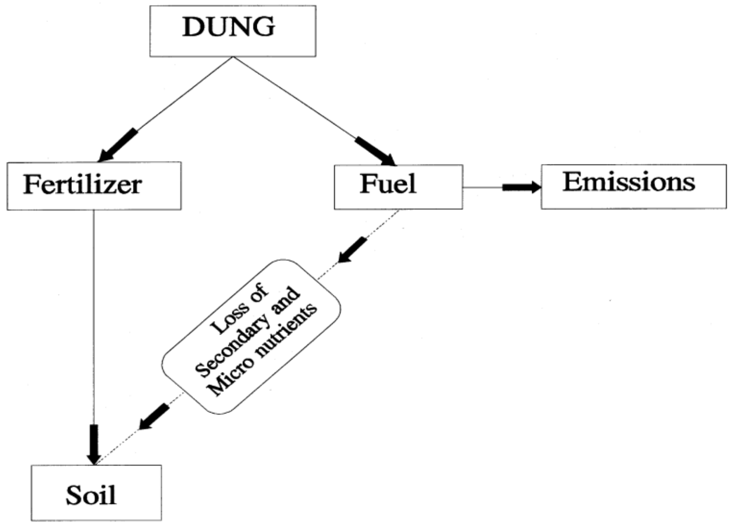

Figure 1.3 Environmental consequences of traditional uses of dung (Parikh, 1999).

The deforestation resulting from the use of trees for fire wood in Bangladesh has resulted in the continuous decline of forest cover, which reduced from 15.6% to 13.4% between 1973 and 1987 and presently, at less than 9% (Khalequzzaman, 2007). The decrease in forest cover contributes, among other adverse affects on the environment, to the increase in flooding propensity. Therefore, an alternative source of fuel generation is an absolute prerequisite for the overall development of the country.

Bangladesh has a suitable climate for biogas production. The ideal temperature for biogas is around 35^{o}C. The temperature in Bangladesh usually varies from 6^{o}C to 40^{o}C. But the inside temperature of a biogas digester in Bangladesh remains 22^{o}C – 30^{o}C, which is very near to the optimum requirement (Gofran, 2007). Raw feedstock for biogas; cow dung, poultry litter are easily and cheaply available everywhere in the country and the process does not only produce gas, but also kills all harmful bacteria and produces a high nutrient fertilizer (Grameen Shakti, 2005).

Sustainable and economically viable waste management is urgent for all countries in the world. Anaerobic digestion reduces methane emissions and is one option available towards more sustainable waste management. It thus has economic, environmental and energy benefits. In the agricultural sector, the implementation of anaerobic digestion technology can lead to improved air and water quality, odour control, improved nutrient management, a reduction of Greenhouse Gas (GHG) emissions, and finally the capture and use of biogas as a source of clean renewable energy (United States Environmental protection Agency, 2010). Demand for biofuels has been growing as the world is running short of fossil fuels. Oil and gas prices had been raised within the past several years, while the pressure to reduce carbon emissions to mitigate global warming is increasingly pointing to biofuels as one of the main solutions (Elizabeth et al, 2006). Beneficial and optimized production of biogas is needed for the world. It is very important to know the potential biogas yield capacity of Bangladesh and to understand the environmental impact of anaerobic digestion.

This study was carried out to determine the potential AD energy capacity in Bangladesh from the potential feedstock. This study uses Life Cycle Assessment (LCA) tools and methodology to determine the Global Warming Potential (GWP) of a domestic AD plant. It is to evaluate the contribution GHG emissions of AD as biogas components methane and carbon dioxide are greenhouse gases.

1.1 Aims and objectives

The aim of this study is to determine the potential energy contribution and Greenhouse Gas mitigation of small and medium anaerobic digester systems in Bangladesh.

The main specific objectives of this thesis are:

a. To reveal the current management of waste and energy issues in Bangladesh;

b. To determine the current AD practices including size, feedstock and distribution of small and medium AD plants in Bangladesh;
c. To determine biogas yield and composition generated from different animal feedstock;
d. To investigate the country's AD potential with AD size distribution;
e. To assess the life cycle impact for a domestic Anaerobic Digestion plant in Bangladesh.

The first objective was to establish the current management of waste and energy issues in Bangladesh. This was done by investigating the feedstock availability of the country and realizes the countrywide energy scenario.

The second objective was to determine the current AD practices including size, feedstock and distribution of small and medium AD size in Bangladesh. The action plan was to visit experts and AD plants of different sizes, feedstocks and areas. This was done on the basis of a farm survey on animal numbers and suggested the potential AD feedstock and AD facility types.

Another important objective (3^{rd} objective) is to find the biogas and methane yield capacity of the current and future prospective AD feedstock. This result helps to determine the countrywide AD potential.

To investigate the country's AD potentiality with AD size distribution is the key objectives (4^{th} objective) of this research. Countrywide potential AD capacity from potential feedstocks was determined through scaling up district findings to Bangladesh. Data from two Government bodies: District Livestock Office, Gazipur and Division of Livestock Services, Dhaka were the vital resources of this part of work.

To undertake a life cycle impact assessment for an anaerobic digestion plant in Bangladesh was the final (5^{th} objective) objective of this research. This was done for a 3.2 m^3 AD plant. The current review showed that 3.2 m^3 biogas plants are the most common types in Bangladesh (Gofran, 2009).

1.2 Layout of the thesis

This thesis is divided into the following nine chapters.

Chapter 1 Introduction

This chapter represents overview, aim and objectives of the thesis. It also contains the layout of the thesis. A brief description of the overview of the thesis is also included in this chapter.

Chapter 2 Introduction to Bangladesh, AD and LCA

This chapter presents background information on Bangladesh to set the context for this thesis. This includes data information and the issues on the waste management and energy generation. It will introduce the concept and implementation of AD in Bangladesh. The concept of LCA is also introduced in this chapter.

Chapter 3 Literature Review

This chapter will review the literature on the energy scenario of Bangladesh, contextual AD and energy capacity of AD, impact of AD including consideration of social, economical and environmental issues. Potential AD feedstock and the factors affecting biogas production are the two main parts of contextual AD section. It also includes GHG mitigation of AD and CDM.

Chapter 4 Methodology

This chapter will describe the methodology used in this thesis. It will describe in five systematic steps; field work and meeting with industry experts, identifying the representative AD facility types, determine the energy parameters, farm surveys and Life Cycle Assessment.

Chapter 5 Determine Potential AD facility types

This chapter assesses the current practices and thus potential prospect for a) cattle, b) poultry and c) cattle market rice straw feedstocks for increased AD capacity in a given district. A representative sample of farms or potential sites was visited. Relevant Government data was collected as required. A formal farm survey was undertaken to find out the farm animal capacity to estimate the district potential of AD. The end result of this chapter will be how many domestic/medium/large size AD plants could potentially be developed in the district.

Chapter 6 AD plant and Energy Parameters of AD

In order to undertake an LCA, input data is required on key parameters including AD construction materials, biogas yield and biogas composition. This chapter reviews the data available and the approach to obtain new primary data where needed. These results are important especially for environmental concerns and energy planning.

Chapter 7 Countrywide AD potential

Survey results of the district potential will be scaled up to determine the whole countrywide AD potential. It will also include the digester size estimation of three common sizes of AD facility types. Common digester sizes and their required building materials are also an important parameter for LCA of AD. The objective of the chapter is to look at the energy potential of the country with potential AD size.

Chapter 8 LCA of AD and GHG mitigation

This chapter will describe the LCA of a domestic AD plant and will determine the GHG mitigation capacity of this plant. Having a huge potential of AD facilities, it is rational to do a life cycle assessment of AD providing data regarding carbon emissions. It is also a supporting and essential criterion for CDM which can be an important carbon based funding program for AD.

Chapter 9 Conclusion

Finally, this chapter presents the conclusions of this research work, and recommendations for future work.

1.3 Overview of the research Framework

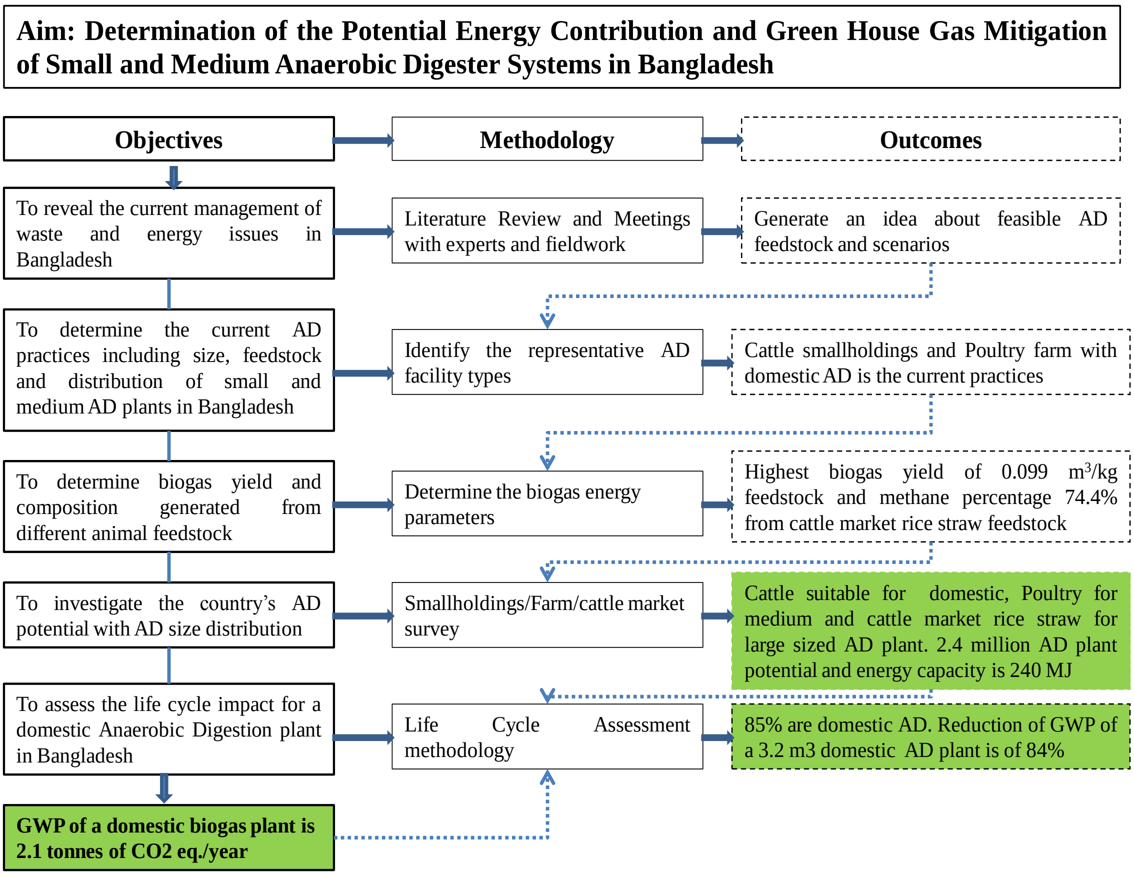

Figure 1.4 Methodology Framework for this thesis

Overviews of the research work are described chronologically as follows.

1. Meetings with experts and fieldwork

Meetings with different experts and expert organizations were carried out and fieldwork undertaken to determine the common waste and AD situation in Bangladesh. Collection of local information on energy and information on feedstock potential of the country were the two major issues. Thus, the collection of local information was required for a realistic overview.

2. Identify the representative AD facility types

A limited number of representative AD facility types had to be identified and decided on that could be used to model the whole country. For example, the representative AD facility types were dung and poultry based domestic and medium AD facility types. The aim was to find out the "spanning representative" of AD which covers a large fraction of scenarios in the country where AD could be used.

3. Determine the biogas energy parameters

Biogas energy parameters were determined due to two prospects: i) to determine the AD energy capacity and ii) integrate into LCA. The parameters key to energy production had to be determined for the chosen facility types in detail, including:

a. Biogas yield

b. Biogas composition

c. AD plant requirements

    I) AD building materials

    II) Initial and daily charge of feedstock

4. Smallholdings/Farm/cattle market survey

A survey of a farm (and smallholding) in a sample area was required to estimate the actual potential number of each representative AD facility type base on the animal population i.e. a field survey for one district, to allow scaling up to the country level later. This was in order to determine the countrywide AD potential.

5. Life Cycle Assessment

Environmental considerations are important for any energy source as well as the calculated energy potential; it is very necessary to determine environmental impact. This is very financially important for Bangladesh as renewable energy can bring CDM funds to the country. Thus, the environmental impact should be assessing via Life Cycle Analysis (LCA).

Chapter 2 Introduction to Bangladesh, AD and LCA

This chapter presents key information to set the context for this thesis. It will describe contextual information, energy status and evolution of biogas technology of Bangladesh. It will also include an overall description concept of anaerobic digestion and Life Cycle Assessment (LCA).

2.1 Contextual Information of Bangladesh

This section includes a brief history on the country's background, Bangladesh and agriculture, energy status and biogas technology in Bangladesh.

2.1.1 Country background

A profile of the country, its people, their livelihood and needs is presented in this chapter. It will highlight the geographic position, climate, agriculture and economy of Bangladesh. It will also explain the importance for development of the energy sector of Bangladesh.

A map of the country and its boundaries is shown in Figure 2.1 (Van Nes, Wim, 2005). Bangladesh has a land area of about 147,570 square kilometres. The borders are the Bay of Bengal in the south; the Indian states of West Bengal in the west and north, Assam and Meghalaya in the northeast, and Tripura and Mizoram in the east; and Myanmar in the southeast. Dhaka is the capital and largest city; the nation's other major city is Chittagong. A humid, low-lying, alluvial region, Bangladesh is composed mainly of the great combined delta of the Ganges, Brahmaputra, and Meghna rivers. Except for the Chittagong Hills along the Myanmar border, most of the country is no more than 90 meters above sea level. Bangladesh is laced with numerous streams, distributaries, and tidal creeks, forming an intricate network of waterways that constitutes the country's main transportation system.

Along the south-western coast is the Sundarbans, a mangrove swamp area with numerous low islands (Scott, 1989)

Bangladesh has a tropical monsoon climate with a distinct dry season in the winter. It receives an average annual rainfall of about 2,000 mm, with most falling during the summer monsoon period; the Sylhet district in the northeast, is the wettest part of the country, having an annual average rainfall of 3,560 mm. The low-lying delta region is subject to severe flooding from monsoon rains, cyclones, and storm surges that bring major crop damage and high loss of life. The cyclones of 1970 and 1991 and the monsoon floods of 1988, 1998, and 2004 were particularly devastating. The climate has a direct impact on agriculture and the economy (Bangladesh Forest Department, 2008).

Figure 2.1 Map of Bangladesh with the capital Dhaka in the middle and Chittagong in the Southeast of the country (Van Nes, Wim, 2005).

Table 2.1 A general comparison between Bangladesh and UK in area, population and population density (CIA-Central Intelligence Agency, The World Fact Book, 2009, Office for National Statistics, UK, 2010, IMF, 2011).

Parameter	**Bangladesh**	**United Kingdom**
Area	147,570 sq kilometre	244,820 sq kilometre
Population	144 million	62 million
Population density	1057/sq kilometre	249/sq kilometre
Annual rainfall (mm)	2000	754
GDP (million US$)	104,919	2,247,455

Bangladesh is one of the world's ten most populated countries with an estimated current population of 144 million and has one of the highest population densities with an annual growth of 1.7%. The population density of Bangladesh and the UK is shown in Table 2.1. The great majority of Bangladesh's population is Bengali, although Biharis (Pakistani) and several tribal groups constitute significant minority communities.

Except for natural gas (found along its eastern border), limited quantities of oil (in the Bay of Bengal), coal, and some uranium, Bangladesh possesses few minerals. Dhaka and Chittagong (the country's chief port) are the principal industrial centres; clothing and cotton textiles, jute products, processed food, steel, and chemical fertilizers are manufactured in these cities. In addition to clothing, textiles, jute and jute products, exports include tea, leather, fish, and shrimp. Capital goods, petroleum, and textiles are major imports. Western Europe, the United States, India, and China are the main trading partners. The gross national income per capita in 2003 amounted to USD 400 (World Bank, 2005). Having the resources, favourable climate and business facilities with overseas, the development of the country became slow due to the scarcity of energy supply in Bangladesh.

2.1.2 Bangladesh and agriculture

Bangladesh has a predominantly rural population, with over 60% of the workforce engaged in agriculture. The country's economy is based on agriculture with rice, jute, tea, sugarcane, tobacco, and wheat as the chief crops (Asian Development Bank, 2001). Fishing is also an important economic activity, and beef, dairy products, and poultry are also produced. The predominantly agrarian economy is characterized by small-scale, fragmented farming. Though the country has achieved near self sufficiency, the majority of the population lack food security. Agriculture serves as the mainstay of the population contributing about 50% of the Gross Domestic Product (GDP).

All the cultivable land is in use and the increasing population has reduced the average farm size holdings to less than a hectare (0.01 square kilometres) (Hossain 2001). The basic aim of agricultural development policies over the last four decades remains at increased food production. In the early 1960s, flooding during the monsoon and lack of irrigation facilities during the dry periods was identified as the major constraints hindering use of modern agricultural inputs. Inadequate energy supply is the main cause obstructing irrigation. As such, the government aimed at building large scale irrigation and drainage facilities. In the late 1960s, increased distribution of highly subsidized chemical fertilizer and High Yielding Varieties (HYVs) of rice and in the early 1970s, HYVs of wheat were introduced. Depletion of soil fertility in Bangladesh is mainly due to exploitation of land without proper replenishment of plant nutrients in soils. The problem is enhanced by intensive land use without appropriate soil management. The situation is graver in areas where HYVs are being cultivated with little or no organic recycling. Depletion of organic matter is an important factor in the process of soil fertility decline. Over the past 20 years, the average organic matter content of top soils (high land and medium highland situation) has gone down from

2% to 1% (BARC, 1999). A good soil should have an organic matter of more than 3.5%. Most soils in Bangladesh have less than 1.7%, and some soils have even less than 1% organic matter. Nutrients in the soil are replenished by use of fertilisers; these are currently derived from animal husbandry. In the future anaerobic digestion plants will offer good quality digestate as a by-product of biogas fuel production (BARC, 1999).

Today, most of the rural households of Bangladesh have 2 - 3 cattle with 1 buffalo but their quality is very poor (Figure 2.2). Cattle and buffalo are fed principally on agricultural by-products, such as crop residues. They graze on natural pastures of non-arable land. During the day, they are allowed to graze on communal grazing land, natural pasture, homestead forest or fallow land. Since no arable land is available for livestock feed production, non-arable land contributes most of the green fodder for ruminant animals. Using shrub and tree leaves, and tender shoots and twigs as fodder is traditional in the villages (SNV survey, 2005).

Figure 2.2 The domestic cattle of rural household.

Rearing of dairy cattle has been increasingly viewed as a means of alleviating poverty and is believed to improve the livelihoods of landless and small households. Many non-governmental organisations (NGOs), such as Proshika Manobik Unnayan Kendra (PROSHIKA), BRAC (Bangladesh Rural Advancement Committee), Grameen Bank and

Aftab Dairy, are involved in the promotion of micro-credit for small livestock enterprises, including dairy cattle production. As an input to cropping systems, dung continues to be an important link between crop and animal production in Bangladesh. The yearly total cattle dung production in Bangladesh in 2000 was estimated to be 80 million tonnes of which 68% and 32% are used as manure only in rural and urban areas, respectively. This is an inefficient use of dung because of loss of valuable resources for biogas production. This means dung could be better used in AD as feedstock producing both biogas and fertiliser (DLS, 2000).

2.1.3 Energy status Bangladesh

Per capita energy consumption of developing countries is very low compared to developed countries. Energy consumption of Bangladesh per capita is even very much lower than among south Asian countries. Per capita electricity generation of Bangladesh is 182 kWh and it is amongst the lowest in the world. 83% of electricity is generated from natural gas (BPDB, 2010). Only 3% of urban people have access to natural gas from centralised pipe lines. The rest of the population of Bangladesh relies on biomass fuel and LPG for cooking, but LPG is very expensive for the rural population (Bangladesh Power Development Board, 2010).

The total annual per capita energy consumption of the country in 1995 was estimated at 8.5 GJ. The shares of commercial energy (coal, oil, gas and hydropower) and biomass fuels were estimated at 3.2 and 5.3 GJ respectively (Islam, 2001). Bangladesh, being a rather flat country, has limited hydro-electric potential. The total potential is estimated to be 755 MW with a total installed capacity of 230 MW (Islam, 2001).

According to Akbar (2004) the energy-mix in Bangladesh is 65.5% renewable (biomass and hydropower), and 34.5% non-renewable including coal, natural gas, petroleum products and crude oil. Domestic sectors consume 60.36% of the total energy. Industrial sectors account for 21.57% of the total national energy consumption. Energy sources in Bangladesh can be broadly classified into three categories: a) traditional b) commercial and c) renewable. The energy scenario for Bangladesh is summarised in following Table 2.2. Table shows that per capita electricity consumption and per capita commercial energy consumption in Bangladesh is 153 KWh and 160 kg of Oil Equivalent respectively. This figure indicates a poor energy status of the country.

Table 2.2 Energy scenario of Bangladesh (Integrated by author from different sources) (1=SNV, 2=IDCOL, 3=REB, 4, 5, 6=Energy Bangla)

References	Sector	Status
1	Traditional (biomass fuel) energy user	55%
2	Consumption biomass fuel annually	45 million tonnes
3	Access to Electricity	30%
4	Per capita electricity consumption	153 KWh (versus UK- 5546 KWh
5	Per capita commercial energy consumption	160 kg of Oil Equivalent
6	Contribution of renewable energy (biogas, solar and hydro)	19 MW equivalent power

Traditional energy

Traditional energy is biomass and includes fuel wood, agricultural residues, leaves and dried dung cake. An estimate of traditional biomass fuels supplied in the year 2002/03 was approximately 11,199 million tonnes of coal equivalent. The energy is mostly fuel for cooking. Use of traditional energy has a number of drawbacks including deforestation, depletion of organic matter in soil, air pollution, respiratory disease, time lost, laborious and low efficiency (Gautam *et al* 2009). The gathering of wood and agricultural residues is hard work and time consuming.

The use of biomass appears to be not only an ineffective means of energy generation; it is also extremely detrimental to the environment. In Bangladesh the average cooking requirement per family per day is estimated to be 5 hours in rural households. Each household needs about 3 tonnes of biomass per year to cook their food. Assuming that 55 % of households use biomass for cooking, about 45 million tonnes of biomass fuel will be required every year for cooking only. Supply of such large quantity of biomass can exert high pressure on the forest. Excessive use of wood for fuel may have already exceeded the regenerative limit of some forest (Asaduzzaman and Latif, 2005).

76% of people in Bangladesh live in rural areas and use mainly traditional stoves for cooking their three meals (morning, afternoon and evening) and other heating purposes (BBS, 2006). The stove used for cooking is usually a mud-built cylinder with three raised points on which the cooking pot rests. One opening between these raised points is used as the fuel-feeding port and the other two for flue gas exit. The stove may be built under or over ground. In some cases, two potholes are joined together and a single fuel-feeding port is made for common use. Cooking in this manner causes indoor air pollution, as biomass smoke is considered to be a significant source of public health hazard, particularly to the poor and vulnerable women and children (Figure 2.3).

Figure 2.3 Traditional cooking scenario of rural Bangladesh (left), dried dung Sticks (right) dried for cooking purposes

Dasgupta *et al*. (2004) investigated indoor air pollution, more in particular respirable airborne particulates from cooking in Bangladesh. Biomass fuels cause much more pollution than clean fuels like natural gas, kerosene or biogas. In order to prevent further environmental and agricultural deterioration, it is imperative to promote new sources of energy technologies in Bangladesh. Biogas produced from dung and poultry litter is undoubtedly one of the most appropriate sources of energy for rural Bangladesh.

Commercial energy

Bangladesh has small reserves of oil and coal, but potentially large natural gas resources. Commercial energy consumption is around 66% natural gas, with the remainder mostly oil and limited amounts of hydropower and coal (SNV, 2005). Only around 30% of the population have access to electricity, and per capita commercial energy consumption of about 200 kg of Oil Equivalent (kg OE) is among the lowest in the world (REB, 2007). The total recoverable reserves of natural gas are 439 billion m^3 (i.e. 15.5 trillion cubic feet) of which 110 billion m^3 was produced up to June 2000 (Islam, 2001). The gas is being used for the manufacturing of fertiliser, generation of electricity, for direct use in some industries and as cooking fuel in major urban areas. Economically, it is not feasible to supply the gas to the rural areas through pipelines. Petroleum products like high speed diesel oil and superior kerosene oil are predominantly used for transport and rural lighting. The total consumption of petroleum in 2000 was 3.23 million tonnes, all of which was imported (Government of Bangladesh, 2002). The yearly consumption of coal in the country is over 1 million tonnes, almost exclusively used for brick burning and met by imports. The total coal deposits located in North Bengal are 1.75 billion tonnes. Mining has started on a small scale by Baropukuria Coal Mines under Petrobangla, the national agency for exploration and production of oil, gas and minerals under the Ministry of Power, Energy and Mineral Resources (MoPEMR). The coal from this mine will be used in a power plant currently under construction. The total peat deposits of the country are about 150 million tonnes, but the costs of mining with the current technology are high (BPDB, 2001). From the above discussion it is clear that an alternative energy sources is essential for Bangladesh at the present condition.

Renewable energy

Biogas, solar, hydro and wind energy are known as renewable energy or alternative energy sources. By December 2005 about 30,000 biogas systems and 60,000 solar home systems had already been constructed in Bangladesh. These renewable energy systems alone are contributing about 19 MW to the nation (SNV/IDCOL, 2005).

Biogas, which is mainly composed of methane (60 - 70%) and carbon dioxide (30 - 40%) is a combustible gas produced by anaerobic fermentation of organic materials by the action of methanogenic bacteria. Methane is an odourless gas and burns with a clear blue flame without smoke. It produces more heat than kerosene, fuel wood, charcoal and dung-cakes (Rouf, 2008). When biogas is used in suitable designed burners, it gives a clean, smokeless, blue flame, which is ideal for cooking. If biogas is used in specially designed lamps it gives a light similar to the kerosene pressure lamps. Biogas can be used for other purposes, such as electricity generation, refrigeration, space heating and running engines, but higher amounts of gas will be required for these purposes. A family sized biogas plant is appropriate only for domestic use such as cooking and lighting.

This thesis is to determine the potential AD capacity in Bangladesh and the life cycle impact assessment of family sized domestic biogas plants. Biogas is suggested to be the best alternative to traditional biomass energy without the drawbacks associated with biomass. This is because biogas generation does not cause deforestation, burns more efficiently and cleaner with no associated air pollution due to smoke. The digestate prevents depletion of organic matter in soil and a better grade fertiliser than manure (Islam, 2008). Due to the availability of different types of feedstock and a favourable climate condition for anaerobic digestion, it can be predicted that the potential energy generation through biogas would be higher compared to any other renewable energy sources in Bangladesh.

2.1.4 The Evolution Biogas Technology in Bangladesh

Anaerobic digestion dates back as far as the 10th century, when the Assyrians used it to heat bath water. It was historically insignificant before reappearing in 17th century Europe, when it was determined that decaying organic matter produced flammable gases, again used to heat water. The first full scale application was in the 1890s when the city of Exeter, UK used it to treat wastewater. From there, it continued to be widely used as a way to stabilize sewage sludge, as it is today (Mahony, O'Flaherty et al. 2002).

AD in developing countries differ from developed country on the basis of feedstock, size of plant and purposes of AD. Most of the AD plants in developing countries are smaller facilities which are used for cooking and lighting. AD in developed countries are generally bigger facilities and used for electricity production.

At present, biogas technology is widely used in many developing countries including China, India, Nepal, Vietnam, Cambodia and Thailand. There are now about 20 million biogas plants in China, four million plants in India, and about 160,000 plants in Nepal.

Table 2.3 Domestic AD plant installed in some Asian countries and position of Bangladesh (Gofran, 2011)

Country	**Starting year**	**Installed AD plant**
China	1930	40,000,000
India	1900	5,000,000
Nepal	1974	230,000
Vietnam	2006	100,000
Bangladesh	1972	40,000

In Bangladesh, the first biogas plant was set up by Professor Karim in 1972 at Bangladesh Agricultural University (BAU), Mymensingh (Gofran, 2009). It was a floating-dome type plant of $3m^3$ gas production capacity (see section 2.2.1.3 for explanation). Following the success of the pilot plant, a few more plants were constructed in the surroundings. These plants did not last long due to leakages in the domes. In 1974, the Bangladesh Academy for Rural Development (BARD) constructed a biogas plant using the same design. The Institute of Fuel Research and Development (IFRD) constructed another plant at Bangladesh Council of Scientific and Industrial Research (BCSIR) in 1976. As the construction costs were high and no subsidy was available, the technology did not have any attraction for the common people.

In 1981, the government established a department named Environment Pollution Control Department (EPCD), through which they started a programme at a cost of 3.4 million taka (Bangladeshi currency) which is equivalent to £34,000. Under the project, about 150 floating-dome and 110 fixed-dome plants were installed until 1984. The floating-dome plants initially worked successfully, but did not last long due to lack of after-sale service and leakage in the gas holder. The fixed dome plants did not even work for a day due to a design fault. This has created negative perception among the common people as well as the policy makers. During this period, at the initiative of the former chairman of BSCIC, some engineers of the organisation were trained with technical support from BCSIR, and constructed 92 plants. The

Department of Livestock (DLS) also trained many of its engineers in biogas technology and constructed about 70 plants by 1990. Some Non Governmental Organizations (NGO) like DANIDA, BRAC and Grameen Bank took initiatives to popularize the technology. These NGOs, with technical support from BCSIR, constructed about 250 biogas plants in districts of Bangladesh including, 17 bag type digesters by Grameen Bank. These plants also did not last long (BCSIR, 2001).

Local Government Engineering Department (LGED) constructed their first floating-dome model biogas plant in Kurigram district, and arranged a seminar there on December 27, 1986. About 300 scientists, experts, engineers, politicians, and persons interested in biogas technology joined the seminar. Until 1992, they constructed 7 – 8 plants following the same design. The plants initially worked successfully, but after 4 – 5 years went out of order due to leakage in the gasholder, pipeline and burner. In 1989, one of the scientists of BCSIR received training on biogas technology from Biogas Research and Training Centre (BRTC), Chengdu, China and constructed one fixed-dome Chinese model biogas plant at BCSIR campus. Till today, the plant is working successfully. Following the design, one LGED engineer constructed two biogas plants in Noakhali district in 1992, with financial support from DANIDA. These plants are still in operation. Subsequently, two engineers from LGED and BCSIR constructed about 50 fixed-dome type biogas plants in different districts at the cost of the users, and thus the fixed-dome model biogas plant was introduced in Bangladesh. An important distribution push was delivered by the “Biogas Pilot Plant (1st phase) Project” implemented by BCSIR in the period from July 1995 to June 2000. In total 4,664 fixed-dome plants were constructed throughout the country (ADB, 2003).

BCSIR and several other institutes like BRAC, LGED and DLS made an agreement for research, training, and dissemination of the biogas technology. The biogas farmers received an investment subsidy of 5,000 Taka (£50) under the project. An interim evaluation report in 1999 stated that 99% of the plants installed under the project were in operation, while 91% of the owners could meet their household fuel demand through biogas. Bio-slurry from the biogas plants was used in horticulture, pisciculture, and agriculture. The average saving per plant amounted to 759 Taka (£7) per month (BCSIR, 2001). As the 1st phase was successfully completed, and the potential for biogas in Bangladesh considered huge, BCSIR implemented the 2nd phase of the Biogas Pilot Plant in the period from July 2000 to June 2004. The target for this phase was put at 20,000 biogas plants, out of which 17,194 plants were finally built.

In 1994, the government of Bangladesh created a public limited company named Infrastructure Development Company (IDCOL) with financial assistance from the World Bank to support all kinds of infrastructure development, with focus on energy-related infrastructure. These organizations, with the support from Netherlands Development Cooperation (SNV), launched a project for the extension of biogas technology in Bangladesh. Under the program, 36,450 biogas plants were due to be built by 2009. Grameen Shakti (GS) operates huge activities to promote, develop, and popularise biogas technologies in the remote rural areas of Bangladesh (Gofran, 2007).

The recent data shows that AD installation in developing countries is increasing at a high rate. Table 2.4 summarises the progress of biogas installations in Bangladesh. By 2008, a total of 4,934 had been installed by the Construction Partner Organization (CPO) under IDCOL and the number of plants and organisations involved increases every year.

Table 2.4 Organizations involved in the dissemination of biogas plants in Bangladesh and number of plants installed (Renewable Energy and Environmental Information Network REEIN, 2008).

Organization	**Installation Period**	**Number of Biogas plants installed**
Bangladesh Council of Scientific & industrial Research	1973-2005	22,100
Local Government Engineering Department	1985-2001	7,000
Department of Environment	1979-1983	260
Bangladesh Rural Advancement Committee	1987-2005	300
Department of Livestock	1988-1994	70
Thengamara Mohila Sabuj Sangha (TMSS)		
Bangladesh small & Cottage Industries Corporation	1983-1988	30
Bangladesh Agricultural Development Corporation	1983-1984	20
Danish International Development Agency	1982	4
Bangladesh Agricultural University	1971-1973	2
Housing & Building Research Institute	1981	2
Bangladesh Academy for Rural Development	1974	1
Bangladesh Commission for Christian Development	1978	1
Bangladesh Rice Research Institute	1983	1
Total		**29,789**
Construction Partner Organization(CPO) under IDCOL		
Grameen Shakti (GS its own programme + IDCOL)		1,957
SOUL		1,000
Kamrul Biogas		517
Rahman Biogas		368
Hosain Biogas		301
RSF		205
Srizony Bangladesh		240
Shubashati		116
BRIDGE		23
SAPNO		44
Nirapod Engineering Ltd.		30
Sangram		25
BASA		20
Sonali Unnayan Foundation		35
DESHA		23
Practical Action		18
Nurunnabi Biogas		11
Change Maker		3
Palli Shakti		2
Jahanara Biogas		1
Total		**4,934 (19 Nov 2008)**
Grand total		**36,450**

2.1.5 Large sized AD facility in developed world

UK and almost all the European countries are now expanding their anaerobic digestion plants. For instance Germany guarantees a subsidy by means of revenues for electricity and heat produced from renewable resources (EEG, 2004). The United Kingdom has not invested significantly in AD until recently. A few anaerobic digestion projects are now in operation with others to follow. Figure 2.4 compares UK and other European countries anaerobic installations on the basis of feedstock and process.

In 2010, 162 anaerobic digesters generated 453 million kWh of energy in the United States in agricultural operations, enough to power 25,000 average-sized homes (The Agstar Program, 2011). In Europe, anaerobic digesters are used to convert agricultural, industrial, and municipal wastes into biogases that can be upgraded to 97% pure methane as a natural gas substitute or to generate electricity. Germany leads the European nations with 6,800 large-scale anaerobic digesters, followed by Austria, France, Switzerland, the Netherlands and Sweden with 551, 468, 459, 237 and 230 respectively (IEA Bioenergy, 2011). The United Kingdom has 84 large scale commercial anaerobic digestion plants.

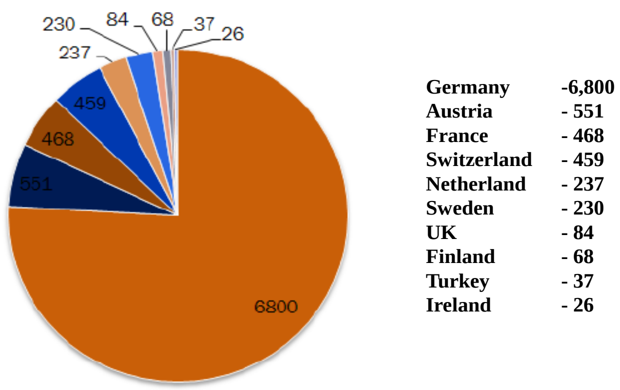

Figure 2.4 Number of operating anaerobic digesters in select European countries (IEA Bioenergy, 2011)

2.1.6 Organizations involved in this research

This research is done by the help of some governmental and non-governmental organization in Bangladesh. Grameen Shakti, Advance Engineering, Bangladesh Council for Scientific and Industrial Research, Division of Livestock Services are the main organizations. A brief history of their activities is also included in methodology chapter.

2.2 Anaerobic digestion

This section will introduce the systems on the basic concept of AD. It will consist of the general concept of anaerobic digestion, including the process, chemistry and factors affecting the performance of anaerobic digestion.

The agrarian economy and growth of the livestock industry in Bangladesh create opportunities for the proper disposal of the large quantities of manure generated by cattle and poultry farms. Pollutants from unmanaged livestock wastes can degrade the environment, and methane emitted from decomposing manure contribute to global climate change. Consequently, manure management systems that enable pollution prevention are becoming increasingly important. Anaerobic digestion (AD) is a management system that not only provides pollution prevention but can also convert a manure problem in a profitable way. Economic evaluations and case studies of operating systems indicate that the AD of livestock manures is a commercially available bioconversion technology with considerable potential for providing profitable co-products: a cost-effective renewable fuel for domestic cooking and a nutrient rich fertilizer (SNV, 2005). According to Bangladesh Centre for Advance Studies (2005), 8.44 million households in Bangladesh are potential biogas AD producers. These are households that own cattle, buffalo and poultry farms which produce significant amounts of animal dung per day.

2.2.1 Context of anaerobic digestion

2.2.1.1 Concept of anaerobic digestion

Anaerobic Digestion (AD) is a biological process that happens naturally when bacteria breaks down organic matter in environments with little or no oxygen. This process is run in a man-made vessel; schematic of a simple anaerobic digester system as shown in Figure 2.5. It requires a feedstock (e.g. organic waste) and a reactor vessel where microbial reactions act on the feedstock, and produce a methane-rich biogas as the principal product and a slurry or digestate as the secondary product which can be turned into fertiliser if the quality of the feedstock is appropriate. Biogas is formed solely through the activity of bacteria, unlike composting in which fungi and lower creatures are also involved in the degradation process (Arthur, 2005).

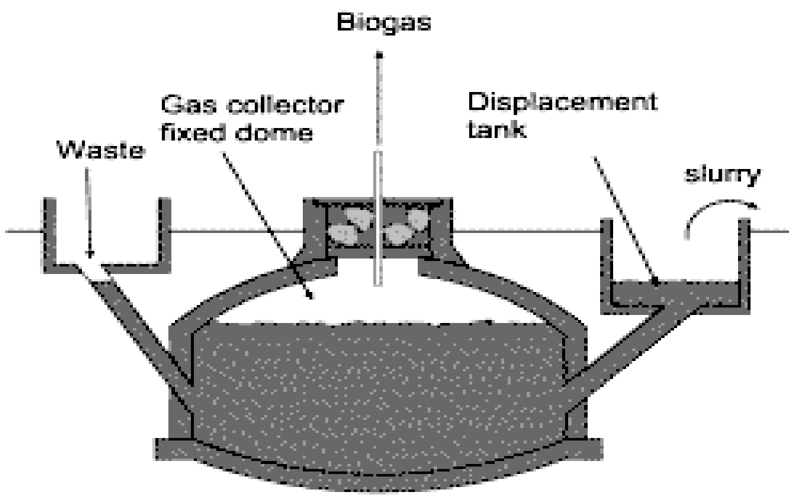

Figure 2.5 Chinese fixed-dome AD plant model widely used in Bangladesh (IDCOL, 2008).

In the absence of a reactor vessel, microbial growth and biogas production are very slow at ambient temperatures. They tend to occur naturally where wet organic matter accumulates in the absence of dissolved oxygen, most commonly in the bottom sediments of lakes and ponds, in swamps, peat bogs, intestines of animals and in the anaerobic interiors of landfill sites. Animal faeces like cow dung contain these microbial organisms.

The overall process of AD is shown by Figure 2.6. The conversion of complex organic compounds into methane and carbon dioxide requires different groups of micro organisms and is carried out in sequence of four stages: Hydrolysis, Acidogenesis, Acetogenesis and Methanogenesis. During hydrolysis organic substrate is converted into smaller components, and then acidogenic bacteria use these smaller compounds to produce volatile fatty acid, ethanol, CO_2 and H_2. Acetogenic bacteria convert these fermentation products into acetic acid, CO_2 and H_2. Finally methanogenic bacteria use hydrogen and acetate (the most important substrate) and produce methane and carbon dioxide.

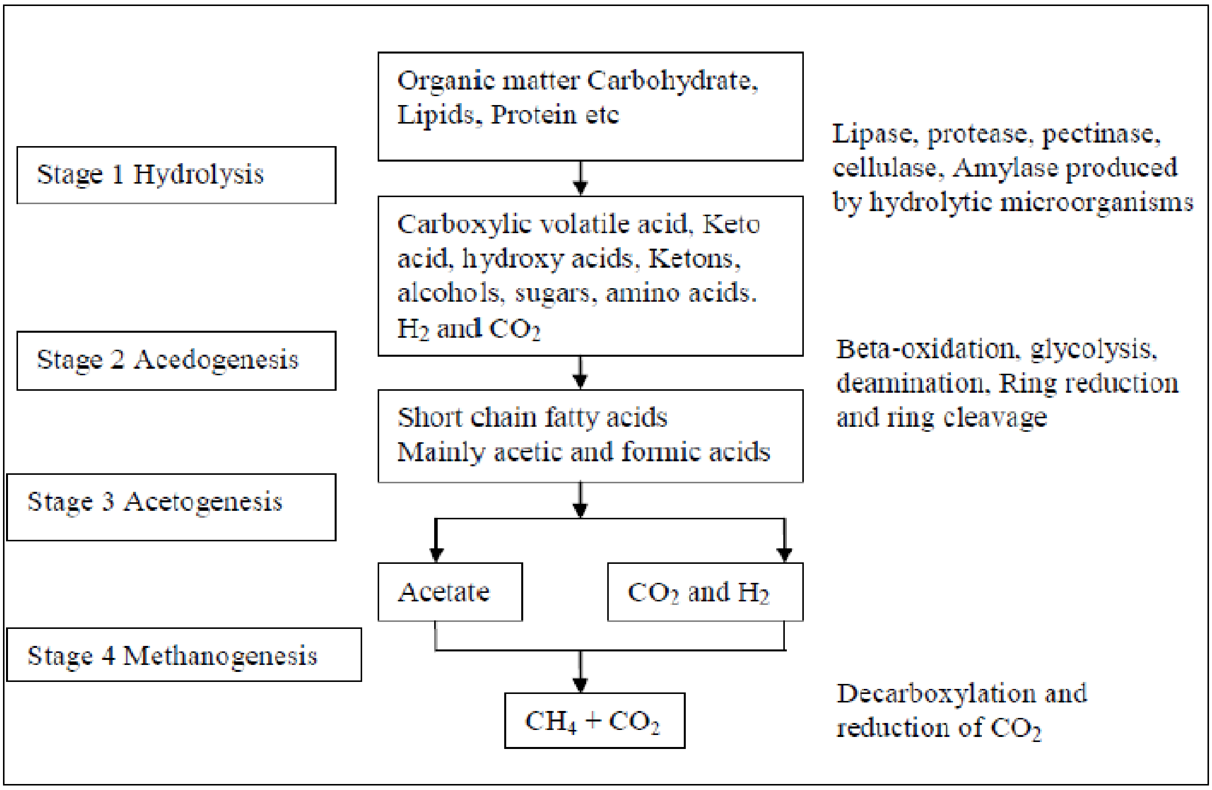

Figure 2.6 Scheme of anaerobic digestion process (Modified from Evans G, Bio waste and Biological waste treatment 2001)

Digestion refers to various reactions and interactions that take place among the methanogens, non-methanogens and substrates fed into the digester. This is a complex bio-chemical process involving different factors and stages of change. This detailed process of digestion (methanization) is summarized below in its simple form. The breaking down of inputs which are complex organic materials is achieved through three phases:

Phase 1 Hydrolysis

The waste materials of plant and animal origins consist mainly of carbohydrates, lipids, proteins and inorganic materials. Large molecular complex substances are solubilised into simpler ones with the help of extracellular enzymes released by the bacteria. This phase is also known as the polymer breakdown stage. For example, the cellulose consisting of polymerized glucose is broken down to dimeric and then to monomeric sugar molecules (glucose) by cellulolytic bacteria.

Phase 2 Acidification

The monomer such as glucose which is produced in phase 1 is fermented under anaerobic conditions into various acids with the help of enzymes produced by the acid-forming bacteria. At this stage, the acid-forming bacteria break down molecules of six carbon atoms (glucose) into molecules of less carbon atoms (acids) which are in a more reduced state than glucose. The principal acids produced in this process are acetic acid, propionic acid, butyric acid and ethanol.

Phase 3 Methanization

The principal acids produced in phase 2 are processed by methanogenic bacteria to produce methane. The reaction that takes place in the process of methane production is called Methanization.

Typically anaerobic digester reactors are designed to operate in either the mesophilic (20 - 45°C) or thermophilic (45 - 60°C) temperature ranges. Methanogenesis is also possible under low temperature (< 20°C). This is referred to as psychrophilic digestion and this requires longer hydraulic retention times and destruction of pathogens present, for example, may not be completed in raw manure (Safley and Westerman, 1992).

The overall reactions involved can be represented as follows.

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$$

$$CH_3COOH \rightarrow CH_4 + CO_2$$

AD produces a biogas made up of around 60% methane (CH_4) and 40% carbon dioxide (CO_2). There are a number of important factors which can directly and indirectly affect the anaerobic digestion process, biogas and methane yield.

2.2.1.2 Factors affecting anaerobic digestion

Temperature

The methanogens are inactive in extreme high and low temperatures. The optimum temperature for anaerobic digestion is 35°C (mesophilic). When the ambient temperature goes down to 10°C, gas production virtually stops. Satisfactory gas production takes place in the so called mesophilic range; between 35º to 37°C. Proper insulation on top of the digester, i.e. by the placement of a haystack, helps to increase gas production in the cold season. When the ambient temperature is 30°C or less, the average temperature within the dome will then remain about 4º C above the ambient temperature (Lund *at al*., 1996).

Loading rate of raw materials

The loading rate is the amount of raw materials fed per unit volume of digester capacity per day. If the plant is overfed, acids will accumulate and methane production will be inhibited. Similarly but for different reasons, if the plant is underfed, the gas production will also be low.

Retention Time

Retention time (also known as Hydraulic Retention Time, HRT) is the average period that a given quantity of input remains in the digester to be acted upon by the methanogens. The theoretical retention time is calculated by dividing the average slurry holding volume of the digester by the volume of substrate added daily. Depending on the vessel geometry, the means of mixing etc., the effective retention time may vary widely for the individual substrate constituents. Selection of a suitable retention time thus depends not only on the process temperature, but also on the type of substrate used.

In general the optimum retention time can vary between 30 and 100 days. For a night soil biogas digesters the retention time is extended with another 10 days so that the pathogens present in human faeces are largely destroyed.

Volatile Solids

Volatile solids are part of the total solids content of the substrate that can be converted into biogas. It is the organic fraction of total solids in manure that will oxidize and be driven off as gas at a temperature of 600^oC. The weight of the dried biomass minus the weight of the remaining ash after gasification will be the weight of the volatile solids. The biogas production potential of different organic materials can also be calculated on the basis of their volatile solid content. The higher the volatile solids content in a unit volume of fresh dung, the higher the gas production. For example, a kg of volatile solids in cow dung would yield about 0.25 m^3 of biogas (Sathianathan, 1975)

pH value

The optimum biogas production is achieved when the pH value of input mixture in the digester is between 6 and 7. The pH in a biogas digester is also a function of the retention time. In the initial period of fermentation, as large amounts of organic acids are produced by acid forming bacteria, the pH inside the digester can decrease to below 5. This can inhibit or even stop the digestion or fermentation process. Methanogenic bacteria are very sensitive to pH and do not thrive below a value of 6.5. Later, as the digestion process continues, concentration of NH_4 increases due to digestion of nitrogen which can increase the pH value to above 8. When the methane production level is stabilized, the pH range remains buffered between 7.2 - 8.2.

2.2.1.3 Common Digester types in Bangladesh

Mainly there are two types of biogas plant designs that have been tried in Bangladesh since the 1980's (Islam, 2006); Floating dome digester and fixed dome digester.

Floating dome digester

The system works on the principle of constant pressure and changing volume. The digester, a cylindrical well commonly made from brick and cement, is covered with a floating steel cylinder with an open bottom. As the steel cylinder has a constant weight, it moves up when gas production is higher than consumption and comes down under the reverse conditions.

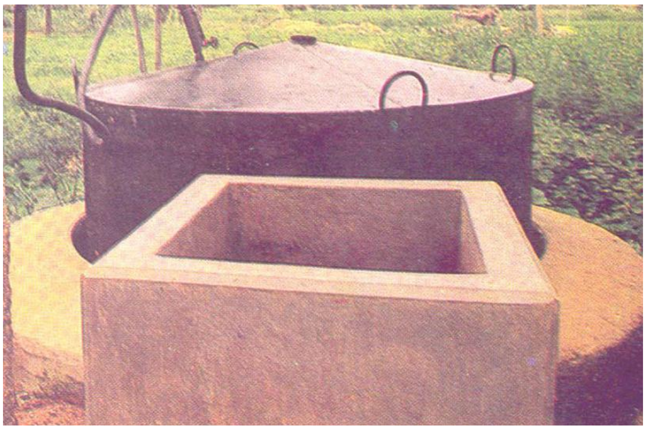

Figure 2.7 Biogas reservoir is floating on the Floating dome anaerobic digester

Fixed dome digester

It works according to the principle of constant pressure and changing volume. When the rate of gas production is higher than that of gas consumption, pressure inside the digester rises and expels some digester contents into the outlet compartment. When the consumption is higher than production, the pressure inside the digester falls and the expelled material in the outlet compartment runs back into the digester.

Types of fixed cover or dome plants

1. Chinese fixed-dome plant is the archetype of all fixed dome plants (Sasse, L. - GATE; 1987). Several million have been constructed in China. The digester consists of a cylinder with round bottom and top.
2. Janata model was the first fixed-dome design in India, as a response to the Chinese fixed dome plant. The mode of construction leads to cracks in the gasholder - very few of this plant have been gas-tight.
3. Deenbandhu, the successor of the Janata plant in India, with improved design, was more crack-proof and consumed less building material than the Janata plant with a hemisphere digester.

In the early 1980's, the floating type design was used for biogas plants. But due to corrosion of the steel dome, the gas leakage problem occurred and could not be removed. Bangladesh Council of Scientific and Industrial Research (BCSIR) tried the fixed dome type design and it has been successful in all biogas plants. Today the fixed dome type is mainly used in Bangladesh and very few of the floating dome type are used.

The construction of a fixed dome biogas plant with layout is given in Figure 2.8.

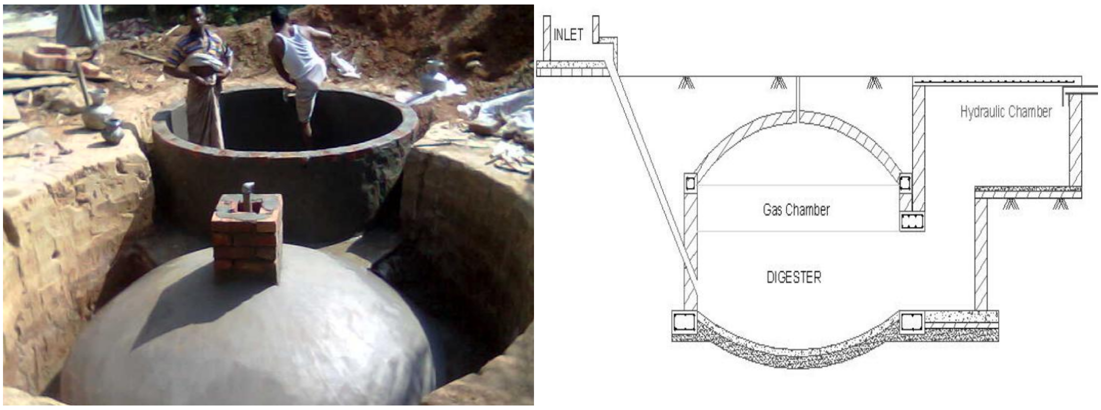

Figure 2.8 Construction of Brick-Sand-Cement fixed dome domestic biogas plant

Fibreglass digester

A fibreglass bio digester is another type of digester made by recycled fibre glass. Grameen Shakti introduced both fixed dome and floating dome fibre glass bio digesters in domestic sizes. Some details of two common domestic fibre glass floating dome bio digesters sized at 2.4 m^3 and a 3.2 m^3 are given in the following Table 2.5.

Table 2.5 Some parameters of two common sized glass fibre bio digesters (Gofran, 2011)

Parameter	**2.4 m^3 bio digester**	**3.2 m^3 bio digester**
Weight in kg	100	150
Top dome diameter (m)	1.6	1.9
Top dome height (m)	0.5	0.6
Bottom dome diameter (m)	1.7	2.00
Bottom dome height (m)	1.6	1.9
Cost of digester (£)	200	400

Fibreglass bio digesters are used as domestic AD plant and are portable. The cost of bio digester is also comparatively reasonable. The weight of a 2.4 m^3 and 3.2 m^3 bio digester is 100 and 150 kg respectively. The cost for a 2.4 m^3 fibreglass bio digester is £200 and the cost for 3.2 m^3 bio digester is £400.

2.3 Life Cycle Assessment

2.3.0 Introduction

Waste management is a complex phenomenon with a range of consequences for the involved stakeholders and the society. One of the many parameters to evaluate is the environmental impact of different treatment options or technical solutions. There are many tools in the assessment of environmental impacts, but one of the most commonly used is life-cycle assessment (LCA). It helps expand the perspective beyond the waste management system. This is important since the environmental consequences of waste management often depend more on the impacts on surrounding systems than on the emissions from the waste management system itself (Ekvall, 1999). The production of biogas from AD can be either brick-sand-cement made or both brick and a plastic digester. Whichever materials are used to build the digester and the process that follows all types of digester has their own life span. For example, the life time of a brick made fixed dome digester is considered to be 20 years (although it was only 10 years in the very beginning of the technology) (Gofran, 2009). Life cycle analysis assesses the environmental impact arising from the contribution of the biogas plant structural materials and construction of the overall AD system.

Life Cycle Assessment is potentially the most important method for assessing the overall environmental impact of products, processes or services**.** It is also sometimes referred to as Life Cycle Analysis or LCA (Royal Society of Chemistry, 2005). This work uses life cycle analysis to assess the whole environmental impact and global warming potential of anaerobic digestion.

2.3.1 Life Cycle Assessment; an assessment tool

2.3.1.1 Concept of LCA

LCA is a tool that can be used to assess the environmental impacts of a product, process or service from design to disposal i.e. across its entire lifecycle, a so called cradle to grave approach. LCA includes the collection and evaluation of quantitative data on the inputs and outputs of material, energy and waste flows associated with a product over its entire life cycle so that the environmental impacts can be determined. To assess the life cycle impact, SimaPro software was used in this study. The software has an associated database which contains small LCA studies of production or service. The software returns the impact values for several environmental indicators such as global warming potential (GWP). The LCA for a product is a summation of the aspects of extraction of the relevant raw materials, refinement and conversion to process materials; manufacturing and packaging processes transportation and distribution at each stage of operation or use during its lifetime and at the end of its useful life, final transportation, waste treatment and disposal. According to ISO 14044 an LCA follows four steps: goal and scope, inventory, impact assessment and interpretation (Joep and Meijer, 2011).

2.3.1.1.1 Goal and Scope

The first part of an LCA study consists of defining the goal of the study and its scope. The goal of the study should include a statement of the reason for carrying out the study as well as the intended application of the results and the intended audience. In the scope of an LCA is the functional unit, system boundary and type of impact assessment methodology and interpretation. The impact of a system is evaluated on its whole life cycle. It also includes all side activities such as energy, building materials and reagents production, transport etc.

Functional Unit

The functional unit provides a reference to which the inputs and outputs are normalised. In this research 1 kg of feed stock (cow dung and poultry litter) was considered as the functional unit to AD process analysis.

System boundary

A system boundary of an LCA defines what input and outputs are considered in the study. The inputs of waste treatment anaerobic digestion are residual waste dung and water. In the anaerobic atmosphere the primary output is biogas and secondary product is digestate. Both the biogas and digestate can cause environmental impacts, both of which remain in system boundary.

2.3.1.1.2 Inventory

This is the full listing of the required raw materials and the air, water and soil emissions relative to the considered functional unit. Data are collected resulting in a list of input and output flows, which are derived from mass and energy balances evaluated on the system under consideration. Any assumption made during this phase, especially in the case of missing data, should be mentioned. Data collection is the longest phase of an LCA.

2.3.1.1.3 Impact assessment

This part of LCA (3^{rd} step of LCA) evaluates the environmental impacts of different emissions. Different methods have been developed to reduce comparison criteria to a few environmental impact categories. Toxicity encompasses several aspects such as human toxicity and eco toxicity, the latter being subdivided into freshwater, marine, terrestrial, etc.

The basic structure of impact assessment methods in SimaPro is characterisation, damage assessment, normalisation and weighting. LCA methods CML 2 Baseline 2000 and EDIP 96 are problem oriented methods where the participation of each process flow to an environmental effect (such as global warming, eutrophication, etc.) is accounted for. CML version 2 is well adapted for SimaPro 7. SimaPro version 7 software (see section 2.3.1.3), a program to conduct life-cycle inventory studies and Ecoinvent database with method CML 2 baseline 2000 were used to process the data and measure environmental impacts in terms of material use and emissions (Guinee, J, 2001). SimaPro is the most widely used life cycle assessment (LCA) software, used by major industries and consultants, through to research institutes and universities. It allows complex life cycles to be modelled and analysed in a systematic and transparent way (Pieragostini *et. al.*, 2011). In this study, SimaPro version 7 software was used because it is available in the computer laboratory of University of Brighton and CLM 2000 (Centre for Environmental Studies) impact parameters were used to report environmental impact categories. The explanation for the terms used and the units in the Impact Category is briefly given in appendix 1.

2.3.1.1.4 Interpretation

Interpretation steps involves to interpreting the results of each of the former steps and pointing out the key factors for environmental decision making. Results are presented and discussed and a simple sensitivity analysis (6.3.3) has been conducted in interpreting results. But a detailed sensitivity analysis is not included in this work.

2.3.1.1 Publicity Available Specification (PAS)/PAS 2050

A standardisation process was initiated by the Carbon Trust and DEFRA (Department for Environment Food and Rural Affairs) aimed at developing a Publicly Available Specification (PAS) for LCA methodology used by the Carbon Trust to measure the embodied greenhouse gases in products (DEFRA, 2007). This is done through compilation and evaluation of inputs, outputs and potential environmental impacts of a product system throughout its life cycle (extraction to end-of-life). UK PAS 2050 is a consistent method for assessing the life cycle Greenhouse gas (GHG) emissions of goods and services.

According to ISO 14040 (International Organisation for Standardisation, 2006), LCA assesses the environmental aspects and potential environmental impacts for the whole process, from raw material acquisition through production, use, end-of-life treatment, recycling and final disposal. PAS 2050 uses process maps to carry out LCA analysis.

The example of a process map for AD biogas production is given in Figure 2.9. In this research animal manure and rice straw are considered as raw materials. Production means to build an AD plant where bricks and cement are the major construction materials for AD plant. Distribution indicates the supply of primary and secondary product to the consumer.

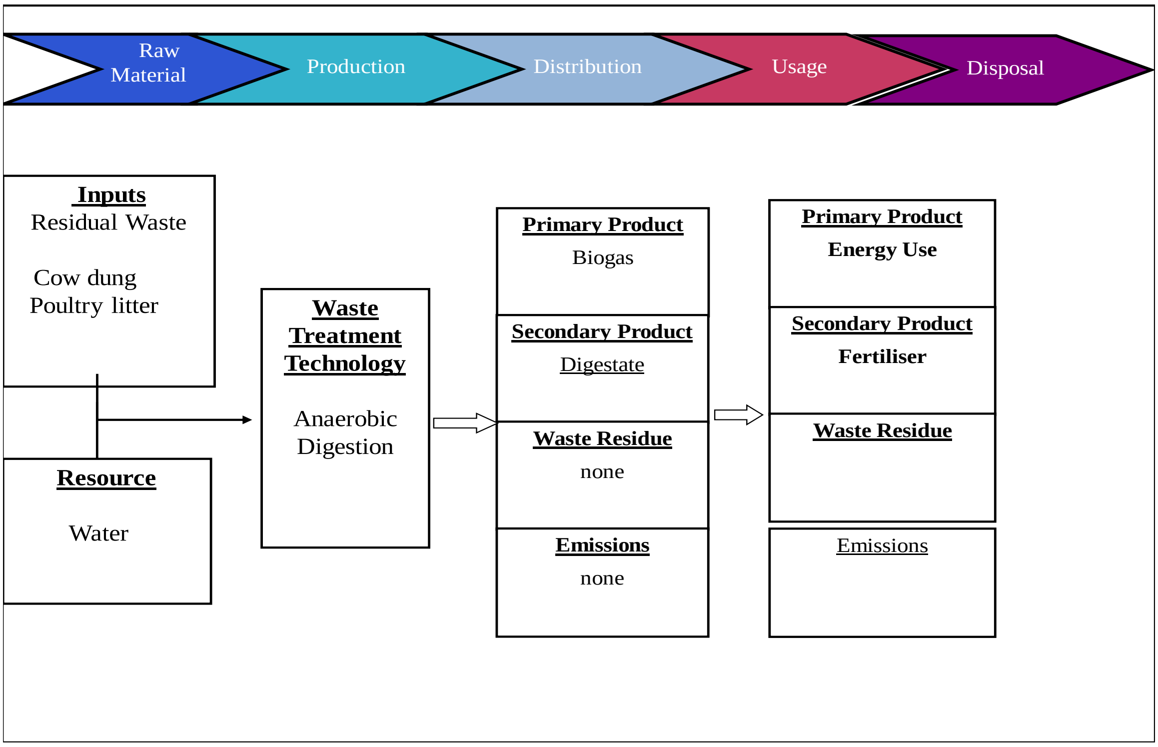

Figure 2.9 The process map of anaerobic digestion biogas production.

2.3.1.3 LCA Software SimaPro 7

SimaPro 7 Life Cycle Assessment Software is a professional tool to collect, analyse and monitor the environmental performance of products and services. It was first released in 1990 and is a proven, reliable and flexible tool used by major industries, consultancies and universities. It consists of a large standard database and some optional databases. This data is meant to be used as background data which is not specific for the life cycle being modelled, like electricity or transport. SimaPro has features that support its extensive use as a product development and LCA management tool.

It can model and analyze complex life cycles in a systematic and transparent way, following the ISO 14040 series recommendations. SimaPro stands for "System for Integrated Environmental Assessment of Products". It is not only used for product assessment; its generic setup means use has expanded to analysis of processes and services. SimaPro is a LCA software used worldwide. Regarding the impact assessment stage, Eco invent inventory database and CML 2000 baseline World, 1995 impact assessment factors were chosen. The LCA methodology using PAS 2050 guidelines were used for this study of anaerobic digestion.

Summary of chapter

This chapter described the energy status of Bangladesh and gave an overview of anaerobic digestion and LCA of AD. It emphasized biogas technology in Bangladesh with respect to feedstock, factors affecting biogas and AD digester types. From this chapter suggest that the potential feedstock could be potential sources of energy which is needed for the country. Potentially in the millions of AD plants with huge AD capacity, a study of the life cycle impact assessment of an AD plant is really needed. Furthermore, for future implementation of AD and funding opportunities, carbon counting is a pre-requisite. LCA of AD is an important tool for the Clean Development Mechanism approach (CDM). The avoided GHG emissions from the CDM projects could generate CERs (Certified Emission Reductions) that can be bought by Annex 1 countries (41 industrialised countries). This can help finance further biogas growth in developing countries (Bajgain and Shakya, 2005). AD has various types of impacts e.g. social, economical and environmental. Literature review on energy status in Bangladesh, AD energy capacity and impact of AD will be presented in chapter 3.

Chapter 3

Review of Literature

3.0 Introduction

This chapter will review literature that is significant and pertinent to the aims and objectives of the thesis. It will review the relevant literature mainly in three sub headings. The first section (3.1) will describe the energy scenario of Bangladesh. Contextual AD and energy capacity of AD (section 3.2) will be described using the feedstock potential, construction materials, AD biogas and methane yields with energy capacity and the factors affecting these yields. Section 3.3 will describe the overall impact of anaerobic digestion. It will describe the social, economical and environmental impact of anaerobic digestion as well as the GHG mitigation of AD and CDM opportunity from AD technology.

3.1 The energy scenario in Bangladesh

Bangladesh is an energy-starved country which generates a huge amount of biodegradable waste including farm feedstock. Per capita energy consumption in Bangladesh (220 kg OE) is among the lowest in world and there is vast potential for the use of anaerobic digestion in Bangladesh from animal farm feedstock (CIA World Fact book, 2009). In 2005, nearly 40 percent of Bangladesh's 140 million residents and 44 percent of its rural residents were below the poverty line (World Bank, 2006). Inadequate energy provision in Bangladesh is one of the most important reasons for poverty (Ministry of Finance and Planning, 2008). The per capita energy consumption of developing countries is very low compared to that of developed countries, and the per capita energy consumption in Bangladesh is among the lowest of all south Asian countries.

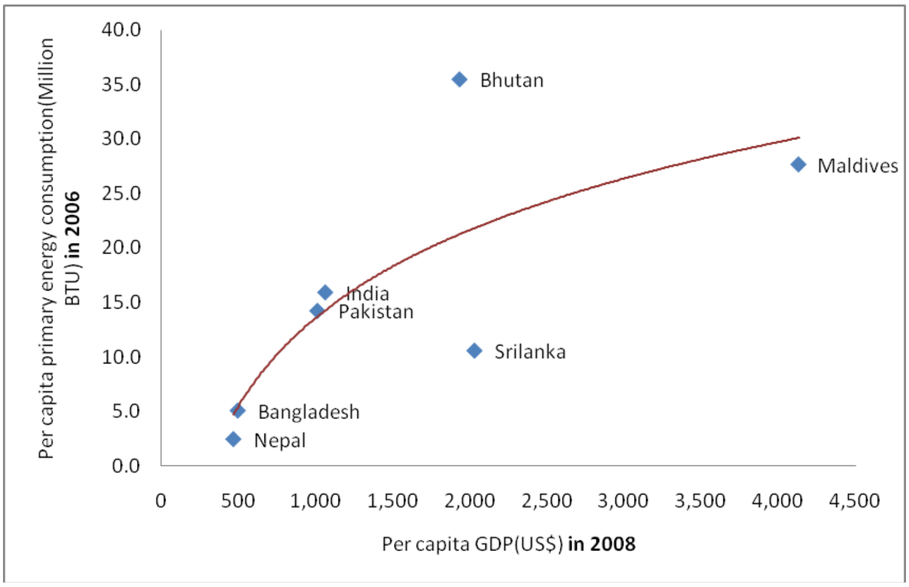

Figure 3.1 Comparative Status of per Capita Energy Consumption and per capita GDP in South Asia (US Energy Information Administration's, and United Nation Statistic Division, 2008).

Energy sources in Bangladesh can be broadly classified into three categories: traditional, commercial and renewable. Traditional energy (biomass) includes fuel wood, agricultural residues, leaves and dried dung cake. It is estimated that about 55% of the country's energy is met by traditional energy sources (Asaduzzaman and Latif 2005) most of which are used for cooking. Excessive use of biomass energy may already exceed the regenerative limit and an energy crisis prevails in rural areas. An estimated total amount of traditional fuels (biomass) supplied in 2002/03 was approximately 11,199 million tonnes of coal equivalent (Bangladesh Bureau of Statistics; BBS 2002). Research by Asaduzzaman (2005) showed that over 90% of energy consumption in rural areas of Bangladesh consisted of biomass with a per capita consumption of 2.93 tonnes per year in 2004. It is worth pointing out that the data on biomass is very sketchy. Renewable energy other than biomass and hydropower constitutes less than 1% of the total energy consumption (Gofran, 2009). Ekkehard Kürschner (2009) found that access to biomass is becoming more expensive and scarce due to high demand.

Research by BBS (2003) found that less than 30 per cent of households have electricity and approximately 4% of households are supplied by natural gas. This of course excludes the use of sunlight for various drying operations by households, commercial establishments and industrial units. The transition to modern fuels like kerosene, Liquid Propane Gas (LPG) and natural gas is taking place at an extremely slow pace and is driven predominantly by increasing prosperity (BBS, 2002).

According to Bangladesh Power Development Board, BPDB (2008), 83% of electricity is generated from natural gas and 70% of the commercial energy supply in Bangladesh comes from natural gas. Only few urban people (about 3%) are enjoy natural gas by pipe line in their household. The rest of the people of Bangladesh rely on biomass fuel and LPG for cooking, but LPG is very expensive for the rural people. On the other hand natural gas is running out quickly. Natural gas is the only indigenous non-renewable primary energy that is consumed in comparatively large quantity in Bangladesh. Gas is the main source of commercial energy supply. It counts for 70 % (NEP, 2004) of the country's commercial energy supply. The power sector is the largest consumer of gas followed by industries.

According to National Energy Policy, Bangladesh's (2004) total coal reserve from four fields is 2,527 million tonnes from which 492 million tonnes are recoverable (NEP, 2004). This is equivalent to 14 Trillion Cubic Feet (TCF) gas. The National Energy Policy (2004) has guidelines for renewable energy and the Government of Bangladesh adopted a Renewable Energy Policy in December 2008. Bangladesh has huge potential for solar power and biogas.
The energy scenario in Bangladesh can be developed by increasing the uses of renewable energy. But waste management in Bangladesh is not satisfactory due to the lack of proper monitoring. Poor governance is one of the most important reasons hindering waste

management in Bangladesh. Kironde and Yhdego (1997) assert that solid waste management problems in developing countries are mainly due to poor governance. The most serious waste management problem in Bangladesh currently is dumping.

The biogas industry in India and China is further ahead than that of Bangladesh. All three countries had to come up with an alternative source of energy in order to preserve their woodlands and soil fertility. Although rural households in Bangladesh use about 0.35 kg of firewood daily per person, which is less compared to India's rural household use of 0.62 kg per person and China's use of 0.55 - 0.83 kg per person, the soil fertility of Bangladesh is far lower than that of China and India. For instance, the recycling of biodegradable organic waste (this includes all food waste, garden waste as well as dung) in Bangladesh is only about 11% compared to 40% and 65% in India and China, respectively (Aktaruzzaman, 2003; Chowdhuri et al., 2008). This could be due to the over exploitation of biomass fuels through burning beyond their regenerative limits. Loss of soil organic content makes land more vulnerable to desiccation and erosion leading to land degradation. Since loss of soil organic content makes the land more vulnerable to climate change (drought and flooding), the use of the Decentralised Rural Electrification (DRE) can lead to decreased soil stress and decreased climate change vulnerability.

Small-scale biogas technology is a simple and inexpensive solution that has gained increased interest in many developing countries. For example, India and Nepal have installed family sized biogas plants at 31% and 8% of their estimated total capacities, respectively (Gautam *et al.*, 2009; Rao *et al*., 2010) while Bangladesh has installed less than 1% (Islam et al., 2006; Al-muyeed and Shadullah, 2010). At present there is still a very large unused potential in many developing countries globally. The above scenario clearly indicates Bangladesh's desperate need for an alternative source of energy. Also, both Bangladesh and India have lost valuable bio fertilizer with the use of dried cow dung as fuel (Biogas Digest, 1995).

The infrastructure for energy generation and distribution is deficient. It is not sufficiently extended to match the high demand and electricity is unreliable because of insufficient power generation capacities.

3.2 Contextual AD and energy capacity of AD

Anaerobic Digestion (AD) is the process whereby bacteria break down organic material in the absence of air, yielding a biogas containing methane (Biomass Energy Centre, 2010). This section presents a review of information relevant to AD plant context for Bangladesh, AD potential feedstock, AD biogas and methane yield and factors affecting biogas production. This information is important for overall environmental life cycle considerations and calculations as well as for calculating a unit's energy potential and deducing the energy potential for the country.

Bangladesh works with both Chinese and Indian models of AD digesters but the Chinese model is most widely used in Bangladesh (see Figure 3.2 and Figure 3.3) (Gofran, 2009). To ensure the digester is gas tight, several layers of cement and wax are added alternatively (BCSlR, 2004).

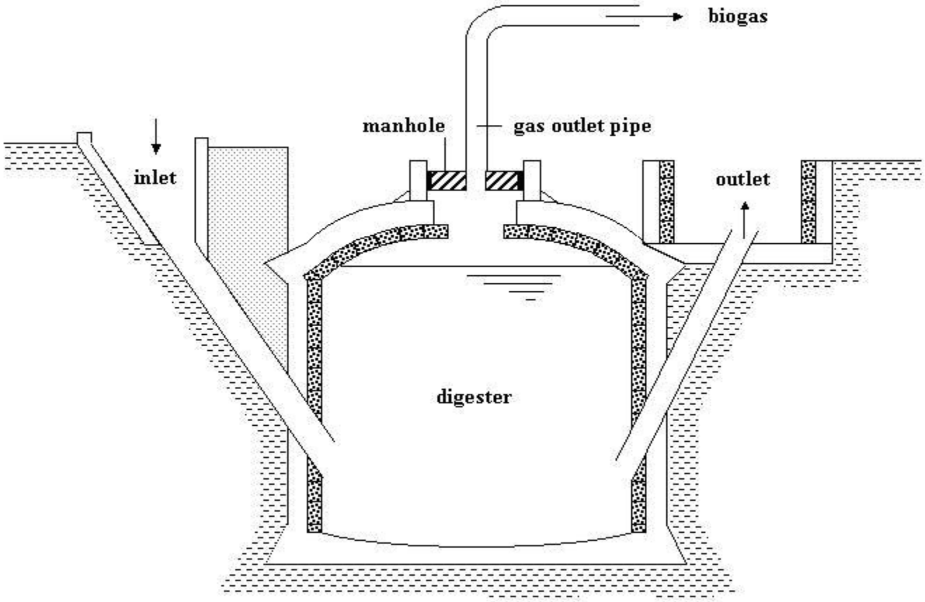

Figure 3.2 Chinese fixed dome anaerobic digestion plants (Gunnerson and Stuckey, 1986).

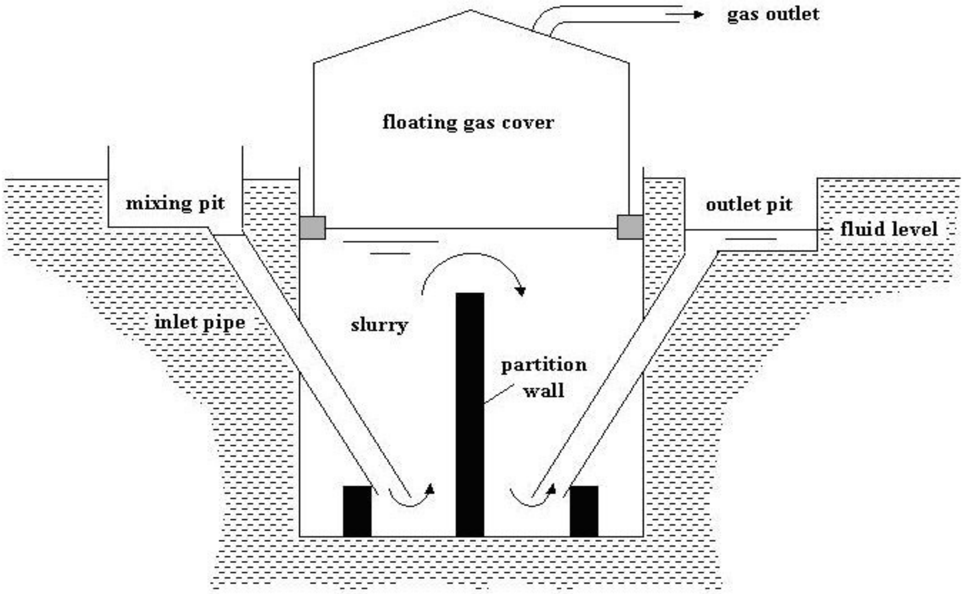

Figure 3.3 Indian floating cover anaerobic digestion plants (Gunnerson and Stuckey, 1986).

3.2.1 AD plant construction materials

There are two main types of biogas plants being constructed in Bangladesh: fixed-dome plants and floating-drum plants. There are various designs of these two plants. In developing countries, the design is determined by the space and raw materials available as well as cost minimization. There are three different feeding methods of a biogas plant: continuous mode, batch mode and semi-batch mode. Systems operating in continuous mode are fed and emptied continuously. The overflow of sludge is emptied automatically as new material is filled in. Systems operating in batch mode are filled and then emptied completely after a certain amount of time. In semi batch mode plants, materials are fed continuously and in batch fillings. Akteruzzaman et al (2005) found that 70% of all plants constructed in Bangladesh are fixed dome plants and 30% are floating dome plants. A floating-drum plant consists of a dome-shaped digester and a moving, floating drum. The digester is usually made of brick or concrete masonry and the drum is made of steel (Biogas Digest, 1995). There are several technical problems that can arise in traditional fixed dome type digester due to poor construction materials. Meher *et. al*. (1990) reported that the performance of a floating dome biogas plant was better than the fixed dome biogas plant, showing a statistically significant increase in biogas production by 11.3%. If there are heavy rains, biogas digesters that are below ground can get flooded and as a result have to be drained which adds to maintenance time and costs. A common problem is pipes getting blocked due to lack of service. Leakage is also a problem that is not unusual in fixed dome biogas plants. Furthermore methane (biogas) is a poisonous gas as well as an aggressive GHG (Woods *et al* 2006; Bajgain, Shakya, 2005; Han *et al* 2008).

Although there is huge potential for biogas plants in Bangladesh and efforts have been made by various organizations to develop this, the rate of installation is very low compared to neighbouring countries like China and India (BCSIR, 2004). It is well known among the biogas stakeholders that a large number of biogas digesters constructed by Bangladesh Council of Scientific and Industrial Research (BCSIR) and Local Government Engineering Department (LGED) are functioning partly or not at all (Gofran, 2009). Different organizations and poultry and dairy farm owners hesitate to invest in large biogas plants because of past failures of domestic biogas plants.

During 1972 - 1992, different organizations undertook initiatives in promoting this technology, but without proper attention to appropriate technology and after-sale service. The results were very discouraging. An internal report of the Local Government Engineering Department (LGED), in 1992 (Rahman et al.1996) states that about 75% of the constructed biogas plants did not operate properly mainly due to design, construction and maintenance problems.

SNV (2005) conducted a survey of domestic AD plants in Bangladesh. Out of the 66 plants under analysis, 47% plants were functioning satisfactorily, 32% plants were functioning partly and the remaining 21% plants were not functioning. They identified digester leaks and improper management of AD during field investigation which caused poorly functioning AD plants. The plants surveyed were at 3.9 m^3 average gas production capacities.

This result shows that the trend of longevity and reliability of biogas plants in Bangladesh is improving with a reduction in plants not functioning properly from 75% to 53% from 1992 to 2005 – but clearly there is still a significant problem with many units not yet working properly.

3.2.2 AD potential feedstock

Livestock, next to crops, is the most important sub-sector of agriculture in Bangladesh. The contribution of the livestock sub-sector to the nation's agricultural gross domestic product is about 11%. The annual growth rate of the livestock sub-sector in 1996 - 97 was 8%, which was one of the highest in the economy. In 2005, the numbers of livestock in Bangladesh were estimated to be 22.8 million cattle, 1.21 million buffalo, 20.74 million goats, 2.68 million sheep, 206.89 million chicken, and 39.8 million ducks (DLS, 2006). This animal population generates a huge amount of manure daily, which can produce a substantial amount of biogas through anaerobic digestion processes. Cow dung and poultry litter are the most common feedstock for biogas digesters in Bangladesh. In 2008-2009, DLS (2009) estimated a total of 22.97 million cattle in Bangladesh which can produce 0.2297 million ton of dung every day. The trend shows that the cattle population has been increasing at a slow rate.

Table 3.1 Livestock and poultry population in Bangladesh (in millions) (DLS. 2009)

Fiscal year	**2000-01**	**2001-02**	**2002-03**	**2003-04**	**2005-06**	**2006-07**	**2007-08**
Cattle	22.39	22.46	22.53	22.8	22.87	22.9	**22.97**
Buffalo	0.92	0.97	1.01	1.16	1.21	1.26	1.3
Goat	16.27	16.96	17.69	19.94	20.74	21.56	22.4
Sheep	2.11	2.22	2.29	2.57	2.68	2.78	2.87
Chicken	142.68	152.24	162.44	194.82	206.89	212.47	**221.39**
Duck	33.83	34.67	35.54	38.17	39.8	39.84	41.23

Poultry is increasing at a rapid rate. This means that cattle numbers are not following a similar trend to poultry and remain between 22.39 - 22.97 millions in recent years (2001-2008). The total number of poultry bird in 2000 - 2001 was 142.68 million and in 2008 - 2009 was 221.39 million. According to estimation, 29.7 billion m^3 of biogas can be obtained from the livestock of Bangladesh which is equal to 1.5 million tonnes of kerosene (Islam, 2006). The poultry population was about 262.62 million in the year 2008 - 2009 (ibid) which can produce 26,200 tonnes of poultry litter every day. One tonne of cow dung can produce 37 m^3 of biogas (PREGA, 2006). Estimated biogas potential in rural areas of Bangladesh is 29.7 x 10^8 m^3 which means 80.27 million tonnes of cow dung available per year.

According to BCAS (2005), the number of birds per poultry farm in Bangladesh is in between 100 - 50,000. The most poultry farms in Bangladesh (about 80%) can contain 250 - 5,000 birds. Only 1% of poultry farms have poultry populations of >10,000.

Table 3.2 A pattern of number of birds in each poultry farm (BCAS, 2005).

Size (No of birds)	**No. of farms (approximate)**	**Percentage (%)**
100-249	15,000	12.90
250-499	35,000	30.11
500-999	45,000	38.71
1000-4999	12,000	10.32
5000-9999	8,000	6.88
10000-50000	1,200	1.03
> 50000	50	0.04
Total	11,6520	

According to estimation (DCC, 2004), every day 3,500 tonnes of waste is produced in Dhaka, the capital of Bangladesh consisting of Municipal Solid Waste (MSW), food waste and agricultural waste. Sujauddin et al. (2008) showed that the household solid waste can be converted from burden to resource in developing countries. Like other developing countries, the major portion (about 84%) of the total solid waste in Bangladesh is organic (Sinha and Enayetullah, 2010).

The National Domestic Biogas and Manure Program implementation plan 2010 - 2012, IDCOL, mentioned that the total technical potential of domestic biogas plants is 3 million. "Mobilizing market for the biogas technology" of German Development Organization (GTZ)'s study explained that the large potential market for biogas digesters in 100,000 poultry farms could benefit from the technology.

IDCOL installed 22,000 domestic biogas plants by the year 2011 and has a target to install 37,269 (IDCOL) biogas plants by 2012. GTZ is also providing technical and financial assistance to its partner organizations to install commercial and institutional biogas plants. Up until May 2010 GTZ implemented 1,250 commercial and institutional biogas plants. It is also providing technical assistance for electricity generation from biogas (Local Government Engineering Department, LGED/GTZ) (Barua, 2010). BCSIR (2001) produced an estimate to find out the potential for biogas and organic fertilizer from major feedstocks in Bangladesh. The results are shown in Table 3.3.

Table 3.3 Potential for biogas and organic fertilizer in Bangladesh (BCSIR, 2001)

Raw materials	**Biogas (10^6 m^3/year)**	**Bio-fertilizer (10^6 tonnes /year)**
Cow/Buffalo dung	2971.1	60.20
Poultry droppings	191.6	2.05
Human excreta	1226.4	32.85
Garbage	115.00	1.72
Water hyacinth	740.00	10.00
Pressed mud	384.00	0.07
Total	5628.1	106.89

A survey of 66 domestic biogas plants in Bangladesh was done by IDCOL and SNV (2005), and the feeding materials digested for biogas production were observed. Cattle dung (44) and poultry droppings (10) were the two major feedstocks materials used. Besides these, kitchen and household wastes (1), human excreta (3), urine of animals, water hyacinth (1) and urea were also used to feed biogas plants.

Poultry litter is an important potential raw material for biogas plants in Bangladesh. Over the last two decades, the poultry sector has grown rapidly in Bangladesh. However poultry litter is being managed very poorly and being dumped in open pits near the farms. The poultry sector alone could generate about 490 GWh of electricity per year, which is nearly 2% of the total electricity generation of the country in 2008 - 2009's financial year. Up until 2009 the total number of installed biogas plants was 34,484 (Renewable Energy and Environmental Information Network, REEIN, 2008).

Water hyacinth grows very rapidly and is capable of rapid multiplication in the presence of water. It is a menace in agriculture, fisheries and navigation and is readily available in lakes, ponds and rivers. Yield per acre is estimated at 20 tonnes per year (Eusuf, 1995) but its supply is limited to the rainy season. Rice is the staple food of Bangladesh, its straw an important food for cattle as it grows all year round; thus biogas production from rice straw also has good prospects in Bangladesh (Gofran, 2009).

An agriculture-based country like Bangladesh has high prospects for utilizing biogas technology as it fulfils all requirements for its use. According to Institute of Fuel Research and Development, IFRD, there is potential for 4 million domestic biogas plants in the country (Islam, 2006). Another report on "Feasibility of National Programme on Domestic Biogas in Bangladesh" has estimated that about 950,000 households have the potential to construct biogas plants and 80,000 biogas plants can be constructed for poultry dropping (Nes et al. 2005).

A study was done by Zaman (2007) in the Gazipur district and found only 8% farms running their biogas plant to their full potential. The farms using the biogas plants to their full potential vary from 800 birds to 2000 birds. All the farms holding more than 5,000 birds use less than 20% of their potential for biogas production. Due to the lack of proper gas supply technique and infrastructure they could not fully maximise the potential of the gas. There is huge potential for large size biogas plants in Bangladesh as dairy and poultry farms in Bangladesh are run on a commercial basis. There are about 100,000 poultry farms and 47,000 dairy farms. The farm owners could meet their energy demand from their own farms. They can sell excess biogas to their neighbours for cooking purposes (IDCOL, 2006) by utilizing their total potential feedstock. These developments of local entrepreneurial activities have important potential for nationwide energy in Bangladesh.

It was also found that Grammen Shakti is currently constructing a biogas plant in a poultry farm of 48,000 birds which is located in Mymensingh district. The aim is to produce electricity for back up during power cuts. The capacity of the biogas plant is 70 m^3 which is designed to use the poultry droppings of 10,000 birds only. With the total potential the size would be 340 m^3. That means it is going to use only about 20% of its total potential.

Table 3.4 summarises the potential for AD in Bangladesh on the basis of livestock and households. Van Nes (2005) in their report on 'Feasibility of national programme on domestic biogas in Bangladesh' came out with the figure of about 950,000 households as potential for biogas plant construction. This data was based upon the households who have five or more cattle. The dung produced by 5 cattle is sufficient to feed a biogas plant with a gas output of 2 m^3 per day. Similarly, poultry droppings were also considered to be an excellent feeding material for biogas generation. Poultry farming is seen as a big business in Bangladesh (DLO, Gazipur, 2010). According to an estimate (BCAS, 2005) about 116,000 poultry farms were in operation all over the country. Out of them about 80,000 poultry farms were estimated to be capable of keeping 200 - 1,000 birds. The construction of domestic size biogas plants would be quite feasible. In this context about 80,000 biogas plants using poultry droppings were considered to be technically feasible for domestic use. According to the estimation presented by Khan (2002) the total biogas potential in Bangladesh is 4,470 million m^3/year.

Table 3.4 The number of Household with cattle and poultry birds in Bangladesh (BBS, 2005 and BCAS 2005).

Livestock	**Size of cattle smallholding/poultry farm**	**Number of households**
Cattle	With 1-2 heads	5,106,994
(Cows and buffaloes)	With 3-4 heads	2,111,498
	With 5 heads and above	952,872
Poultry	Less than 249	15,000
birds	With 250-999	80,000
	With 1000or more	21,250
	Total	8,287,614

According to BCSIR, there are about 22 million domestic cattle in the country. This number of domestic cattle can give about 220 million kg of animal excreta which is able to produce 29.7 billion cubic meters of biogas. This is equivalent to 1.52 million tonnes of kerosene, which is the prominent fuel in the rural areas.

3.2.3 Factors affecting biogas and methane yield

Factors that impact the efficiency of the AD processes are biogas potential of feedstock, design of digester, pH value of feedstock, temperature, organic loading rate (OLR), retention time (RT), total solids (TS) and volatile solids (VS). Research done by Demirel (2009) investigated the attributes of biogas production of energy crops. It was found that during operation, the hydraulic retention time (HRT) varied between 15 and 9.5 days and the organic loading rate (OLR) ranged from 2.6 to 4.7 g/l/d. The average pH, specific gas production rate and volumetric gas production rate were determined to be 7.12, 0.31 L g VS/d and 1.084 L/L/day, respectively. The average methane (CH_4) content of digester biogas was about 56%. Methane content from poultry manure biogas was found to be 58.72% from an experiment in Bangladesh (IFRD-BCSIR, 2001). This result indicates that those biogas and methane yields are variable and can never be constant due a few interfering factors.

3.2.3.1 Feedstock

Types of feedstock can also influence biogas production rate. An example can be drawn from the experiences of Indian researchers and farmers. Farmers of Jodhpur, Rajasthan, in India successfully used tea leaf waste as a feedstock, which gas yielded 12 ft^3/kg of waste. Conventional biogas digesters require 10 kg of cattle waste to produce an equivalent quantity of biogas. Sahota and Rajinder (1997) reported that addition of rice husk soaked in water at 20% to cattle dung increased the gas production.

Another study was done by Somayaji and S. Khanna (1994) for biomethanation of rice straw and wheat straw added with cow dung. When rice or wheat straw was added to cattle dung slurry and digested anaerobically, daily gas production increased from 176 to 331 L/kg total solids with 100% rice straw and to 194 L/kg total solids with 40% wheat straw. Not only was methane production enhanced by adding chopped crop residues but a greater biodegradability of organic matter in the straws was achieved.

Research has been conducted showing that positive biogas yield can be achieved through adding energy crops to farm manure. Abbasi et al (1990) studied the biogas potential of eight aquatic weeds and reported that *Salvinia* and *Ceratopteris* yielded a biogas output as high as 0.2 m^3/kg volatile solid. Abbasi and Nipaney (1991) reported that addition of inoculums sustained biogas production from *Pistia* for 10 days. Balasubramanian and Kasturi Bai (1992) suggested that *Wolffia* and *Lemna* grown in the slurry from cow dung-fed digesters can be effectively used for biogas production together with cow dung. It means there is a positive effect on biogas production from dung feedstock when crops or weeds are added.

The loading rate of feedstock can influence biogas production. Loading rate is the amount of raw materials fed per unit volume of digester capacity per day. If the plant is overfed, acids will accumulate and methane production will be inhibited. Similarly but for different reasons, if the plant is underfed, the gas production will also be low.

3.2.3.2 % Total Solid (TS)

In anaerobic digesters, cow dung raw materials are mixed with water in the inlet tank at 1:1 ratio; 10 kg of cow dung is mixed with 10 litres of water (BCSIR, 2004). The %TS of dung feedstock is 17 - 18 and water mixed slurry at 1:1 ratio is at 8% TS. 8% TS is considered suitable for bacterial activities (methanogenesis). Shivraj and Seenayya (1994) reported that digesters fed with 8% TS of poultry waste gave a better biogas yield and attributed the lower yield of biogas at higher TS levels to high ammonia content of the slurry. This ratio becomes 1:2 for poultry litter feedstock because its % TS is 23 - 25% (BCSIR, 2004).

Percent TS can be classified into three types. Low solids (LS) AD systems contain less than 10 % TS, medium solids (MS) about 15 - 20% and high solids (HS) processes range from 22% to 40% (Tchobanoglous, 1993). An increase in TS in the reactor results in a corresponding decrease in reactor volume. Hu Rongdu (2006) conducted research to investigate the biogas attributes of animal manure. It was observe that the biogas yield, methane percentage and total solid (TS) percentage of cow dung and poultry litter was 0.25 and 0.33, 50 - 77 and 60 - 65, and 17 and 25 respectively (Table 3.5).

Table 3.5 Energy parameters of other researchers (Hu Rongdu, 2006)

Manure source	% TS	Gas yield (m^3/kg TS)	% Methane
Cattle	17	0.25	50-77
Chicken	25	0.33	60-65

3.2.3.3 Temperature

Anaerobic digestion is a temperature-dependent process, which is normally operated at defined and constant temperatures. Nevertheless, situations exist in which reactors are subject to repeated sudden and abrupt changes in temperature. Bioreactors may be subject to temperature fluctuations due to large variations in outdoor temperature, especially in highland and northern climates (Alvarez *et al*., 2006; Masse´ *et al*., 2003). The anaerobic digestion process is normally classified into three different temperature ranges, namely psychrophilic (<20^{o}C), mesophilic (20 – 40^{o}C) and thermophilic (>40^{o}C) (El-Mashad *et al*., 2004). The microorganisms involved in anaerobic digestion are characterized by an optimal temperature as well as by an upper limit that would cause immediate death of the considered group of bacteria (Chen, 1983).

The anaerobic digestion of manure in conventional treatment tends to have high process stability. Sudden environmental changes e.g. dramatic increases or drops in temperature may cause severe disturbances in all parameters of the process, and the overall adaptation to new stable operation requires a long period of time (Bouskova *et al*., 2005; Cha *et al*., 1997). A decrease in temperature typically causes lower chemical oxygen demand (COD) removal efficiencies, lower biogas production and the accumulation of volatile fatty acids (VFA) (Alvarez *et al*., 2008).

The temperature fluctuations between day and night are no great problem for plants built underground, since the temperature of the earth below a depth of one meter is practically constant. Methanogenic bacteria develop slowly and are sensitive to a sudden change in physical and chemical conditions. The bio digester can therefore function all through the year, with a sufficient gas production in summer season. The Janata biogas plant in India is located in hilly conditions; the digester slurry temperature followed the same pattern as the ambient temperature. The fall in the mean ambient temperature from 25 - 26°C in summer to 9 - 10°C in winter month resulted in the lowering of the digester temperature from 22 - 23^{o}C to 13 - 14^{o}C. The digester temperature remains in lower mesophilic ranges of (16 - 24°C) for nearly eight months and the rest of the year in the psychrophilic range (l3 - 14°C). This results in lowering of the gas production by 23 - 37% in winter (Kalia and Kanwar, 1998). Kashyap *et al.*, 2003 and Zeeman *et al.*, 1988 noted that the biogas production can occur over a wide range of temperatures, in nature from 0 – 97^{o}C.

3.2.3.4 Hydraulic Retention time (HRT)

Hydraulic Retention time is the average period during which a given quantity of input remains in the digester to be acted upon by the methanogens. The theoretical retention time is calculated by dividing the average slurry holding volume of the digester by the volume of daily added substrate. In general the optimum retention time can vary between 30 and 100 days.

A research result showed that the HRT of dung and poultry manure feedstock is 30 - 40 days in the mesophilic range temperature in Bangladesh (IDCOL, 2009). In tropical countries like India, HRT varies from 30 - 50 days while in countries with colder climate it may go up to 100 days. Hence there is a need to reduce HRT for domestic biogas plants based on solid substrates. It is possible to carry out methanogenic fermentation at low HRT’s without stressing the fermentation process at mesophilic and thermophilic temperature ranges (Zennaki *et al*., 1996; Singh et al., 1995; Garba, 1996). On the other hand Sanchez *et al*. (1992) found improvement in organic matter removal on increasing HRT while anaerobically treating cattle dung. Baserja (1984) observed that at a TS concentration of 7%, the duration of digestion could be reduced to 10 days without compromising the stability of the process, but the optimum period was 16 - 20 days.

Zeeman (1991) showed a stable digestion process when digesting cow manure at a process temperature of 15^oC and an HRT of 100 and 150 days. The chemical oxygen demand (COD) reductions were 14 and 18% respectively. Even at 150 days HRT the gas production was lower as in comparison to that at 30^oC and 20 days HRT.

Safely and Westerman (1994) evaluated the performance of lagoon anaerobic digesters under low temperature that shows digestion is feasible at a minimum digester temperature of 10^oC with minimum hydraulic retention time of 50 days at the maximum loading rate of 0.12 kg VS/m^3/day. This could be adjusted upward for higher temperatures. Sutter and Wellinger (1988) indicate that the gross biogas production by a digester operating at 20^oC and retention time of 40 - 50 days is comparable to a digester operating at mesophilic temperature but at half the retention time.

3.2.3.5 Organic Loading Rate (OLR)/ Volatile Solid (VS)

Organic loading rate (OLR) is a measure of the biological conversion capacity of the AD system. When feeding the system above its OLR results in low biogas yield due to accumulation of inhibiting substances such as fatty acids in the digester slurry (Vandevivere, 1999). In such a case, the feeding rate to the system must be reduced. OLR is a particularly important control parameter in continuous systems. Many plants have reported system failures due to overloading (RISE-AT, 1998). Vandevivere (1999) reports that OLR is twice in high solid in comparisons to sow solid.

Volatile solids are the part of the total solid content of the substrate which is converted into biogas. Biomass that is completely dried and then heated to about $600^{o}C$ will gasify. The weight of the dried biomass minus the weight of the remaining ash after gasification will be the weight of the volatile solids. The biogas production potential of different organic materials can also be calculated on the basis of their volatile solid content: the higher the volatile solid content in a unit volume of fresh dung, the higher the gas production.

The volatile solids (VS) in organic wastes are measured as total solids minus the ash content, as obtained by complete combustion of the feed wastes. The volatile solids are comprised of the biodegradable volatile solids (BVS) fraction and the refractory volatile solids (RVS). Kayhanian (1995) showed that knowledge of the BVS fraction of MSW helps in better estimation of the biodegradability of waste, of biogas generation, organic loading rate and C/N ratio.

3.2.3.6 pH

Optimum biogas production is achieved when the pH value of the input mixture in the digester is between 6 and 7 as methanogenic bacteria are very sensitive to pH and do not thrive below a value of 6. The pH in a biogas digester is also a function of the relation time. In the initial period of fermentation, as large amounts of organic acids are produced by acid forming bacteria, the pH inside the digester can decrease to below 5. This inhibits or even stops the digestion or fermentation process. Later, as the digestion process continues, concentration of NH_4 increases due to digestion of nitrogen, which can increase the pH value to above 8. A pH more than 8.5 shows toxic effect on methanogen population. When the methane production level is stabilised, the pH range remains buffered between 7.2 - 8.2 (FAO/CMS 1996).

3.2.3.7 Other factors

There are a few more factors can influence biogas production and amount of methane directly or indirectly i.e. chemicals, digester leak, C/N ratio and pH of feedstock.

Chemicals such as antibiotic, pesticide, chemical fertilizer or other chemical products may damage bacteria that break down the organic materials in the chamber. A disadvantage of anaerobic digester is they often leak some gas. A fixed dome biogas digester of 2 m^3 size could annually leak 20 - 55 kg of methane depending on the slurry temperature (Khoiyangbam, 2004). Different organic matters contain different concentrations of carbon (C) and nitrogen (N), these two elements being the bacteria's most important nutrients. Normally, fermentative bacteria will require thirty times more carbon than nitrogen. Therefore the optimum carbon-nitrogen ratio (C/N) ratio of the digester input is 30/1 (Karki and Dixit, 1984). Plant material such as weed and straw tend to have a very high C/N ratio resulting in carbon redundancy and very slow decomposition. The C/N ratio of pig and cattle manure is more suitable for biogas Using both animal dung and plant materials input for the bio digester is not recommended as it will reduce the fermentation process and result in incomplete decomposition of the vegetal portion.

3.3 Impact of Anaerobic Digestion

This section will overview the life cycle impact assessment of anaerobic digestion plant. It will also review the GHG mitigation of AD with its clean development mechanism scope. This will be an overlap of social, economical and emission issues of AD plant.

Because of energy shortage, more and more agricultural residues and animal dung are being used as fuel depriving the soil of organic matter and essential nutrients (Eusuf, 1993). As a result, soil fertility is declining and the farmers are becoming more and more dependent on chemical fertilizer. Organic matter content in 50% of Bangladesh's agricultural land has decreased to an alarming less than 1.5%, which should be more than 3% (Sinha and Rahman, 2005). The results of this development are not only financial and economical losses to the people and country, but also to the environment and ecosystem. Moreover, the use of biomass as fuel in traditional stoves is responsible for in-door air pollution causing health hazards to the users, mainly women and children who cook and spend much time in the kitchen.

So, before widening the dissemination of biogas plants, it is necessary to determine the status of functioning and socio-economic impacts of existing biogas digesters.

3.3.1 Social impact

Biogas is a promising renewable source that could meet the energy demand of rural Bangladesh. Most of the cases it can meet up the energy demand of neighbours and communities from the surplus gas. Domestic biogas plants have gained popularity as alternative energy sources in Bangladesh, but there are a growing number of slightly larger scale biogas plants operating on a commercial basis. Some of these biogas plants are generating electricity and some of the plant owners are selling biogas to their neighbours (Talukdar, 2010). Consequently, it is contributing towards social and community development.

Generally women cook food for the whole family in rural Bangladesh. Biogas produced from cattle dung and poultry litter is widely used as a cooking fuel (Nes Wim Wim *et. al*, 2005). The use of biogas for cooking is cleaner, odour free and improves public health especially for the rural women and children.

A study by Ghimire (2005) explained that interest in biogas technology in Bangladesh is growing due to the increasing awareness of the importance of renewable energy sources and their potential role in decentralized energy generation in rural areas. The rate of growth of biogas technology is expected to accelerate in the future in line with the realization of the importance of biogas in enhancing rural livelihoods.

There are also some negative impacts from biogas in rural areas of Bangladesh among the biogas user. For example, Bangladesh has the potential for generating 12.26 x 10^8 m^3 of biogas per year from human excreta (BCSIR, 2001). Despite its big potential there are significant barriers to its implementations. Firstly, people have a negative attitude to using gas generated from night soil; and secondly, there is hesitation among people to handle the bio slurry coming out of the toilet attached to the biogas plant (Van Nes Wim *et. al*, 2005). These barriers are based upon peoples negative perception and health concerns in regards handling human waste – whereas dung and poultry has wider acceptance.

People's awareness and co-operation tendency can be important criteria for implementation of a biogas program. A good example is the independent non-profit organisation "The Nepal Biogas Support Program", BSP which is funded by the Netherlands. They have been very successful in the deployment of biogas technology in Nepal (Gautam *et al* 2009) in the rural community. Because the main objectives of BSP are to provide training to biogas companies and plant users, ensure the quality and long-term reliability of plants, and manage the subsidization programme that makes biogas plants affordable. BSP accredits the work of private installation companies, an approach that has helped the private biogas sector to thrive (Ashden Awards, 2005).

Since BSP started, training in plant construction has been provided to over 6,000 people and 120,000 users have been trained in operating biogas plants and making minor repairs. Roughly 61 private installation companies exist and BSP monitors quality control by scrutinizing constructions and only subsidizing accredited companies. The mix of affordable finance, support, quality control and quality installations has led to a high success rate for biogas plants in Nepal: around 97% of plants installed under BSP are still in operation (Ashden Awards, 2005). The success story of BSP-Nepal could be applicable for Bangladesh as a neighbour country having similar energy deficiency.

Biogas production has no negative effects on the environment or on human health if properly managed. Proper management of biogas plant could be ensure through introduce training in operating and repairing of biogas plants. There is also a reduction of workload, mainly for women since they are the ones who are responsible for collecting firewood and cooking. All of the evidence indicates that AD has a significant social impact on the community.

3.3.2 Economic impact

Domestic biogas programs are often justified on the basis of the private benefits and costs accruing to the individual households, in terms of providing a superior cooking fuel, improved indoor air quality and saving time spent on collecting firewood. For instance, Bala and Hossain (1992) evaluated the economics of biogas digesters in Bangladesh in terms of firewood and fertilizer values. The net present benefit was computed from the digester cost, kinetics of biogas production and nutrient contents in the treated slurry. The model was analysed to test the sensitivity to changes in retention time, annual operation period, subsidy, price of fuel wood, construction cost, interest and inflation rate. It indicated that the total AD potential could be influenced by some important economic factors. The consumptive use of the biogas for cooking and the non-consumptive and indirect value derived from the biogas plant providing feedstock for other processes and other such benefits as greenhouse gas mitigation (positive externalities) needs to be accounted for.

According to Gofran (2009) one biogas plant of 2.4 m^3 gas enables a saving of about 2.4 tonnes of biomass per year. Biogas is an efficient fuel among the other fuels used in Bangladesh for traditional cooking stoves. The combustion efficiency of biogas is 99% and the overall efficiency of biogas is 57% and is followed by 54%, 50%, 23%, 14% and 11% in LPG, kerosene, fuel wood, crop residues and dung respectively (RWEDP and UNEP, 2000). A survey analysis by SNV on 66 biogas plants showed that the average wood fuel saving is 156 kg/household/month (SNV, 2005).

Eusuf (1989) has found that only a small section of large farmers, owner-cultivators and landless labourers buy fuel, and that the last two categories buy dung sticks and tree branches mostly during the rainy season. In the last 20 years, the rural people of Bangladesh have seen their real incomes being eroded away. The cooking costs for many lower income households during the rainy months, when nearly all their cooking fuel has to be purchased, may reach 30 to 50% of their monthly income.

Talukder (2010) surveyed 30 biogas plants in order to investigate the types of biogas plants in Bangladesh. Out of the total 30 surveyed biogas plants, 78% of them had a plant size ranging from 2 to 10 m^3. Income generation should be the main objective of commercial biogas plants. An interesting practice seen in Bangladesh is bigger poultry farms selling biogas to their neighbours by distributing it through pipe systems. They usually charge about 300 - 500 taka (£3 - £5) per month per family. This could also be a good source of income which eventually pays back the total cost of biogas in a shorter period of time (IDCOL, 2006). This study found one poultry and one dairy farm who were selling biogas to their neighbours by a flexible pipeline. Similarly another plant owner, Sudorshon Mondol used to sell biogas to 6 households from a 10 m^3 biogas plant. Each household used to pay 500 taka (£5) per month. His monthly income from biogas was 3000 taka (£30).

Furthermore, loans are an important tool in promoting biogas. Even if generous subsidies are available loans are often needed for poor rural households to be able to invest in something that has several years payback time. Loans can be granted from the government, banks and other financial institutions or NGOs (Biswas *et al* 2001; Nancy and Elaine, 2007).

Figure 3.4 Biogas supply by flexible pipeline to the neighbours at Pubail, Gazipur.

From the preceding discussion, an important linkage can be established between rural electrification and adaptation to climate change. The National Rural Electric Cooperative Authority, NRECA's (2000) study indicates that electrification decreases fuel costs and increases household income by increasing income generation activities.

The efficiency of traditional technologies and that of improved ones which are practically applicable or already in use somewhere else are compared and the potential of biomass savings were calculated by Bhattacharyae *at al* (1999). They found that the total biomass saving potential in seven Asian countries (China, India, Pakistan, Nepal, Philippines, Sri Lanka and Vietnam) together has been estimated at 322 million tonnes per year. While investment into renewable energy and energy efficiency projects in 2006 was approximately triple the official development assistance support for energy policy and renewable energy projects in many developing nations (Clemencon, 2008).

3.3.3 Environmental impact

Now, Environmental Impact Assessment (EIA) is firmly established in planning processes in many countries. Many scientists (Briffett, 1999) suggested that despite the existence of good EIA guidelines and legislation, environmental degradation continued to be a major concern in these countries. EIAs have not been able to provide 'environmental sustainability assurance' (ESA) for these countries (Sadler, 1999). For Bangladesh, it was not until 1992 that the country had its first EIA guidelines. Various policies are now under preparation by relevant ministries that aim for a sustainable approach towards environmental management and development (Bangladesh: State of the Environment, 2001).

Studies by Ahammed and Harvey (2004) and Momtaz (2002) have shown that the EIA system in Bangladesh has not been appropriately implemented. The requirements for an effective EIA system have not been adequately fulfilled and this has affected the implementation of EIA at the strategic level. There are no specific guidelines for conducting and reviewing the environmental assessment of non-industrial projects, for which, currently, EIAs done by the project sponsor are sent to the Department of Environment (DOE) for environmental clearance by the sectoral line agencies of the government (Ahammed *et al*., 2004). On the basis of a research finding Chowdhury *et al*. (1999) mentioned the main components of the Environment Conservation Act (1995) are few important points including the "declaration of ecologically critical areas, and restriction on the operation and process", which can be carried or cannot be initiated in the ecologically critical area. Another policy framework that refers to renewable energy is the Bangladesh National Environment Policy which was approved in 1992. The National Environment Management Action Plan 1995 also stresses the importance of renewable energy in rural areas, and further emphasizes the exploitation of renewable for a cleaner environment.

According to ISO 14040 (International Organisation for Standardisation, 2006), LCA assesses the environmental aspects and potential environmental impacts of an AD plant for the whole process; from raw material acquisition through production, use, end-of-life treatment, recycling and final disposal. A standardisation process for LCA has been initiated by the Carbon Trust and Defra aimed at developing a Publicly Available Specification (PAS) for LCA methodology used by the Carbon Trust to measure the embodied greenhouse gases in products (DEFRA, 2007).

Livestock such as cows, sheep, goats, camels, buffalos and termites release methane. Bacteria in the gut of the animal break down food and convert some of it to methane. When these animals belch, methane is released. In one day, a cow can emit 1/2 pound of methane into the air (Envirolink. 1998). AD biogas production can restrict this methane emission through proper utilization of it methane.

Biogas plants produce gas for cooking hence reducing emissions of carbon-dioxide as they produce less of it than fuel wood and burned methane (natural gas), which is a more dangerous greenhouse gas than carbon dioxide (Houghton, 2004). Removing wet/moist dung from the ground surface and putting it into a plant below ground also reduces greenhouse gas emissions; methane is naturally given off when it decomposes, going into the atmosphere; with AD, the methane produced is burned (Smith *et al*, 2007).

There are a number of processes and procedures being developed to standardise LCA by the British Standards Institute. An analysis of energy balances from a life cycle perspective of large scale biogas plants operating in Swedish conditions indicates that the net energy output turns negative when transport distances of feedstock manure are large (Berglund, 2006).

Ram Chandra (2002) carried out a life cycle costing technique taking into account the time value of the money to meet as much electric energy demand as possible by an optimal decentralized mix of photovoltaic, biogas generator and biomass gasifier generator. Another approach was presented by Reddy *et al.* (1979) to reduce the size and cost of the biogas system. Sodha et al. (1987) developed a new concept of green house in which the biogas plant is covered by a transparent plastic or glass sheet. A mathematical model based on periodic heat transfer equations was also developed to analyse the GHG effect. An analytical expression for instantaneous thermal efficiency, instantaneous loss efficiency and instantaneous loss efficiency factors was developed by Usmani *et al.* (1996) for a given capacity of a biogas system. Venkatarama Reddy (1979) described a brief history of building materials, energy consumption in manufacture and transportation of some common and alternative building materials and the implication on the environment.

Figure 3.5 shows the overview of a biogas system from different feedstock sources with its energy flow. A system boundary is also shown through the boundary line. This example uses energy crop as input to the digester, as is practiced widely in Germany, for example.

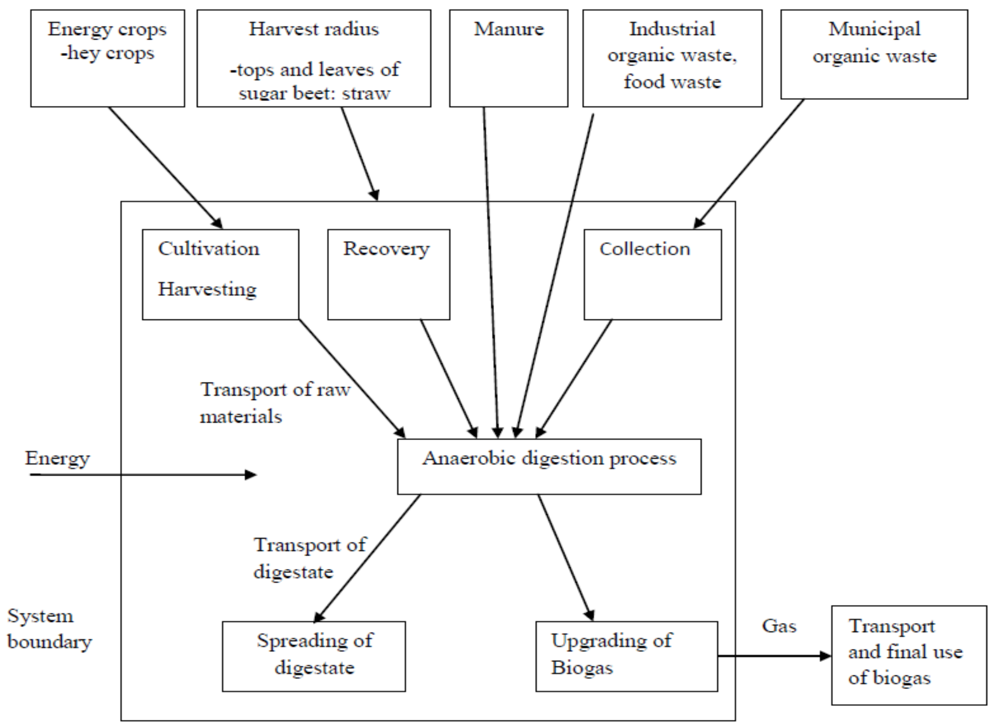

Figure 3.5 An example of system boundary of a biogas system. The arrows represent the energy flow in the system (Berglund, 2006).

Research conducted by Barton (2007) focuses on six options of waste management: the base case of open dumping; three options for landfill (passive venting, gas capture with flaring, and gas capture with energy production), composting and anaerobic digestion with electricity production and composting of the digestate. The highest impact in terms of carbon emissions was from a sanitary landfill without gas flaring or electricity production; this was worse than the baseline case using open dumpsites. Composting or anaerobic digestion with energy production and composting of the digestate were the two best options with composting being neutral in terms of carbon emissions and anaerobic digestion being carbon negative. AD has dual benefits as it can provide energy and soil conditioner at the same time. In this context AD became more popular in the developing world.

Biogas technology benefits the environment through the protection of soil, water, air and forests. In many regions of Asia, including Bangladesh, firewood is consumed in great amounts. Every year, about 30.9 million tonnes of firewood are used for cooking and other household purposes in Bangladesh (Grameen Shakti, 2005). This leads to deforestation and degradation of forests and woodlands. Biogas is an excellent solution to this problem because it is a substitute for firewood and helps maintain good soil conditions with the slurry that is produced.

Bio slurry can play a vital role in restoring fertility as well as organic matter status of the soils. Bio slurry organic fertilizer is environmentally friendly, 100% organic, has no toxic or harmful effects and can easily reduce the use of chemical fertilizers up to 50%. Nutrients from organic sources are more efficient than those from chemical sources. Field trials conducted in Bangladesh have shown the beneficial effects of bio slurry organic fertilizers in increasing the yields of cabbage, aubergine, tomato, onion, potato and papaya (Islam, 2006).

3.3.4 GHG mitigation and CDM

The Asia Least-cost Greenhouse Gas Abatement Strategy (ADB, 1998) studies revealed that per capita emission of GHG for Bangladesh in terms of CO_2 equivalent is less than a tonne, about 670 kg per year. The detailed estimate revealed that total GHG emissions of the country is 72 million tonnes in CO_2 equivalent of which the agricultural and livestock sub-sector has the highest contribution i.e. 40 percent. The energy sector and the forestry sector including land-use change contribute about 30 and 27%, respectively. The remaining comes from industrial processing sub-sector.

The Intergovernmental Panel on Climate Change (IPCC, 2006) projects a high frequency of extreme climatic events (sea level rise, droughts, floods and cyclones) for Bangladesh exacerbated by rapid population growth. According to the investigation of MOEF, other climate change induced challenges are: scarcity of fresh water, river bank erosion, discharge of wastewater, frequent floods, prolonged and widespread drought, and more widespread salinity in surface water, ground water and soil in the coastal zones (MOEF, 2005). These climate induced impacts, are in fact indirectly affecting the security of energy services. Haq (2001) conducted an investigation on climate change in Bangladesh and from his research it was revealed that Bangladesh's contribution to global climate change via emissions of CO_2 from energy systems was insignificant compared to many industrialised nations. Bangladesh contributes less than 0.1% of global emissions of CO_2 compared to 24% of the USA and emits about 0.19 tonne of CO_2 per capita (Haq, 2005)

Uddin, *et. al*. (2006) conducted an experiment on the advancement of renewable energy in Bangladesh. In the experiment a few important prospective of energy development in Bangladesh were concluded. In the context of Bangladesh, sustainable development and climate change are interlinked as climate change influences human life, and society's priorities towards sustainable development can cause rising emissions of GHG's and thus enhance climate impacts and vulnerability.

Biogas, a clean renewable energy source can reduce carbon dioxide emission by a significant amount. It is the right time to emphasize on biogas technology because developing countries are going to be responsible for a significant amount of GHG emissions worldwide in the future. For example, in the year 2000 developing countries were responsible for about 29% of these emissions and this share is predicted to increase to 64% in 2030 and 76% in 2050 (Monni *et al*., 2006). The major GHG emissions from the waste sector are landfill CH_4 and, secondarily, wastewater CH_4 and N_2O (IPCC, 2006). Another reason for increased GHG emissions is rising living standards in the developing countries. A series of initiatives were highly successful and showed that large reductions in emissions are possible from AD implementation. Reduction of GHG emission through AD can be the sources of funding for a developing country like Bangladesh through Clean Development Mechanism (CDM).

Bhattacharya and Salam (2002) had done research and analysis of a number of selected options available for developing countries in the context of reducing total GHG emission per unit of useful energy for cooking. They found the total GHG emission from traditional wood-fired stoves is estimated to be about 110 g of CO_2 equivalent per mega joule of useful energy (g CO_2 equivalent/MJ of useful) delivered to the cooking pot; this can be compared with 42, 5, 2, 350, 166 and 196 g CO_2 equivalent/MJ of useful in the case of improved wood, biogas, producer gas, kerosene, natural gas and LPG fired stoves, respectively. Modern biomass based cooking options such as improved biomass; biogas and producer gas fired stoves can potentially play an important role in mitigating GHG emission from domestic cooking by providing an alternative to kerosene, natural gas and LPG fired stoves.

E+Co is a Carbon Finance Industry which makes clean energy investment in developing countries like Bangladesh. E+Co (2009) calculated and showed that a biogas plant of 2 m^3 capacity of biogas plant could save 2.2 tonnes of CO_2/year in the Gold Standard method (Grameen Shakti, 2009).

If dung is used for cooking directly, CO_2 emission from 1 tonne of dung is equal to 0.648 tonne. If dung is used for cooking through biogas technology then CO_2 emission per tonne of dung is equal to 0.0677 tonnes (PREGA, 2006). By using these values CO_2 emission mitigation through biogas plants from 1 tonne of dung is 0.5803 tonnes CO_2 equivalent. Total possible CO_2 emission mitigation is 46.58 million tonnes per year by introducing biogas technology in Bangladesh.

The most important thing with respect to developing CDM projects is the baseline. If the baseline is such that not enough emission reduction is possible, then the CERs generated will add very little value to the project. Therefore, CDM projects are only possible when the baseline (existing situation and its trend) is such that a fair bit of improvement with respect to GHG emission is possible. At this point it is instructive to study the existing disposal methods employed in Bangladesh (Sinha, 2005).

Bangladesh did not mobilize significant investment in renewable energy and particularly in relation to advancement of renewable energy under CDM. In Bangladesh, to date, only two projects (composting organic waste and landfill gas extraction and utilization) have been registered as CDM project activities (UNFCCC, 2008), and two projects (renewable electricity) are at the validation stage. The emissions reduction potential of CO_2 from least-cost greenhouse gas mitigation projects in the energy sector in Bangladesh has been estimated to be around 50 million tonnes of CO_2 per year according to the Asia Least-Cost Greenhouse Gas Abatement Project (ALGAS) (ADB, 1998). Thus mitigation of CO_2 emissions (about 2.5 million tonnes of CO_2 per year) from the currently designed CDM project activities remains insignificant compared with the estimated potential reduction of CO_2 emissions.

With a view to participate in the growing trade of the Kyoto Protocol CDM project, the government of Bangladesh has set down a two-tier DNA through a government notification, (Waste Concern, 2008) although the initiative has been taken much later in comparison to other developing countries. In the meantime, a number of developing countries including Costa Rica, Brazil and other South American countries have developed CDM projects. Apart from setting up DNA, the government has also enrooted national procedures for evaluation and approval of CDM projects, developed sustainable development criteria for the evaluation of CDM projects and finalized the CDM strategy (Waste Concern, 2008).

China's experience clearly indicates that the capacity building and the strengthening of local institutions are the key to jump-starting CDM projects. Bangladesh needs to be ambitious to get CDM in the biogas sector. Most recently, an application for registration was successfully submitted to the Clean Development Mechanism (CDM) Executive Board for the Certified Emission Reductions (CERs) credits associated with the biogas programme in Nepal.

3.4 Conclusion from Literature Review

Anaerobic digestion has a significant socio-economic and environmental impact in Bangladesh. Anaerobic digestion has not yet reached its potential level in Bangladesh, this process having started in Bangladesh in 1972. Governmental, non-governmental and international organizations are operating mainly small and medium AD in Bangladesh. The review shows that Bangladesh has huge potential for biogas energy production from anaerobic digestion of animal manure and agricultural waste. The review also shows that in a few cases village communities shared biogas from medium sized AD plants.

Most of the AD plants in Bangladesh are fixed dome brick digesters with very few cases of floating dome digester. AD produces methane and carbon dioxide rich biogas and soil conditioner digestate. Biogas production through anaerobic digestion reduces greenhouse gas emission. Life cycle impact assessment is an important tool of carbon counting for anaerobic digestion although Bangladesh is its infancy with regards to LCA.

From an individual perspective, biogas can be an alternative source of energy and the use of biogas significantly improves the indoor air quality whilst meeting energy requirements. In addition, the construction of biogas plants results in better sanitation and a smoke-free environment inside the house. It reduces a considerable amount of green house gases from two perspectives: the carbon released from the burning of biomass is minimized; and the equivalent space of forest saved can act as sink basin to absorb carbon dioxide.

The initiative of AD technology with implementation of CDM under the Kyoto Protocol could facilitate sustainable energy development in Bangladesh through sustainable energy generation and combat adverse effects of climate change on a global scale. An immediate priority acknowledged by Bangladesh is the need for development of national adaptation strategies to comprehensively address climate variability risks. Thus a climate-driven energy strategy could lead the nation towards a sustainable energy future. A short, medium, and long term target oriented approach towards clean energy development could be the initial steps towards such strategy (Uddin, *et. al*., 2006). The CDM generates funds, and funding is one of the most important factors hindering the biogas program in Bangladesh. Emission reduction through a biogas program can assist CDM and ultimately can be a sustainable waste management process in a developing country like Bangladesh. In next chapter it will be detailed the whole methodologies that was applied in this research.

Chapter 4

Methodology of research

4.0 Introduction

The aim of the research of this thesis is to determine the potential of Anaerobic Digestion (AD) to provide energy for Bangladesh. There are many different possible combinations and types of AD facilities that could potentially be used, but within this thesis it is not possible to deal with all of them. So a key method will be to determine a small number of more likely AD systems, suited for Bangladesh from early explorations in the field, and then to fully develop the information for these to determine energy estimates. An important challenge was to identify AD facility types which truly represent what is achievable on the ground and which are "spanning representatives" in that, between them, they cover a large fraction of scenarios in the country where AD could be used. For this reason, the use of fieldwork was vital, and thus an important part of the methodology. Furthermore, current literature indicates that published details of AD systems do not contain sufficient data or realistic data for performance on the ground, so collection of this data, as needed, will be an important part of this work. A life cycle assessment methodology was followed to determine the GWP of a domestic AD plant which will be included in this chapter. The detailed methodologies are described as follows.

4.1 Meetings with experts and field trips

The plan of these meetings was to identify a small number of AD facility types that would be useful to model the whole country. Bearing this target in mind, an overview of waste and the use of AD practices of Bangladesh was undertaken through initial exploratory AD field visits and meeting with key government and non-governmental organizations of Bangladesh;

Grameen Shakti (GS), Advance Engineering (AE), Bangladesh Council for Scientific and Industrial Research (BCSIR), Netherland Development Organization (SNV) and Infrastructural Development Company Limited (IDCOL). A review of the above organizations is described in this section. Those organizations are the key sources of data and are deeply involved with AD research through contributing field and lab facilities in Bangladesh. GS provided a number of AD sites for visits for this research. Advance Engineering provided the experimental AD plant site facilities for this research. The experiment on rice straw based biogas plant of this research was done with the field and site facilities of this organization. The laboratory facilities of this research were taken from Bangladesh Council of Scientific & Industrial Research (BCSIR), Dhaka.

Having a few limitations for finding out detailed data, analysed data and information were compared with some government and non-governmental organizations for verification. After comparing, the most reasonable data was selected for use. The format of the information collection was both manually and personal contact with some organizations described below. A brief history of their activities is also included in the description.

4.1.1 Grameen Shakti

Grameen Shakti (GS) is one of the largest and fastest growing rural-based renewable energy companies in the world. This organization provided a number of visits to AD sites for this research. It is a non-governmental organization working with the renewable energy program through microfinance. They started the biogas program in 2005 and GS's biogas program is the first market-based program in Bangladesh. GS used its Grameen Bank's experience to evolve a financial package based on instalment payments which reduced costs and helped it reach economy of scale.

Grameen Shakti has a vast programme for spreading renewable energy to the remote areas of Bangladesh. GS's main areas of focus are solar energy, bio-gas, organic fertiliser and improved cooking stove (ICS). Grameen Shakti has been operating bio-gas plants in different areas of Bangladesh as an alternative energy to replace the usage of traditional fuels like wood. Grameen Shakti installed 8,000 biogas plants since December 2009. To further expand this programme, Grameen Shakti is planning to establish exclusive branches for biogas.

4.1.2 Advance Engineering, Dhaka

Advance Engineering (AE) is a renewable energy research, development and manufacturing company established in 1997 and also provided the experimental AD plant site facilities for this research. The rice straw based biogas plant experiment of this research was done with the field and site facilities of this organization. It is a non-governmental organization in Bangladesh involved in biogas appliances. Advance operates continuous research on the development of biogas plants, economic use of biogas, different design of biogas burners, hajack light (locally used device for lighting), generators, portable reserves, community based biogas plants and low cost biogas plant.

Advance Engineering has a wider range of experience and expertise in biogas technology. In 1997 Advance started its successful journey with small biogas plants. Their first project was a 1.2 m^3 fixed-dome biogas plant. In 1998, they successfully took up a recognizably larger project. It was a dual-fuel biogas generator. It had the capability of producing 10 kW and they successfully supplied 8 kW of energy for practical use. In the year 2001 Advance Engineering added portability to a biogas system. In 2002, the company was able to start marketing biogas appliances and is one of the significant landmarks. Advance has brought out biogas appliances such as burners and mixture device.

4.1.3 Bangladesh Council of Scientific & Industrial Research (BCSIR)

The laboratory facilities in this research were taken from the Bangladesh Council of Scientific & Industrial Research (BCSIR) in Dhaka. It is a government organization under the Ministry of Science and Information Communication Technology. BCSIR was established in 1955 bearing the name of East Regional Laboratories under the erstwhile PCSIR (Pakistan Council of Scientific & Industrial Research) as a multidisciplinary research establishment. Current areas and major fields of research and development activities of the laboratories are analytical chemistry, tissue culture, biotechnology, pulp and paper, fibre and polymer chemistry, arsenic mitigation, aromatic and medicinal plants, industrial physics, physical instrumentation and production of chemical and allied products.

BCSIR plays a very important role in the scientific and industrial field in the country. Most of our country's inventions have originated from this institution. A development example would be biogas technology, which is an outstanding invention of this institution, and is now being used all over the country. BCSIR have also developed other environment-friendly products, such as efficient stoves which require only half of the energy needed for the commonly used stoves. Therefore, it can be said that BCSIR has advanced remarkably, both scientifically and industrially.

4. 1.4 District Livestock Office and Division of Livestock Services

The Division of Livestock Service, Dhaka and the District Livestock Office in Gazipur are the two government sources offices which hold data and information on poultry and livestock numbers in the country and the district respectively. Various information was collected via personal interviews and telecommunication with the relevant person of those organizations.

4.1.5 Initial AD facility field visit

After getting background information on the use of AD in 11 domestic (biogas yield capacity 2 - 5 m^3) and medium (biogas yield capacity 5 - 25 m^3) sized biogas plants visits were carried out in four different districts of Bangladesh in different parts of the country in 2009. The main objective of the visits was to look at how the AD facilities are constructed, operated, funded the use of feedstock, and the collection of views of the local people about the AD system. It was done through a face to face interview with the AD entrepreneur.

The domestic and medium AD farms visited were randomly selected but covering different sizes and feedstock of both dung and poultry litter. Only one of them was poultry based and the rest of them were dung based AD plant. Out of 11 AD plants, 2 of them were medium sized AD plants and rest of the plants were domestic in size. A preliminary view about the plant size and feedstock of AD facilities was developed from those visits. A categorization of AD plant sizes is given in Table 5.2 of chapter 5.

4.1.6 On-site AD with biogas production

A number of households were visited during the above AD facility field visits as some sites consisted of 4 - 5 families. During visiting 11 AD plant sites, 50 households were visited. During these visits the aim was to determine how many cattle each household had and was thus suited for a domestic or medium sized AD plant. A further aim was to determine the same factors for poultry farms. An assessment was made of how many poultry farms had the capacity for medium sized AD systems but had implemented domestic sized plants only. All of this information is important to generate an idea about feasible AD scenarios i.e. the representative AD facility types which are needed for later modelling. This was done to make a hypothesis about the present AD facility types for Bangladesh where feedstock supply was available.

4.2 Identify the representative AD facility types

The aim of the work in this section was to decide the best representative AD facility types. There is a significant variation in the density of households in rural, urban and semi-urban areas in Bangladesh. Feedstock potential and types of feedstock also varies in different areas of the country. On the basis of feedstock capacity and distribution, and the energy demand, it is possible to get an idea of feasible and realistic AD scenarios. These might cover the present and future prospect of AD feedstock, the availability and distribution of potential AD sites. The most appropriate AD facilities were considered as representative AD facility types for Bangladesh: a) domestic cattle smallholding AD facility, b) domestic and medium poultry farm AD facility. This consideration was done on the basis of visiting AD plant in practical and interview among the stockholders. However, in the meantime, developed the idea that c) cattle market rice straw, water hyacinth and food waste could also be emerging AD feedstock to generate potentially huge biogas yields for Bangladesh. A review was also done to evaluate those three important AD feedstock. In aspect to evaluate author consulted with experts and had visited a few practical site deal with those feedstock. Water hyacinth was not considered potential feedstock due to its unavailability in all around the year and food waste for its improper processing. On the basis of overall evaluations, cattle market rice straw waste is considered potential AD feedstocks. The general information for these options then needed to be obtained i.e. for feedstock and other parameters.

4.2.1 Feedstock production

The number of animals per farm, the feedstock production capacity and the availability of feedstock are the most important parameters to be considered to determine the potential size of a new AD system. During a cattle smallholding visit it was noted that feedstock availability from the same number of cattle could be different. This was due to the food habits and the movement of the cattle in the field: cattle manure availability was less for cattle grazing in open fields compared to farm cattle staying in a fixed place. To avoid this and for consistent data use secondary data was considered shown in Table 4.1. A few factors were considered when using secondary data on the feedstock production rate of cattle, poultry and the market.

Table 4.1 Feedstock production rate of cattle, poultry and cattle market rice straw

AD feedstock sources	Feedstock production (kg/animal)	References
Cattle	10	GS
Poultry	0.1	GS
Cattle market rice straw	35	Advance engineering

According to Grameen Shakti (2009) daily feedstock production capacity of a cow and poultry birds are 10 and 0.10 kg respectively. Rice straw waste generating capacity of cattle from cattle market is 35 kg waste per cattle.

Factor to feedstock production

In this research feedstock per cow was considered constant and the cow was assumed to be staying in a fixed place, not grazing in open fields. An adult local cow was considered for that estimation.

Feedstock removal processes for broiler versus layer poultry farms are different. The quality and amount of feedstock per bird is also different. It is difficult to measure the feedstock production rate of a chicken within a short period of time (Gofran, 2010). Moreover Grameen Shakti had their own data and they are involved in dung and poultry based AD facilities in Bangladesh (Table 4.1).

Practically, the cattle market has a boundary of its own, and thus it is possible to determine the total waste generated from the market. There is no secondary data on rice straw waste production per cattle in cattle markets. The assumption used in this thesis is based upon meetings with Advance Engineering (Jalil, 2010) who are involved in conducting research at Gabtoli cattle market in Dhaka. This market operates everyday and an estimated 35 kg rice straw waste is generated per day per cattle.

Overall the feedstock production rate of cattle, poultry and cattle market rice straw per animal were considered to be 10 kg, 0.01 kg and 35 kg respectively. These figures will be used for calculations later in this thesis.

4.2.2 Review of the community around the site

Interviews were carried out with the rural community of the studied areas. Interview was taken from 50 household either biogas stakeholders or neighbour. The main subject of the interview was about the AD construction materials, AD process, use of biogas and digestate as well as economic, social and environmental issues affecting AD programs. This was done due to see how the AD system functions in rural areas at present and to see its future prospects at the same time. This section also looks at the financial option being used, i.e. with microfinance possibilities for farmers to build AD systems.

4.3 Determining the energy parameters

It is very essential to know the AD biogas yield and biogas composition of these types of AD facilities in the Bangladesh context in order to understand the energy capacity, as the methane content can vary. In order to determine the environmental impact of AD facilities with special focus on GWP it is necessary to collect data on the construction materials used. Those parameters were determined from both primary and secondary data sources.

This section will describe the methods of data collection for these parameters. It will demonstrate how the daily and initial charge, biogas yield, composition of biogas and the required amount of building materials of particular AD plant were obtained.

4.3.1 Biogas yield

Biogas yield is one of the most important parameter influence potential AD energy capacity. Secondary data on biogas yield of cow dung and poultry manure as a Grameen Shakti handbook data which is mostly theoretical. Primary data was observed due to the biogas yield of those feedstocks in practical with the present condition. This is why biogas yield was determined both from primary and secondary data. Firstly, secondary data of biogas yield from dung and poultry litter biogas was collected from Grameen Shakti in Bangladesh. Primary data on biogas yield from dung, poultry and cattle market rice straw was also determined from gas physically collected from biogas plants operated by Grameen Shakti and analysed at the laboratory facility of BCSIR.

Biogas yields were determined by using a portable digital gas flow meter from BCSIR. The flow meter shown in Figure 4.1 (left) was made in Germany by Ritter.

Figure 4.1 The digital flow meter is used to measure the biogas yield at a test site.

The biogas yield was measured using two methods. One of them was unloading gas into the balloon until the gas flow was at a steady level from a loaded biogas plant. The other process was used to determine the gas flow rate by litre/minute in the steady state of gas flow. The first method of measurement was started from a biogas plant loaded for 24 hours and the second method was done in a steady state of biogas production of a biogas plant. The biogas yield from the two measurements was determined and finally the average yield was considered. The two methods were followed in order to ensure more accuracy of the result.

Gas production was loaded for 24 hours and then unloaded adjusting the flow meter so that it could detect the gas yield. A gas reservoir loaded for 24 hours opened with a flow meter reading of zero litres. The gas was unloaded until the gas flow became very steady, indicating no further loads. The amount of gas was recorded in litres and the daily gas yield was measured using this process.

Another process was to take readings of gas flow in normal flow condition (i.e. without loading and unloading). The gas flow reading was taken every 30 minutes for 3 hours and 6 times in every interval. The average value was considered and at a normal flow rate, there was not a big variation in gas flow. The reading comes in yield per unit time and biogas yield was measured by daily yield. A brief description of this process is shown in Table 4.2.

Table 4.2 Methods of data collection from a biogas plant, during biogas flow in steady state, to determine biogas yield.

	Action	**Remarks**
1	Total duration measured flow rate	3 hours
2	Flow rate reading interval	Every 30 minutes (7 times)
3	Number of readings taken every interval	6
4	Total readings during 3 hours	42
5	Measured biogas yield	Litre/day

4.3.2 Biogas composition

Like the biogas yield, the composition of biogas was also obtained from both primary and secondary data. Secondary data of biogas composition from dung and poultry litter biogas was collected from Grameen Shakti. Primary data on biogas composition of dung, poultry litter and cattle market rice straw was obtained by collecting biogas at a plant operated by Grameen Shakti with the laboratory facility of BCSIR.

To determine the biogas composition of varying feedstock 1 cattle, 1 poultry and 1 cattle market rice straw based AD plant was considered. All of these plants were well operated by Grameen Shakti and Advance Engineering. They were functioning well and had a normal yield capacity. These were the strengths of choosing those plants for the experiment. Gas samples were taken twice in each type of plant. The samples were collected for three days. This was done in order to obtain more authentic data. The biogas samples were collected with gas balloons and were analysed in BCSIR's laboratories in Dhaka which had the capacity to determine the methane content and biogas yield. A laboratory scientist from BCSIR assisted with the analysis. The amount of H_2S and CO was determined by using digital gas analyser.

Figure 4.2 The digital gas analyser is used for biogas analysis at BCSIR’s laboratory.

The volume percentage of methane and carbon dioxide was determined by using an Orsat gas analyser. The principle of gas analysis for determination of CO_2 using the Orsat method is given in Appendix 2. Methane is determined by subtraction of the known amounts of CO_2, H_2S and CO from the gas sample. In this research the Orsat gas analyser was used to determine methane and carbon dioxide. The equipments used to determine biogas compositions are shown in Figure 4.3.

Figure 4.3 Orsat gas analyser is ready to analyse CH_4 and $CO_{2.}$

4.3.3 AD requirements

Apart from the AD biogas and methane yield, two important parameters that can influence the AD system are the AD plant building materials and the daily and initial feedstock loading rate. This section outlines the methods used to determine those factors.

4.3.3.1 AD building materials (For later LCA analysis)

The major building materials of an AD plant are sand, cement, brick, iron rods, plastic and paint. In order to conduct an LCA, details on the components of an AD system are needed. Engineer and mason from Grameen Shakti also provided data and information whereas any data gap. IDCOL also gave additional information on AD construction materials. All building materials were calculated as a weight in kg as the data input is fed into the SimaPro software in this format. A brief description of LCA software SimaPro is given in section 4.5.3.

During primary data collection many types of plants were considered: different sizes, digester types and locations. Dung and poultry based plants were made of brick for a fixed-dome type of digester, and the plant that could be used for cattle market rice straw feedstock was a floating-dome anaerobic digester.

Figure 4.4 Fixed-dome and floating-dome anaerobic digester in Bangladesh.

4.3.3.2 Initial and daily charge of feedstock

The feedstock input materials of an AD plant is applied in two measurements; initial and daily charge. During the first research visit to Bangladesh (2009) primary data on the daily charge of 10 cattle and one poultry litter feedstock AD were taken. All of them were operated by Grameen Shakti. On another visit to Bangladesh, the daily and initial charge was collected from three selected biogas plants using dung, poultry and cattle market rice straw feedstocks. These plants were operated by Grameen Shakti and Advance Engineering. The plant sites for dung, poultry and cattle market rice straw AD were in Manikgonj, Mymensingh and Dhaka districts respectively. For further calculation on biogas yield determination, secondary data on feedstock production rate were considered and given in Table 4.1. Biogas yields and compositions of biogas were determined at the same time. The water needed to dilute the manure is sourced from nearby water ponds or tube wells and carried manually to the AD sites. There was thus no embodied fuel energy associated with the water resource. Total solid (TS) of each type of feedstock was determined in this research.

Methods % Total Solid (TS) determination

100 grams of feedstock sample for each feedstock were taken and was sun dried for one day. TS was measured by weight the solids remaining after heating the sample at 105ºC to constant weight. % TS was determine by the following equation.

$\% \text{ TS} = \{(W_1 - W_d)/W_0\} \times 100$

Where, W_1 = Weight $_{\text{Dry pan + dry sample,}}$ W_d = Weight $_{\text{dry pan}}$ and W_0 = Weight $_{\text{sample as received}}$

4.4 Smallholdings/farm/cattle market survey

A survey to identify the feedstock capacity of Gazipur district was carried out and the results are presented in Chapter 5. Figure 4.5a shows the location of Gazipur. The district is situated almost in the middle of the country. From these results, a profile of the energy capacity on the basis of feedstock can be drawn. The result for Gazipur will be evaluated in comparison with results obtained by other researchers for the whole of Bangladesh.

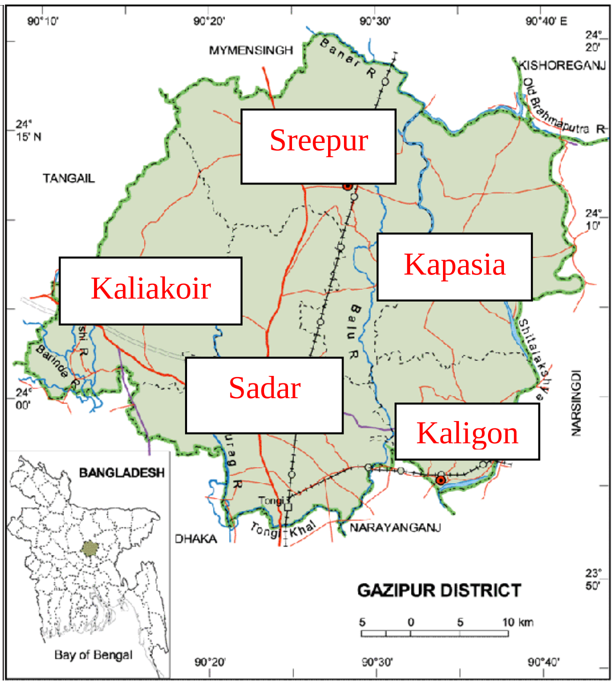

Figure 4.5a Geographical position of Gazipur district shown in the map of Bangladesh (UN, 2004)

4.5b Geography of Gazipur District showing 5 Sub-district

4.4.0 Background survey

The aim of this study is to determination of the potential energy contribution and Green House Gas mitigation of small and medium anaerobic digester systems in Bangladesh. Bangladesh consists of 64 districts with 507 sub-districts and each sub district has a large number of cattle smallholdings and poultry farms of varying capacity (BBS, 2009). Moreover, quantitative data for animal population was not available and reliable for each district. Research was conducted by Wilson *et. al*., (2009) on “Building recycling rates through the informal sector” and found that quantitative data on this topic was scarce and unreliable in developing countries. In these circumstances it was quite impossible to investigate the potential data of every individual district. It was thus decided to select a district to be surveyed within its own 5 sub-districts. The reason for choosing this district is given in the section 4.4.1. The aim was to gather data on the animal population on each farm (smallholdings) to help estimate the levels of animal waste feedstock for AD.

The survey was carried out in order to determine the total cattle population, poultry population and number of cattle markets in Gazipur. 125 sample survey of cattle smallholding, 125 from poultry farm and 30 cattle market; a total number of 280 sample surveys were carried out. It was done over the 5 sub-districts of Gazipur: for each sub district, 25 cattle smallholdings, 25 poultry farms and entire cattle markets were visited. The planning of the survey, preparation of survey pro-formas and content were done by the author who then supervised a local surveyor that carried out the survey. The objective of this survey was to determine the biogas energy capacity from estimated animal population and its feedstock production capacity. An example of the survey sheet is enclosed in appendix 3. This research survey was performed in April - May, 2010. Photographs of cattle smallholdings and poultry farms surveyed during data collection are given in Figure 4.6 and Figure 4.7.

Figure 4.6 A cattle smallholding with 6 cattle surveyed in Gazipur district.

Figure 4.7 Farmer feeding the birds of a poultry farm in Gazipur district.

4.4.1 Consideration plan of survey

Careful consideration was taken to ensure that samples were representative to ensure the data was valid later for scaling to a national level. To decide which farms should be visited, the following steps were taken:

1. Gazipur district is divided into five sub-districts, namely, Sadar, Sreepur, Kapasia, Kaligonj and Kaliakoir (see Figure 4.5b) and each had the same number of surveys undertaken.
2. Each sub-district is made up of several hundred Unions (which in turn are made up of small communities). These were selected "randomly" but with Unions representing more or less the geographic centre, north, south, east and west areas of the sub-district.
3. For each Union, 5 smallholdings/farms were selected for the survey.
4. Hence, 5 sub-districts, 5 Unions per sub-district, 5 farms per Union for a total of 125 smallholdings/farms surveyed in Gazipur. Small, medium and large sized smallholdings/farms were included in the survey.
5. The same procedure was used for cattle smallholdings and poultry farms for a total of 250 smallholdings/farms. The cattle and poultry farms were selected randomly for this survey.

6. For cattle markets, all cattle markets which is a total of 30 markets were visited in Gazipur.

7. Total data are 280 sites including two types of farms and 1 type of market.

During the farm survey some factors were actively considered. During the survey, smallholdings with a cattle population of less than 3 were not included; therefore it could be called a partially random sample survey. Daily requirements of biogas for an average sized (5 people/family) family for their cooking purposes are 2 m^3 and will require at least 5 cows. Smallholdings of 3 - 4 cattle were also included in this survey for two reasons. Firstly, they can produce <2 m^3 (1 - 1.5 m^3) of biogas daily meeting the requirements of a small family (3 - 4 people/family). Another reason, presently there are a number of AD plants in Bangladesh operating which have 3 - 4 cattle per smallholding. A domestic AD plant thus by definition will produce 2 - 5 m^3 of biogas. Some more information was collected in the survey such as if there is an existing on-site biogas plant, that the plant size, the food habits of the animals, the uses of gas and slurry and other products. This was done in order to make a comparison on future potential AD capacity with the current capacity. These parameters are also directly or indirectly related with the social and economic factors of rural entrepreneurs.

Generally an AD plant size can be defined according to the 3 major types; domestic (D), medium (M) and large (L) because they are generally built in those sizes. These categories of AD plants can be used for considerations of biogas yields: domestic (D) for 2 - 5 m^3, medium (M) for 5 - 25 m^3 and large (L) for 25 - 150m^3 of biogas daily (Shamsul Haq, 2010). A biogas yield of less than 2 m^3 and more than 150 m^3 might be considered as small domestic and extra large category of biogas plant. The survey results gave the number of animals per smallholdings/farms (cattle and poultry) or cattle markets (for rice straw).

Selection of Gazipur district

Gazipur district was selected to be surveyed having a representative sample of the animal feedstocks and cattle markets. A report from DLS (2009) showed that 10% of poultry farms in Bangladesh are in Gazipur district. The district had some additional advantages over other districts. Grameen Shakti operates a substantial number of dung and poultry based biogas plants in this district. The author visited several biogas plants operated by Grameen Shakti in this district and already had contact with smallholdings. Another reason for choosing Gazipur district was the author having local knowledge of that district through studying at the University of Gazipur.

Sources for scaled up sub-district

The results of this survey were used to obtain an energy profile of Gazipur and then all of Bangladesh on the basis of potential implementation of domestic, medium and large AD facilities. Whenever needed, data for the total farm feedstock sites and sources of all sub-districts and Gazipur district were obtained from the District Livestock Officer in Gazipur and Grameen Shakti, the information from these references is given in section 7.1 of chapter 7.

4.4.2 Use of secondary data as an independent check

A method for using secondary data to check the total energy potential determined from the farm surveys was devised.

It involved data of the total animal population at both district and country level collected from the Government Livestock Services. The total number of domestic cattle, poultry birds and cattle markets was collected from that source as secondary data. This data was used to check the overall results from the field data, as well as sub-information such as the distribution of differently sized potential AD facilities.

4.4.3 Calculation part of survey results

The energy pattern will be represented as methane yields and energy capacity in MJ. From the analysis of sampled cattle smallholdings and poultry farms (125 for each) and cattle market rice straw (30) anaerobic digestion plants will be categorised in three main types on the basis of biogas production capacity. The percentage of domestic, medium and large sized AD plants will be counted according to the plant size range showed below. The following equation will be applied to find out the different categories of AD farms in Gazipur and Bangladesh. An example is given for poultry farm calculation.

Calculate % of different AD sizes

The calculation determining percent of different AD sizes is shown in Table 4.3. As an example, this calculation is shown where 125 cattle smallholdings/poultry farms were considered.

Table 4.3 An example of a calculation to determine the % of farms for each AD size.

Biogas yield	**% of AD facility**
2 - 5 m^3 (D)	Domestic = (D/125) x 100
5 - 25 m^3 (M)	Medium = (M/125) x100
25 - 150 m^3 (L)	Large = (L/125) x100

Calculate total number of different sized farms

Total Domestic farms = (Total bird Gazipur/bird number of 125 farms) x 125 x % D

Total Medium farms = (Total bird Gazipur/bird number of 125 farms) x 125 x %M

Total Large farms = (Total bird Gazipur/bird number of 125 farms) x 125 x % L

Energy capacity per bird/cattle and per kg feedstock was also measured from the energy parameters and with following formula

Energy (MJ) = Biogas yield (m^3/kg FS) x % Methane (by volume) x D (kg/m^3) x CV

Where, D = Density of methane 0.6565 kg/m^3 and CV = Caloric value of methane = 55.6 MJ.

4.5 Life Cycle Assessment (LCA)

4.5.0 Introduction

LCA methodology was used to evaluate the environmental impacts of anaerobic digestion of animal manure from farm-based holdings in Bangladesh from a life cycle perspective. This is an application of the guidelines described in the proceeding section 2.3 of Chapter 2. The methodology used is consistent with the specifications of UK PAS 2050. This Publicity Available Specification (PAS) specifies requirements for the assessment of the Green House Gas (GHG) emissions associated with the life cycle of goods and services. The software for analysis used is SimaPro 7 and its Ecoinvent database. In developing countries in general, LCA capacity is low, and interest from industry and the government is typically also low. LCA activity is usually only at an academic or research institute level (MTEC, 2005). The emphasis of this thesis is on GHG and its measurement using the global warming potential (GWP) environmental indicator.

This section will describe the methods used to determine the greenhouse gas emissions associated with the installation, operation, and end-of-life disposal of a small farm-based AD plant. This methodology will include description and details of LCA analysis as follows: goal and scope, functional unit, data collection and inventory of material and energy flow. Results and discussion will be presented in chapter 8 including estimated avoided emissions from using AD.

4.5.1 LCA Digester construction

The installation and end-of-life disposal of the AD plant and the LCA boundary and process map of the plant are shown in Figure 4.8. The LCA boundary of this research is from the materials production (e.g. brick, cement production) needed to build the plant to the disposal of AD at the end of its life. The process map for evaluation of the GWP associated with the installation of the AD plant is shown in Figure 4.8. Methodology for the LCA of anaerobic digester will be described according to the requirements for the LCA analysis. This section will be represented in two factions: LCA of AD construction materials and data inventory.

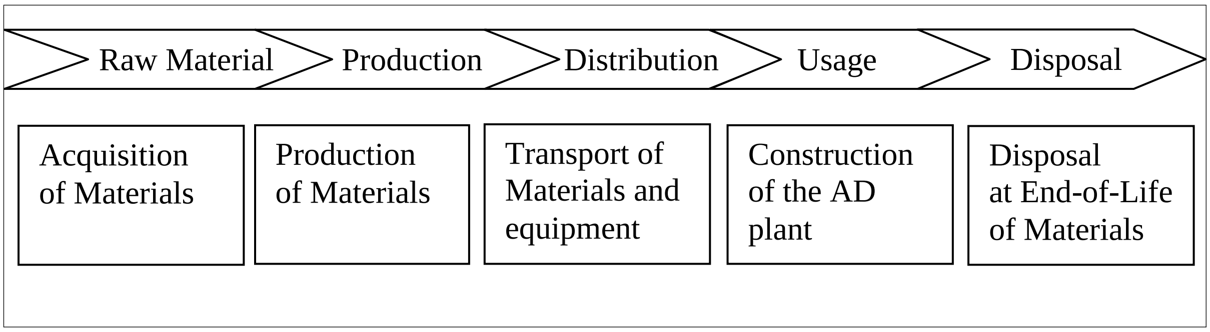

Figure 4.8 End of life disposal (LCA boundary) and a process map for materials use in anaerobic digestion plant.

Although the system boundary for the AD plant is considered the above step (showed in Figure 4.8), the GWP is only considered from the production step of AD construction materials (brick, cement). This is because the AD plant is very small and no embodied energy to be considered in the other step of the boundary.

4.5.1.1 LCA of AD plant materials

The lifetime of the construction materials are considered from brick's and cement's raw material acquisition and use in the AD plant to disposal of the elements after production, distribution and usage.

The major raw materials of the digester building materials are clay soil for bricks, iron for rods and plastic materials. The raw materials used in the manufacture of cement are limestone, clay and iron ore. Limestone makes up approximately 80% of the raw material requirements, composed mainly of calcium carbonate with small intrusions of magnesium carbonate. Quarrying operations are geared to minimizing the intrusions. The limestone is crushed to less than 75 mm. MgO in the cement, if present in sufficient quantities will cause expansion upon hydration thus resulting in unsoundness in the concrete. The inventory of the materials used to construct a 3.2 m^3 AD plant is given in Table 6.6 of chapter 6 (IDCOL, 2008).

The main production materials of the digester are brick, sand and cement. In Bangladesh brick is prepared from clay soil and desiccated in a brick kiln where biomass wood is used as the energy source. Sand is collected from the rivers and seas of the country. Cement is made in cement factories using limestone.

The farmer collects the construction materials to build an anaerobic digester from the local market through physical labour and most of the cases using a small van (called rickshaws locally). In a few cases when building a medium to large anaerobic digestion plant, motor vehicles are used for the transportation of construction materials.

The lifetime of AD plants are considered to be 10 - 15 years (Gofran, 2009). After the lifetime of the AD plant, the bricks of the reactor will be recycled for reuse in homes for home gardening. There will be no waste associated with demolishment of the AD. The AD materials are disposed of at the end of its life. In this research the life time of a domestic AD plant is considered as 10 years.

4.5.1.2 Data inventory

For LCA analysis there are four important steps to be considered. In this research it was followed accordingly.

Functional Unit

The functional unit for this analysis is a 3.2m^3 brick fixed dome AD plant. This is the most popular AD plant in the country and there are 40,000 domestic AD presently installed in the country where 50% of them are 3.0 - 3.2 m^3 AD plants (Gofran, 2009).

Data Collection

A trip to Bangladesh in January – February, 2009 was undertaken to acquire the data for this study. The author visited 11 Grameen Shakti (GS) AD plants. The inventory for the materials used to construct the 3.2 m^3 AD plant was provided by Grameen Shakti (Barua, 2007, and Gofran, 2009). Data on the transportation of materials to site was collected by the author directly from interviewing farmers. The author observed the construction of an AD plant and discussed approaches to end-of-life disposal of the materials used to construct the AD plant.

Materials needed to build the anaerobic digester, the energy used for the digester building materials and final uses of the anaerobic digester after its life time are the major inventories of this section. The entire data inventories are highlighted as materials inventory and energy inventory.

Materials inventory for AD building materials

The data inventory of the materials used to construct a 3.2 m^3 AD plant was provided from Grameen Shakti and IDCOL (IDCOL, 2008). The list of the AD building materials was collected from Infrastructural Development Company Limited Bangladesh from their biogas plant construction manual published in Bengali. All the materials were calculated in kg by the information provider of IDCOL, Grameen Shakti and Advance Engineering Bangladesh.

Energy inventory for AD building materials

There is no associated transportation inventory. Generally, the farmer or rural stakeholder collects bricks, cement and rods from their local market and use the local transport system like a non-fuel derived car (Rickshaw- physically operated) or they carry the materials physically. (Note: the transportation from the cement manufacturer to the market is allocated to the cement manufacturer, not to the user, as part of a business-to-business, B2B, process in PAS 2050, to avoid double counting).

The construction of the AD was done by manual labour. Cement was mixed manually and there is no energy input associated with the construction. A picture of the construction of an AD plant by farm hands is shown in Figure 4.9.

Figure 4.9 Construction of fixed dome AD plant operated by Grameen Shakti.

4.5.1.3 Impact assessment of major building materials

This is the evaluation of the different emissions derived from the process map. The materials acquisition and production are grouped together. The acquisition and production of the material is the embodied energy of the material. For the impact assessment, there is no data for the acquisition of materials to be build construction materials (such as brick or cement) for the plant. So the embodied energy is based on the production of materials only. The materials needed for a 3.2 m^3 biogas digester are predominantly clay bricks and Portland cement. A few other materials like sand, rods, polythene, PVC pipes are also used to make up the digester. According to PAS 2050, if any individual product or process causes less than 1% of the total impact then it can be avoided. So for material consideration, the life cycle inventory analysis and the energy association is for the production of clay bricks and cement. To build a 3.2 m^3 biogas plant a total number of 2,024 bricks (including brick particle) and 1,050 kg of cement are needed (Table 6.6 of chapter 6).

The software used for analysis was SimaPro 7 and its Eco-invent database. The database was adjusted to reflect the production processes in Bangladesh. The following changes were made.

Cement

Cement is made by heating limestone with clay minerals at around 1,500 degrees Celsius to produce an intermediate product called clinker, releasing high levels of CO_2. For cement production data, the information used was according to the cement production of Bangladesh. For example, according to Lafarge Cement Bangladesh (1997) to produce 1.2 million tonnes of cement per year in Bangladesh 1.5 million tonnes of limestone, 280,000 tonnes of clay and 140,000 tonnes of sandstone are needed. The Lafarge cement process inventory is available from Simapro's Eco-invent industry database. Using the input for the material requirements for Bangladesh and the energy required to process the cement using natural gas, the GWP impact is 0.032 kg CO_2 equivalent per kg of cement.

Bricks

Bricks are made of clay soil in Bangladesh. The clay is derived locally from fallow land, road side or river side. The bricks are manually made on site and fired in a brick kiln powered by biomass fuel or coal. The energy used to make the bricks was determined using the Bangladesh brick production process. For example according to the Renewable Energy and Environmental Information Network (REEIN), there are over 4,000 energy efficient kilns in Bangladesh. Each kiln consumes an average of 240 tonnes of coal to produce one million bricks (REEIN, 2008). The carbon emission factor for coal needed to make bricks is 25.4 tonnes of carbon/TJ. Total production in Bangladesh is estimated at 15 billion bricks annually, and given the extensive use of coal and wood in the industry, the GHG emissions are estimated to be 8.75 million tonnes of CO_2 equivalent annually (Ahmed, 2008). According to this CO_2 emission per brick is 0.58 kg.

4.5.2 Methodology for the AD Process

The operation of the AD plant, the usage of its products, the LCA boundary and map of the process are shown in Figure 4.10. It can also be called the process map for evaluation of the GWP associated with the AD process. Methodology of the AD process will be described according to the requirement for the LCA analysis. This section will be described according to the LCA of the anaerobic digestion process and data inventory in section 4.5.2.1 and 4.5.2.2 respectively. The lifetime associated with the calculation is 10 years.

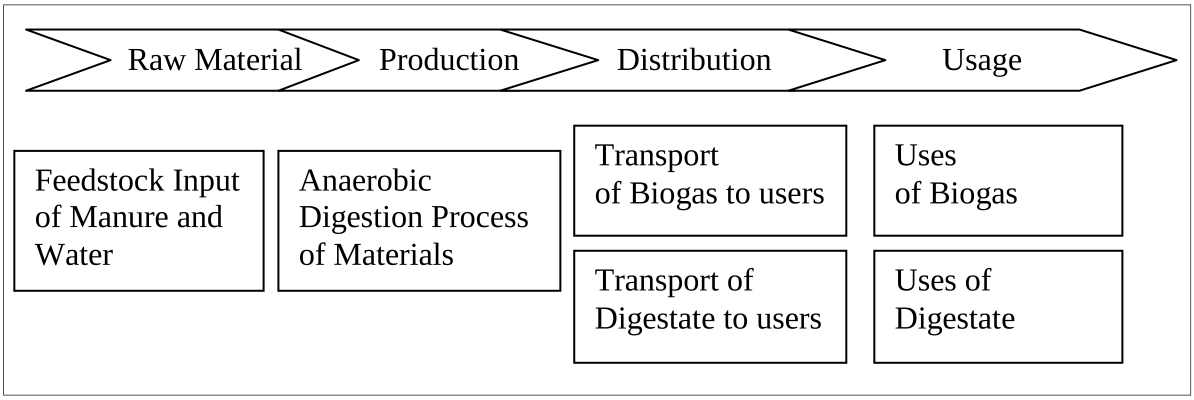

Figure 4.10 The operation of the AD plant, the usage of its products, the LCA boundary and process map.

4.5.2.1 LCA of the anaerobic digestion process

For LCA of the whole anaerobic digestion process raw materials are considered as primary input materials. Through a bacterial decomposition process it produces gas and slurry and this gets transported to the user.

Feedstock and water are considered as the raw materials for the anaerobic digestion process. Water is added to dilute the raw materials for a normal AD process. In this research the feedstock is animal manure: cow dung, poultry litter and cattle market rice straw. Water is added in different ratios according to the total solid percentage of the feedstock (the mixed slurry TS remain at 8%). No embodied energy needs to be considered as the raw materials come from animal’s stomach directly. The farmer collects water from the local pond or tube well.

Through anaerobic conditions by the activity of methanogenesis, bacteria produce biogas which is the primary product of the AD process. The slurry produces digestate, an excellent soil conditioner as a secondary product of AD.

Gas is supplied to the farmer's house gas burner through the gas pipe for cooking purposes. Farmers use digestate to add to their land as a soil conditioner. During secondary data collection it was reported that the use of biogas displaced biomass fuel for cooking and kerosene for lighting. There is no end-of-life of AD when it is a process and is a waste management treatment approach. The only end-of-life choice of AD is means of disposal.

4.5.2.2 Data inventory

The calculation of the GWP associated with the process map is shown in Figure 3.10. The lifetime associated with the calculation is 10 years. The functional unit for this analysis is the conversion of 1 kg of manure to biogas.

Data Collection

Several trips to Bangladesh were undertaken to acquire the data for this study. The researcher visited several Grameen Shakti (GS) AD plants. The secondary data was acquired before the primary data and will be presented in this chapter.

A field visit was done in January 2009 to Bangladesh to collect data and information regarding biogas systems in the country. All the data was collected from the biogas plant operated by Grameen Shakti (detailed in section 4.1.5), a leading renewable energy company of Bangladesh whose founder is Nobel Laureate Professor Mohammad Yunus. The author personally met with Prof Mohammad Yunus and discussed the future of biogas generation. He also met with the founder of Grameen Shakti, Mr. Dipal Chandra Barua, and biogas consultants of the organization.

Figure 4.11 Khondokar Mizanur Rahman with Nobel Laureate and founder of Grameen Bank Professor Mohammad Yunus (left) and Managing director and biogas specialist of Grameen Shakti (right).

This researcher interviewed every single household of plant owners to know their cattle and poultry population. The manure production rate was also taken into account. The primary data on daily charge of input materials of 11 biogas plants were collected from different areas, sizes and locations of plants. A Sample of completed Interview with domestic AD user and detailed data and information on 11 AD plant visited is given in appendix 4. Data and information related with the AD process was collected from this interview.

Material inventory for the AD process

The water needed to dilute the manure is sourced from nearby water ponds and carried manually to the AD site. There is no embodied energy associated with the water resource. The input material inventory or amount of manure as an initial charge (to activate the digester) and daily amounts of cow dung (to maintain the AD operation) needed for a given size of reactor is given in chapter 5. This data and information was obtained from Grameen Shakti.

Energy Inventory for AD process

Movement, transportation of feedstock and premixing and addition of water are process parameters. Because the system considered for this study is the domestic type farm-based AD, there is no transportation of feedstock involved and the mixing is done manually.

The chemical reaction during digestion produces heat. To maintain the reactivity of the micro-organisms the ideal temperature for the digester is between 37^{o}C - 42^{o}C in the mesophilic regime. For the fixed dome design considered in this study, no heaters are used and the process relies entirely on the activity of the organisms. The biogas yields are used directly from the digester using short pipelines hence there is no transportation to usage location. The digestate used as fertiliser is spread without the use of equipment.

3.5.3 Impact assessment of AD product and processes.

Impact assessment using secondary data

This is the evaluation of the different emissions derived from the process map. The material inputs are dung and water. The process is mesophilic without the use of heaters and relies entirely on the outside temperature and soil temperature. The use of biogas replaces the use of biomass for cooking fuel and kerosene for lighting.

Interpretation of results using secondary data

The results for the calculation of impact parameters and interpretation of the impact assessment for the operation of a 3.2 m^3 biogas AD plant will be given in chapter 8. It will also show the methods used to quantify the GHG emissions avoided through the use of AD systems.

LCA Software SimaPro 7

SimaPro is a professional tool to collect, analyse and monitor the environmental performance of products and services. It consists of a large standard database and some optional databases. SimaPro has features that support its extensive use as a product development and LCA management tool. The SimaPro 7 Life Cycle Assessment Software provides a professional tool to collect, analyze and monitor the environmental performance of products and services. The LCA methodology using PAS 2050 guidelines were used for this study of anaerobic digestion.

4.6 Social and economic considerations

Being a low income generating developing country, all development activities including the renewable energy program in Bangladesh can be severely affected by the social and economic conditions of the rural people. Microfinance is a tool widely applied in the renewable energy program in rural Bangladesh. As a result it was emphasised on the socio-economic conditions in implementation of the AD system. This author interviewed and had kept a long period of communication with the rural entrepreneur, experts, and organizations.

4.7 Summary of the chapter

The assessment of waste and waste management, overview of AD facility and the concept of existing AD biogas production was the main reason of the field trips and visits with experts. The Initial identification of representative AD facility types was done through estimation of AD feedstock production and review of the community around the AD site. Biogas parameters: composition of biogas, biogas and methane yield, AD constructions materials and initial and daily feedstock application were counted in order to estimate yield capacity and later LCA to look GHG mitigation capacity of AD. A farm animal survey was done in a district of Bangladesh to find out the accurate AD energy capacity of the country by scaling up the survey result. Availability of all types of feedstock in the district was considered when selecting the district to be surveyed. LCA was done on both product and process of AD system to estimate the GHG emission mitigation capacity of the AD facility types. LCA of biogas, digestate, feedstock and AD plant building materials were done during this research. Socio-economical impact of AD and the scope of AD in Bangladesh was the obvious output of this research due to several field and expert visits during this research work.

This systematic approach of research methodology has identified some representative scenarios of AD facilities and prospective feedstock. The development of the idea of the use of a new feedstock, namely rice straw from cattle markets, will be a novel contribution, as will the idea of developing a small number of robust scenarios which can then be scaled up for consideration in national energy policy and international carbon offsetting.

Considering this methodology the results will be illustrated in chapter 5, 6, 7 and 8. AD potential by facility types, AD energy parameters, Countrywide AD potential and LCA of AD and GHG mitigation will be described in the next four chapters accordingly.

Chapter 5

Determination of AD potential by facility types from Gazipur data

5.0 Introduction

This chapter will determine the current practices and thus potential prospects for a) cattle, b) poultry and c) cattle market rice straw feedstocks for increased AD capacity in a given district. This was done by representative samples of visits to smallholdings and farms and by the use of government data. A formal survey was undertaken to find out the animal population in smallholdings to estimate the district potential of AD across a likely facility size distribution of domestic, medium and large plants. This chapter will present how many of a, b, c domestic/medium/large size AD plants have potential in the district. Considering this it might be recommended that 3 scenarios form the AD implementation point of view on the basis of farm feedstock capacity and local community demand for energy. This chapter will develop the scenarios from the farm feedstock survey analysis. Data will be presented mainly in two ways: (i) biogas potential in units of cubic metres of biogas, m^3; and (ii) potential energy contribution in units of megajoules, MJ. Using Gazipur as a representative district, the data will be used to scale up the potential for AD implementation for the whole of Bangladesh in chapter 7.

5.0.1 Objectives

The objective of this chapter is to investigate the AD energy capacity of Gazipur district. This was done based on feedstock from cattle and poultry population and market place rice straw. The ultimate goal is to provide data to estimate the potential of AD in Bangladesh, as presented in chapter 7. The capacity will be presented in terms of potential development of small, medium and large AD facilities (since AD facilities naturally fall into these categories).

5.0.2 Background of small holdings/farm survey

The potential energy contributions from farm feedstocks of Gazipur district and Bangladesh were investigated in this research. As a result some comparative analytical data and information of Gazipur district and Bangladesh were integrated for later scaling up (chapter 7). Some key statistics for Bangladesh and Gazipur district are given in the following table. The table is divided into two parts: general information and energy data of the district and the whole country. Energy parameters were calculated from the first part of the table.

Table 5.1 Basic statistics of Gazipur district and Bangladesh shown in the table (Bangladesh Bureau of Statistics, District Livestock Officer, Gazipur, CIA The world fact book, 2010 and SNV, 2010).

General Information	**Gazipur**	**Bangladesh**
Area (square kilometres)	1,741	147,570
Population (million)	2	156
Number of households (million)	0.45	30.10
Number of electrified households (million)	0.23	14.10
People cooking using biomass (%)	55	55
Family members per household	4.44	5.18
Energy data		
Energy needed for cooking (million MJ)	20	1325
Burning hours of stove (Cooking hours)	5 hours/day/household	
Biogas utilised for 1 hours use in biogas stove	0.4 m^3 (IDCOL, 2008)	
Daily requirement of biogas for cooking purposes	2 m^3 biogas/household	
Daily energy requirement for cooking purposes	44 MJ/household = 22 MJ/m^3	

The survey results gave the number of animals per smallholdings/farms (cattle and poultry) or cattle market (for rice straw). The daily requirement of biogas for an average sized family (5 people) in Bangladesh for cooking purposes is 2 m^3 (Table 5.1) and this requires at least 5 cows. Smallholdings with 3 and 4 cattle were included during the survey because some

Bangladesh families have less than 5 members and they could use smaller AD facilities. A domestic AD plant by definition will produce 2 - 5 m^3 of biogas (Table 5.2).

The cattle, poultry and cattle market cattle populations were analysed on the basis of different sizes of smallholdings or farms according to their feedstock generating capacity. Data was also analysed for their distribution in sub-districts. Distribution of feedstock and energy capacity of the district will be explained in the results section of this chapter. It will also include a comparison of on-site biogas plants from 3 farm feedstocks. This result will be compare on the number of smallholdings for cattle and poultry feedstock with other published data. It will also include a few more analysis of these results compared with the existing smallholdings/farms feedstock and their energy capacity. This chapter will conclude with summary statements on the impact of this work.

Generally, an AD plant size can be defined according to the following Table 5.2 (Shamsul Haq, 2010) into 3 types; domestic (D), medium (M) and large (L). This categorization is done on the basis of the amount of biogas yield.

Table 5.2 Three categories of AD facilities in Bangladesh based on plant size.

Plant size (Daily Biogas yield)	**Mode of plant size**	**Remarks**
2 - 5 m^3	Domestic	D
5 - 25 m^3	Medium	M
25 - 150 m^3	Large	L

5.0.3 Background of biogas parameters (primary and secondary)

The daily amount of feedstock, the corresponding biogas yield and methane percentage of biogas are the most important parameters needed to determine the energy potential. Primary data was collected for each parameter. Published data on biogas yield and methane percentage of cattle and poultry feedstock was also collected from Grameen Shakti for comparison. The plots presented (Table 5.3) in this Chapter were derived using Grameen Shakti reference data. The measured primary data on biogas yield of cattle and poultry feedstock presented and discussed in Chapter 6, is significantly less than the Grameen Shakti reference data.

For the purpose of determination AD capacity of the district, only Grameen Shakti reference data will be used as it is assumed that future AD facilities will be well managed farms. The rate on successful operation of AD plant in recent year is higher compare to last couple of decades (Gofran, 2010). It was the consideration point to use GS's data for AD energy calculations.

Table 5.3 Daily biogas yield and energy potential (MJ) for each feedstock.

	FS(kg/FS unit)	**Yield (m^3/kg FS)**	**% CH_4**	**MJ/m^3 CH_4**	**m^3/FS unit**	**MJ/FS unit**
Cattle dung	10	0.037	60	36.5	0.37	8.10
Poultry litter	0.10	0.071	65	36.5	0.0071	0.168
Cattle market rice straw	35	0.099	74.4	36.5	3.47	94.10

FS=Feedstock

Results indicate that the energy capacity for each cattle and poultry is 8.10 and 0.168 MJ respectively. AD energy capacity per cattle that produced rice straw waste in cattle market is 94.10 MJ.

5.1 Results of smallholdings/farms/market survey

This section will present results on the basis of smallholdings/farms animal distribution, which will allocate the AD size for individual feedstock. It will also describe the energy pattern of those feedstocks considering the prospect of biogas yields of the district. Finally a comparative analysis will be done between farm feedstock and energy pattern for the AD facility types.

5.1.1 Cattle

Data was analysed from each sub-district to find out the average number of cattle per smallholding and the potential energy capacity.

Feedstock allocation

The average number of cows from 25 cattle smallholdings per sub-district is given in Table 5.4. These are smallholdings with ≥ 3 cows. The average range of cattle per holding varied from 6 - 17 and the average cattle population of the district was found to be about 9 per cattle holder. The average cattle population of Sadar sub-district was 17, which was the highest, and the lowest (4.7) was in Kaligonj district. The communication system of Sadar within the district and with Dhaka is much better than any other sub-district of Gazipur. This factor could be a reason why the rural area of Sadar sub district is more affluent. Because Sadar is affluent economically, their communication system is also better than the others. This might be one important reason for a higher average number of cattle in Sadar.

Table 5.4 Average number of cattle of Gazipur district by sub-district (survey results of primary data)

Sub-district	**Average Number of Cattle/smallholding**
Sadar	17.3
Sreepur	11.3
Kapasia	5.1
Kaligonj	4.7
Kaliakoir	6.4
District average	**8.96**

During the survey, this researcher also noted the number of smallholdings visited which had < 3 cows. It was measured for two sub district Sadar and Sreepur. In Sadar sub-district, 4 smallholdings out of 29 and in Sreepur 3 smallholdings out of 28 visited had < 3 cows. On the basis of this limited data from only two sub-districts, it is assumed that 12% of smallholdings in Gazipur have < 3 cows. According to this and the total cattle smallholdings in the district of Gazipur, the new average number of cattle per smallholding would be 8 cows per holder. Cattle dung feedstock from 8 cows is 80 kg and can produce 3 m^3 of biogas daily: this is a typical domestic AD size in Bangladesh.

The cattle population is the number of cattle in an individual smallholding. There were 125 smallholdings surveyed with a total cattle population of 1,118 cattle. The distribution is represented in two ways: simple cattle population categorization (Table 5.5) and in cumulative percentile, shown in Table 5.6.

Table 5.5 Cattle smallholdings with the number of cows (from survey results)

Number of cattle	**No of smallholdings**	**% smallholdings**
3 – 5	54	43
6 – 10	48	38
11 – 15	8	7
16 – 20	5	4
>21	10	8
Total	**125**	**100**

Table 5.5 shows that 81% of cattle smallholdings have a cattle population of 3 - 10. 25% of smallholdings were found to have ≤ 4 cattle per heads, 50% of them ≤ 5 and 75% of smallholdings had a cattle population ≤ 8. The highest number of cattle found in a smallholding was 54.

Table 5.6 Cumulative percentile of smallholdings with the number of cows (from survey results)

Percent of smallholdings	25%	50%	75%	100%
No of cows	3-4	3-5	3-8	3-54

This information allows for planning for the most common situation. For example, a few smallholdings (< 20%) have more than 10 cattle.

Energy patterns

Table 5.7 shows the energy capacity cumulative percentile versus the cattle population from 125 cattle smallholdings. The total available energy from the total cattle population of 1,118 is 9044 MJ. 25% of the total energy comes from cattle populations of ≤ 6 cows. The cattle populations of ≤ 9 and ≤ 25 cows provide 50% and 75% of all energy, respectively.

Table 5.7 Cumulative percentile of energy with the number of cows (from survey results)

Percent of energy	25%	50%	75%	100%
No of cows	3-6	3-9	3-25	3-54

Due to the variations of feedstock populations of the district, biogas yields were different depending on the smallholdings cattle population. Generally in Bangladesh the daily energy requirement for cooking purposes is 44 MJ/household of 5 members (IDCOL, 2008). The result shows that 29% of smallholdings have a capacity to produce < 2 m^3 of biogas daily and can generate only 29 MJ of energy. This is not sufficient for the cooking purposes of an average sized family (5 people) but is enough for a family of 3 or 4 in Bangladesh. These 29% of smallholdings are categorized as a small domestic AD plant which is an extra category created from these results. The cattle population pattern of the district showed that 58% of cattle smallholdings have feasible potential for domestic biogas plants with yield rates of 2 - 5 m^3 daily (domestic size). The average energy generating capacity for these smallholdings is 57 MJ daily which is more than enough for a family. So, in principle, a total number of 87% cattle smallholdings are feasible for domestic AD plants.

13% of smallholdings were found to yield potential capacity of 5 - 25 m^3 (medium size). The energy production capacity for this size is 232 MJ/smallholdings. This amount of energy can meet the cooking energy requirements for 5 families.

Table 5.8 Cattle smallholding energy pattern with plant size distribution (from survey results)

	Smallholdings	**Cows**	**Energy, MJ**	**MJ/cow**
	125	1118	9044	8.1
	Biogas yield		**Average**	**Average**
AD type	**(m^3)**	**% of smallholdings**	**Cows/smallholding**	**MJ/smallholding**
Small domestic	(< 2)	29	3.5	29
Domestic	(2 - 5)	58	7	57
Medium	(5 - 25)	13	28.6	232

This calculation is based upon the maximum yield capacity from Grameen Shakti's manual and the actual capacity is only 57% of Grameen Shakti. Current AD biogas production scenario says that unless improvement of AD systems in operation can't ensure the above AD capacity.

Feedstock and energy

Figure 5.1 shows cumulative cattle smallholding and energy percentile of Gazipur district. It reflects the energy efficiency according to the smallholdings size in cumulative percentile. This figure summarises the data for cattle. It shows the number of smallholdings with cattle population in cumulative percentile versus the cumulative energy percentile.

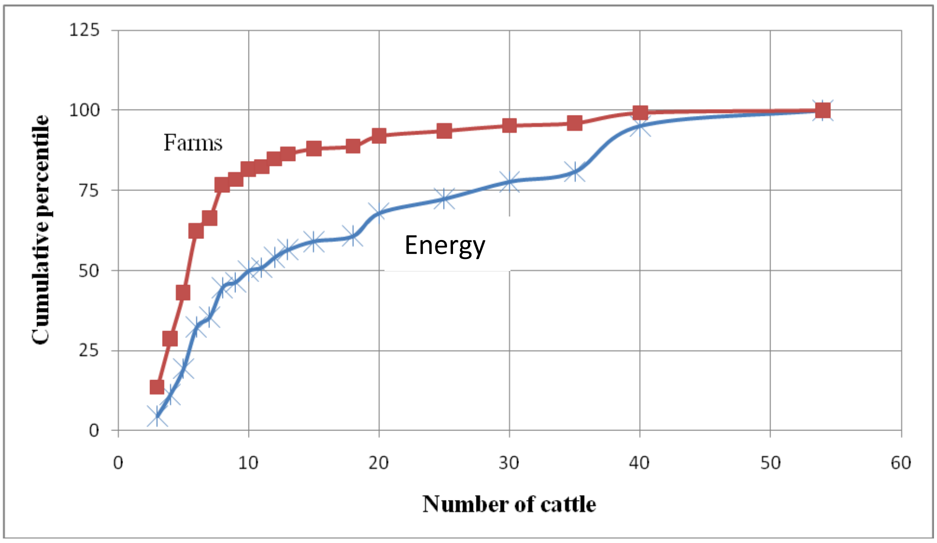

Figure 5.1 Cumulative cattle smallholdings (farms) and energy percentile of Gazipur district (from survey results).

It can be concluded from this section that 50% of AD energy capacity of cattle smallholdings comes from cattle farms having the cattle population of ≤ 9 which is 80% of the total number of farms. This means that even if only domestic sized facilities were used, 50% of the potential could be captured.

5.1.2 Poultry

The poultry feedstock and energy potential will be described in this section. Data is analysed from each sub-district to find out their individual average potential energy capacity.

Feedstock allocation

Average poultry population of 5 sub-districts were investigated to find out the district average poultry population. The average number of poultry population of Gazipur district is shown in Table 5.9. It implies that poultry population range in Gazipur district is about 2600 - 5800. The highest number of poultry per farms was observed in Sreepur sub district and the lowest was found in Kapasia. Most of the land in Sreepur is comparatively plain and high which is suitable for poultry farming (Gofran, 2010). The communication between Dhaka and adjacent district is also well enough to do a good marketing of poultry product eggs. These might be the reason the poultry farm in Sreepur is significantly bigger than any other sub district. Gazipur district has an average poultry population of 3,520 birds per farm.

Table 5.9 Average poultry population of Gazipur district poultry feedstock by sub-district (from survey results).

Sub-district	**Number of poultry**
Sadar	3024
Sreepur	5816
Kapasia	2696
Kaligonj	3324
Kaliakoir	2738
Grand average	**3,520**

The poultry bird population is the number of birds in an individual farm. There were 125 farms surveyed with a total bird population of 439,950 birds. The distribution is represented in two ways: simple poultry bird categorization (Table 5.10) and in cumulative percentile labels, as shown in Table 5.11.

Table 5.10 Poultry farms with the number of birds (from survey results).

Number of birds	**Number of poultry Farms**	**% Poultry farm**
< 1000	15	12
1000 – 2000	55	44
2001 – 3000	15	12
3001 – 4000	10	8
4001 – 5000	8	7
5001 – 6000	3	2
6001 – 7000	4	3
7001 – 8000	2	2
8001 – 9000	1	1
9001 - 10000	3	2
>10000	9	7
Total	**125**	100

Table 5.10 shows that 76% of poultry farms have a poultry population of 1,000-4,000. The cumulative percentile showed that 25% of the farms surveyed had a bird population of ≤ 1,000 birds, 50% had ≤ 1,900 birds and 75% farms had the bird population of ≤ 4,000. The highest bird population of the surveyed poultry farms was found to be 20,000 birds per farm.

Table 5.11 Cumulative percentile of farms with the number of birds (from survey results).

Percentage of farms	**25%**	**50%**	**75%**	**100%**
No of birds	≤1000	≤1900	≤4000	≤20000

Energy pattern

Table 5.12 shows the energy capacity cumulative percentile versus the poultry bird population. The total available energy from the total population of the 439,950 birds is 74,088 MJ. The distribution is represented by the following percentile labels showed below.

Table 5.12 Cumulative percentile of energy with the number of poultry birds (from survey results)

Percentage of energy	**25%**	**50%**	**75%**	**100%**
No of birds	2500	6000	14000	20000

This means that 25% of the energy capacity is from farms with a bird population of ≤ 2,500 birds, 50% is from farms with ≤ 6,000 birds and 75% of the total energy comes from bird populations of ≤ 14,000. 30% of the farms surveyed had a bird population of ≥ 4,000 birds suitable for medium to large AD operation with an energy capacity of 64% of the total potential of 47,216 MJ.

The energy production capacity of 125 poultry farms of Gazipur district is 74,088 MJ. The Table 5.13 summarises the results with the plant sizes. The plot also shows the biogas yield corresponding to the types of AD plant, namely: Domestic (< 5 m^3), Medium (< 25 m^3) and Large (< 100 m^3).

Only 7% of the farms are feasible for domestic sized biogas plants with an average capacity of 93 MJ/farm. 63% of the poultry farms are capable of a medium anaerobic digestion plant with an average energy capacity of 270 MJ/farm. 30% of the poultry farms are suitable for large anaerobic digestion plants. The average energy capacity of these large sized poultry plants is 1,400 MJ which could be suited for small to medium industrial use.

Table 5.13 Poultry farms energy pattern with plant size distribution (from survey results)

	Farms	**Birds**	**Energy, MJ**	**MJ/bird**
	125	439950	74088	0.1684
AD Type	**Biogas yield m^3**	**% of farms**	**Average bird/farm**	**Average MJ/farm**
Domestic	2 – 5	7	572	93
Medium	5 – 25	63	1614	270
Large	25 – 150	30	8305	1399

Previous results showed that it is enough to have 44 MJ of energy for the domestic cooking for a medium sized family. In this reality a domestic sized poultry farm can be feasible for 2 families, medium for 6 families and a large sized poultry farm could be used for small commercial and industrial use. But currently, most of the farm owners who have this AD facilities are domestic in size. It means a large portion of feedstock is not being used which is a loss of energy.

Feedstock and energy

Figure 5.2 shows the cumulative poultry farms and energy percentile of Gazipur district. It reflects the energy efficiency of poultry farms according to the farm size in cumulative percentile. The figure summarises the data for poultry. It shows the number of poultry farms with bird population in cumulative percentile versus the cumulative energy percentile.

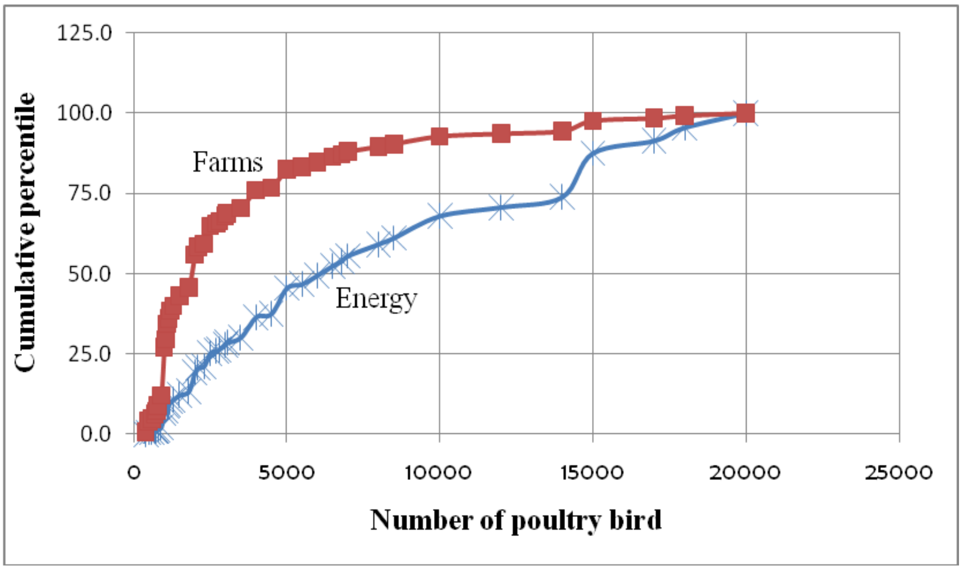

Figure 5.2 Cumulative poultry farms and energy percentile of Gazipur district (from survey results).

It can be concluded from this section that 76% of poultry farms have poultry population of less than 4,000, which give an energy contribution of less than 40%. It means the rest of 25% larger sized poultry farms contribute the maximum portion (60%) of energy. As a result domestic AD plants with poultry farms are not wise for their potential level of energy.

5.1.3 Cattle market rice straw

Energy pattern and feedstock distribution of cattle market rice straw will be described in this section. Data is analysed in each sub-district to find out their individual average potential energy capacity.

Feedstock allocation

The daily average rice straw feedstock from the 30 cattle markets surveyed was found to be 28 tonnes per market with an average cattle population of 796 in Gazipur district. So every day 28 tonnes of rice straw waste is generated per market - 35 kg per cattle.

Table 5.14 Average feedstock per cattle market (from survey results).

Sub-district	Cattle population/market
Sadar	957
Sreepur	808
Kapasia	450
Kaligonj	1067
Kaliakoir	700
Gazipur district	**796**

Table 5.15 shows the number of cattle market cumulative percentile versus the cattle population of the market. There were 30 cattle markets surveyed with a total cattle population of 22,300. 25% of the cattle markets had a cattle population of ≤ 400. 50% and 75% of the markets had a cattle population of ≤ 500 and ≤ 1,000 respectively. The highest cattle population was found to be 2,000 in a market.

Table 5.15 Cumulative percentile of cattle markets with the number of cattle (from survey results).

Percentage of market	25%	50%	75%	100%
No of Cattle	400	500	1000	2000

Energy pattern

Table 5.16 is the energy capacity cumulative percentile versus the cattle population. The total available energy from the total population of the 22,300 cattle is 2,100,000 MJ. The distribution is represented by the following percentile labels.

Table 5.16 Cumulative percentile of energy with the number of cattle

% of energy	25%	50%	75%	100%
No of cattle	500	1000	1400	2000

25% of the total energy comes from ≤500 cattle/market. 50% and 75% of the energy comes from cattle population of ≤ 1,000 and ≤ 1,400 respectively.

Table 5.17 shows the biogas yield and energy generating capacity of cattle market rice straw. Result from cattle market rice straw showed that each cow can produce 94 MJ of energy which is double that of an average sized family energy requirements for cooking. On the basis of feedstock availability of a cattle market, very large type AD is feasible, shown in Table 5.17. It is divided into two types based on their biogas yield. 53% of markets have a capacity to generate 1,000 - 2,000 m^3 of biogas daily with an average energy capacity of 36,750 MJ. The remaining 47% of markets can produce 2,000 - 7,000 m^3 of biogas which are defined here as “very large” types of AD plants. This is another new category - one of the findings of this research. The average energy capacity of these extra large AD plants is 108,000 MJ.

Table 5.17 Cattle market energy pattern with plant size distribution (from survey results)

	Market	**Cattle**	**Energy, MJ**	**MJ/cattle**
	30	22,300	2,100,000	94.10
AD Type	**Biogas yield m^3**	**% of market**	**Average cattle/market**	**Average MJ/market**
Domestic/Medium		0		
Large	1000 - 2000	53	390	36,750
Very Large	2000 - 7000	47	1150	108,000

Figure 5.3 shows the cattle distribution at the cattle markets. The results show that the biogas yield range of a cattle market is 1,000 - 5,000 m^3. 53% of cattle markets have the capacity to

produce 2,000 of m^3 biogas daily. 10% of the cattle markets were found to have a biogas yield capacity of ≥ 5000 m^3. It could be used for planning of construction for AD size in particular for cattle markets. It showed that a number of cattle markets had 500 or less cattle but a few of them had a cattle population of more than 1,000.

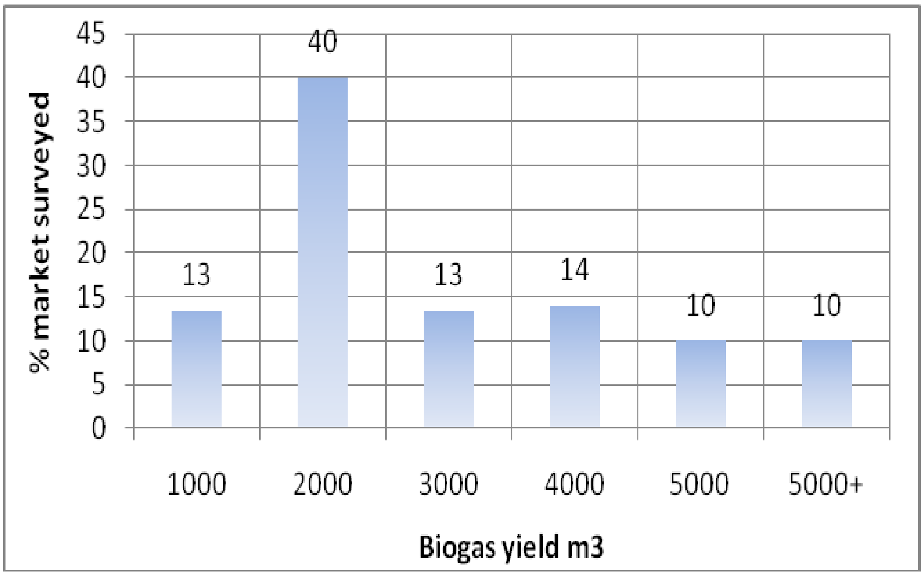

Figure 5.3 Biogas yield distribution of surveyed cattle markets (from survey results).

Feedstock and energy

Figure 5.4 shows cumulative cattle market and energy percentile of Gazipur district. It reflects the energy efficiency of cattle market rice straw according to the market size in cumulative percentile.

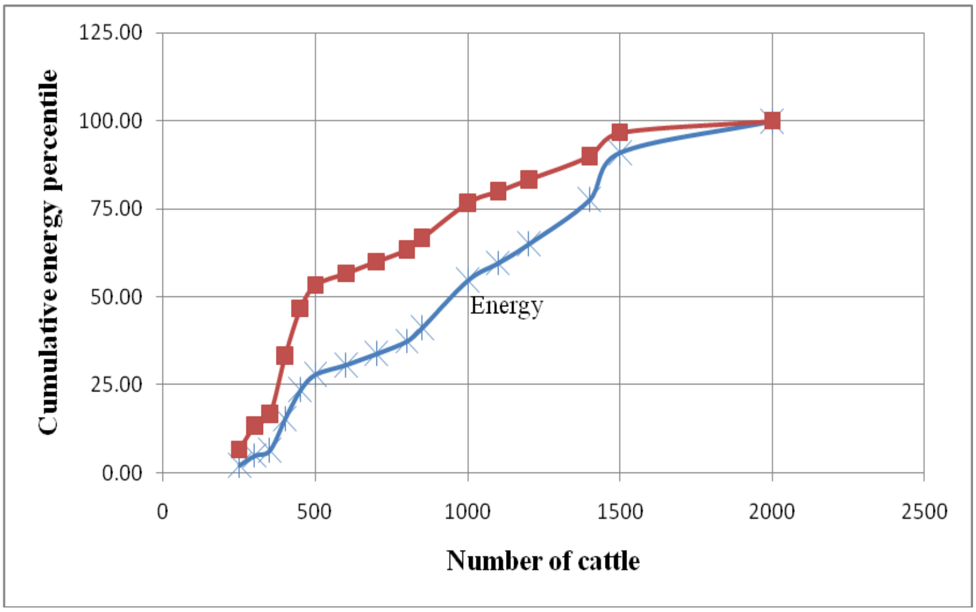

Figure 5.4 Cumulative cattle market cattle numbers and energy percentile of Gazipur district (from survey results).

The energy capacity of cattle market rice straw feedstock from 30 markets is 2,100,000 MJ. It means the per cattle market energy capacity is 70,000 MJ. For cattle market rice straw feedstock it can be concluded that their yield and energy capacity is significantly higher and have a prospect of electricity production with small, medium or large scale use.

On-site existing biogas plants

Out of 250 smallholdings/farms (cattle and poultry) and 30 cattle market visits, only 11% of smallholdings and farms were found to have an existing on-site AD systems. 2.5% of them were from cattle smallholdings, 8.5% of them from poultry and none of them from cattle market rice straw.

Table 5.18 On-site biogas plants in Gazipur district, Bangladesh

Animal manure	Surveyed Farm	Existing AD	Notes
Cattle	125	7	Domestic
Poultry	125	24	Domestic
Cattle market rice straw	30	0	
Total	**280**	**31**	
% Existing AD plant		**11**	**Domestic**

All of the biogas plants found to be operating during the survey visits were domestic sized plants and none of them were medium or large in size. It means the present AD feedstock utilization rate is very poor compared to its potential level of capacity. Table 5.19 represents the cattle, poultry and cattle market rice straw feedstock categorization on the basis of yield production.

Table 5.19 Distribution of different sizes of cattle, poultry and cattle market rice straw feedstock AD potential at individual level.

Feedstock	Distribution of different sized farms (and smallholdings)					
	Small domestic (<2m^3)	**Domestic (2-5 m^3)**	**Medium (5-25 m^3)**	**Large (25-150 m^3)**	**Very large (>150 m^3)**	**Total**
Cattle	29	58	13	0	0	100
Poultry	0	7	63	30	0	100
Cattle market rice straw	0	0	0	53	47	100

5.2 Discussion

5.2.1 Cattle

The result of the cattle smallholdings survey (Section 5.2) is consistent with earlier studies by other researchers. SNV (2005) conducted a survey on the cattle population in 8 districts of Bangladesh including Gazipur district. A comparison was done between the primary data collected in this thesis and the SNV survey. The more smallholdings with the higher number of cattle per holdings were found in this research compared to SNV data (see Figure 5.5). Table 5.20 shows that 50% of smallholdings had the cattle populations of ≥ 6 whereas SNV survey shows at the same cattle range with 30% smallholdings.

Table 5.20 A comparison the results of this survey with the SNV survey results in the year, 2005

	SNV survey, 2005		This survey, 2010	
	Cattle smallholding		Cattle smallholding	
Number of cattle	**Number**	**%**	**Number**	**%**
0 - 2	11	17	3	11
Up to 3	24	36	3.4	12
4 - 5	11	17	7.4	26
6 - 10	12	18	9.6	34
> 10	8	12	4.6	16
Total smallholdings	**66**	**100**	**28 (25+3)**	**100**

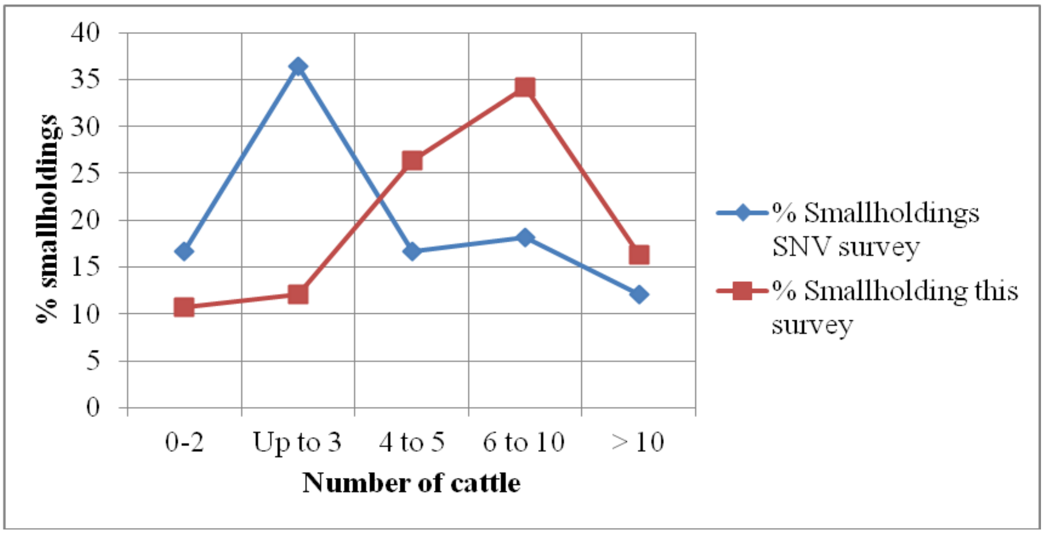

Figure 5.5 Cattle distribution of this survey of Gazipur district compared with SNV's survey, 2005.

This research showed that average cattle number per cattle smallholding is about 8 and the average AD size of a cattle smallholding is 3 m^3 (8 x 10 x .037 m^3) which is higher than the SNV survey result (2005). According to SNV (2005) the average cattle number per cattle smallholding is 5.61 which is feasible for 2.1 m^3 AD plant. This research shows high average cattle population than SNV which is significantly different. Their survey also investigated that there are about 3 million small sized biogas plants technically feasible from dung only. This research also investigated total AD plant potential from cattle dung which will be present in chapter 7.

This independent source of data indicates that the outcome of the current survey is comparable with other surveys. This suggests it is appropriate to use them to project the potential for future AD installations for Gazipur as a full district and scale up the result for Bangladesh, i.e. countrywide. This will be done in chapter 7.

5.2.2 Poultry

A comparison is presented with research by S A Zaman (2007) whose findings of poultry bird distribution of Bangladesh is shown in Figure 5.6 alongside the current research. This survey result showed that about 11% of poultry farms had a poultry population of <1,000, 34% of farm had <2,000 and 21% had <3,000 birds. The reference (Zaman, 2007) showed in the same ranges, the bird populations of the farms were 6%, 28% and 37%. Integrating these three ranges this result showed that 66% of poultry farms had a poultry population of <3,000. According to Zaman (2007) 71% of poultry farm was found within the same ranges (upto 3000/farm) of poultry population. In comparing the poultry population in different ranges it can be said that the trend of poultry populations seem similar in each category.

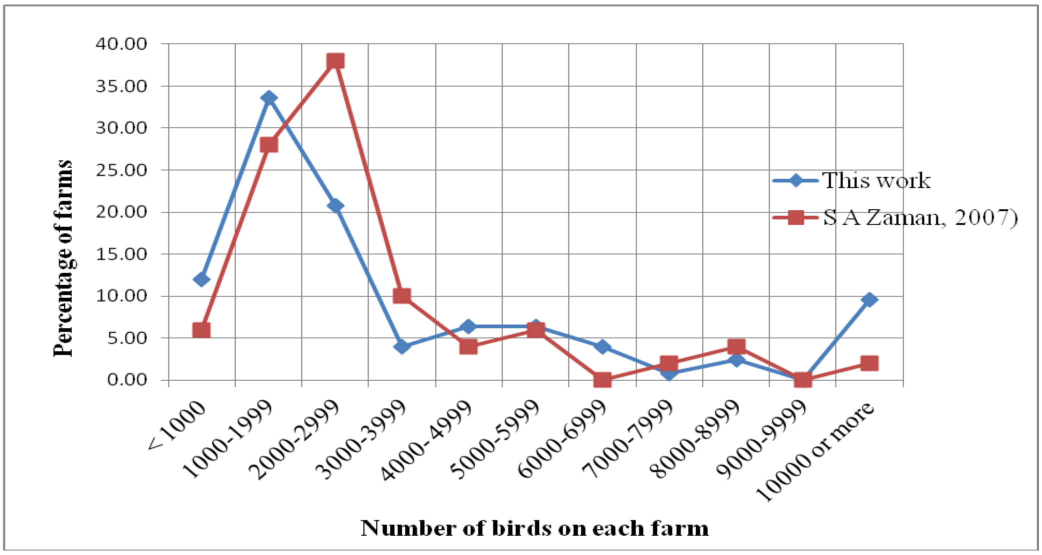

Figure 5.6 A comparison of poultry population survey results of S A Zaman from 2007 and this work.

It is a big reality that the existing data had some limitation. There is the lack of data on poultry population for each sub district of a district. For example, existing data for Gazipur district showed that only two sub district's survey results were available to be compared this work where this research had surveyed all sub-district of Gazipur. However, from this analysis it can be mentioned that the poultry distribution obtained in this work (from 5 sub district) is comparable enough with other research work (2 sub district), and thus is appropriate for taking forward to scale up, e.g. to a national level.

5.2.3 Cattle market rice straw

The total number of cattle markets in Gazipur district is 30, the total cattle population is 22,300 and the energy capacity is 2,100,000 MJ with an average of 70,000 MJ per market. The results analysis of cattle market rice straw showed that a small cattle market will have ≤ 500 cattle, medium markets ≤ 1,000 cattle and large market > 1,000 - 2,000 cattle.

Table 5.21 Distribution of cattle market AD systems

Number of cattle in market	% of markets represent	Potential energy (%)	Average number of cattle in market	Average potential biogas yield m^3	Average potential energy MJ from market	Type of AD
≤500	50	25	400	1400	38,000	Small market
≤1000	25	25	850	3000	80,000	Medium market
1000-2000	25	50	1500	5200	140,000	Large market

Categorization of cattle markets with size distribution shows the yield and energy capacity. It creates an idea about the digester in each category. In this circumstance, the AD designer must thus aim to build ADs with capacity for 1,400 m^3, 3,000 m^3 and 5,200 m^3 plants. In practice, a medium market will be equal to two small market type ADs and a large market will be equal to two medium types ADs depending on its volume and fund allocations.

This is the first research using cattle market surveys to find out the potential AD biogas yield and potential AD energy capacity of cattle market rice straw in Bangladesh. The implementation of potential large AD plants using cattle market rice straw as a feedstock is a new concept in Bangladesh which presently focuses on domestic and medium AD types using cattle and poultry dung only. This is one of the most important contributions to knowledge of this research.

5.3 Size distribution of different AD facility types

The analysed results of three animal feedstocks are summarised in Table 5.22. It shows that cattle smallholdings are mainly suitable for domestic sized AD plants, poultry farms for medium and cattle markets for large or extra large AD plants.

Table: 5.22 Percent of different sized AD plants required for each of the 3 farm feedstocks in Bangladesh

Size of plant required	Cattle	Poultry	Cattle market
Small domestic (<2 m^3)	29	0	0
Domestic (2 - 5 m^3)	58	7	0
Medium (5 - 25 m^3)	13	63	0
Large (25 - 150 m^3)	0	30	53
Extra Large (>150m^3)	0	0	47
Total	**100**	**100**	**100**

This table shows two new categories of AD size; small domestic (< 2 m^3) and very large (> 150m^3) AD. It had been created from cattle smallholdings and cattle market rice straw respectively.

Table 5.23 Daily estimation of the number of families that can live on (for cooking) the categorized AD size (a family of 5 people with 44 MJ of energy).

	Biogas yield (m^3)				
Cattle	**Small domestic (<2)**	**Domestic (2 - 5)**	**Medium (5 - 25)**	**Large (25-150)**	**Extra large (>150)**
Energy MJ	29	57.0	232.0	0.0	0
Number of cattle	4	7	29	0.0	0
Number of Families	**0.7 (small)**	**1**	**5**	**0.0**	**0**
Poultry					
Energy MJ	0	93	270	1399	0
Number of birds	0	572	1614	8327	0
Number of Families	**0**	**2**	**6**	**32**	**0**
Cattle market rice straw					
Energy MJ	0	0.0	0.0	36750	108000
Number of cattle/market	0	0.0	0.0	390	1150
Number of Families	**0**	**0.0**	**0.0**	**835**	**2455**

Table 5.23 shows an estimation on the number of families that can meet their cooking energy requirements with the categorised AD plants. It shows that biogas yield from cattle

smallholdings is suitable for 1 to 5 families and hence categorise mainly in the domestic AD category. Among the three categories, poultry farms are suitable for 2, 6 and 32 families which indicates that medium community based AD is feasible for this sector. A large number of families can benefit from the indicative category of AD size from cattle market rice straw feedstock. As a result commercial and industrial use of AD energy from cattle market rice straw is preferable.

5.4 Conclusion of this chapter

This chapter determined the AD potential of varying facility types in Gazipur district. Result showed that the cattle smallholdings are suitable for domestic, poultry farms for medium and cattle market rice straw for large or extra large AD plants.

87% of cattle smallholdings are suitable for domestic AD plants with 29% for small domestic (< $2m^3$) and 58% for domestic sized AD plant. 13% of cattle smallholdings are suitable for medium sized AD plants. Poultry results showed that 63% of poultry farms are appropriate for medium, 30% for large and only 7% for domestic sized AD plants. 53% of cattle markets were found to be suitable for large and 47% markets for extra large AD plants.

In this chapter, three scenarios for implementation of AD have been investigated during the determination of the AD facility types. These are small sized AD using cattle dung, a community-based large size AD using poultry litter and a commercial large size AD using cattle market rice straw. This information could be very important for the future AD installation providing data on potential plant size and benefits to the rural community.

Introducing the cattle smallholdings AD system up to the potential level can make a significant impact on the ordinary rural family of Bangladesh. From the poultry farms it is implied that a number of families can benefit from an average sized poultry based AD system with a community based programme. From this calculation the biogas energy efficiency of a large and extra large sized rice straw based anaerobic digestion plant can be of a significant amount. Generally the cattle markets take place in rural and urban areas of Bangladesh. Therefore this energy can play a vital role to the vast people of the rural community.

The results at a glance

- Among three farm feedstocks, cattle smallholdings are suitable for domestic, poultry farms for medium and cattle market rice straw perfect for large or extra large sized AD.
- Animal manure: cattle dung and poultry litter are the two major AD feedstocks for Bangladesh. Most of the AD plants are domestic and few of them are medium sized.
- Average sized cattle smallholdings, poultry farms and cattle markets have the capacity to produce 3.2 m^3, 25 m^3 and 2,760 m^3 biogas daily with 72 MJ, 593 MJ and 0.42 million MJ energy output respectively.
- Energy from an average poultry farm AD is equivalent to 8 domestic dung based AD systems and energy from one cattle market AD is equivalent to 110 medium poultry based AD systems and 860 domestic AD systems.

AD potential of Gazipur district results is now ready to be analysed with the key parameters to determine AD biogas and energy capacity countrywide. Key information of plant materials, feedstock and other relevant information will be fed into LCA.

Chapter 6

AD Plant and Energy Parameters

6.0 Introduction

The determination of the potential for three AD facility types in Gazipur was the main finding of the previous chapter. Now it is essential to know the biogas yield and biogas composition of these types of facilities. AD construction materials and AD feedstock is also important to do life cycle impact assessment of AD plant. These results are important especially for energy planning and environmental concerns. This chapter will present data collected on energy parameters; affecting the performance and life cycle impact of AD systems including AD feedstock, AD building materials, biogas yield and composition of biogas and digestate. The feedstock, biogas composition and yield data will be used to calculate energy potentials. The building materials, feedstock and digestate data will be used in the LCA to calculate the environmental impact; GWP counts and savings. Factors which could affect the biogas yield directly and indirectly are then discussed.

Three AD facility types are considered, from three types of animal manure feedstock: cow dung, poultry litter and rice straw waste from the cattle markets. The first two are used commonly; the third is a new idea originating from this work and indicative of prospective feedstock for biogas production in Bangladesh. Primary data was collected for biogas production from all three types of feedstock. This is particularly important because results from this thesis show that actual biogas yields are significantly less than those published, for example guidance produced by Grameen Shakti. This is an important contribution to knowledge and help in the development and planning of future AD projects.

Data from dung and poultry-based biogas plants operated by Grameen Shakti were collected from Manikgonj district. Data for the new idea of the author for cattle market rice straw based biogas plant was collected from Mohammadpur of Dhaka district. The rice straw contains 15 - 20% dung by weight (Jalil, 2010). An existing dung-based AD plant was cleaned up before putting rice straw feedstock in, and data on the biogas yield and composition was collected.

This chapter will be divided into three sections. Section 6.1 will portray the AD feedstock and digester and 6.2 will present the energy parameters of AD; biogas yield and composition of biogas including comparison of the findings with the other references. Section 6.3 will discuss the variation of biogas yields and methane percentages. Thus it will present how the product and process of AD influence biogas yield and potential energy.

6.1 AD plant

This section will present data on AD feedstock and AD digester building materials. The first section will describe the percent of total solid (TS) of feedstock and mixed slurry as well as initial and daily charge of feedstock. The other section will describe the building materials of fixed dome and floating dome digester. The inside digester temperatures were 20 ± 2^0C during data collection (January, 2010).

6.1.1 AD Feedstock

Different farm feedstock has varying yield capacity due to their physical and chemical characteristics. This section will describe feedstock application (both initial and daily) and total solid (TS) of three types of farm feedstock as it influences both biogas and methane yield.

% Total solid of feedstock and mixed slurry

Feedstock and water are considered as the raw materials for the anaerobic digestion process- this is called mixed slurry. Water is added to dilute the raw materials for the normal AD process. In this research the feedstocks are animal manure: cow dung, poultry litter and cattle market rice straw. Water is added in different ratios according to the total solid percentage of the feedstock. Total solid contained in a certain amount of materials is usually used as the material unit to indicate the biogas producing rate of the materials. Most favourable TS value desired is 8% (BCSIR, 2004) for normal biogas production. For cow dung a mix of 1:1 with water and for chicken manure a mix of 1:2 with water are considered in order to keep the slurry at TS 8% (Gofran, 2008). The total solid percentage of cattle market rice straw is 43%. For rice straw feedstock a mix of 1:4 with water was added in this experimental plant due to keep the digester slurry as 8% TS. Research conducted by Ghosh and Bhattachatya (1999) with a batch reactor and using rice straw feedstock found it worked at 30ºC and 64 days retention time at 8 % total solid. In this research the raw materials are added in the following ratios shown in Table 6.1.

Table 6.1 Ratio of manure and water (feedstock) input to the digester

Feedstock	**TS %**	**Manure: Water (by weight)**
Cow dung	19.23	1:1
Poultry Litter	23.82	1:2
Cattle market rice straw	45.08	1:4

It implies that different feedstock has different total solid percentage. % TS is an important factor that can influences methanogenesis. The factor % TS influence biogas production which will be explained in the discussion part of this chapter. Proper mixing of slurry is thus important for the AD process.

Initial charge

The initial charge quantity needs to take into account the size of digester and the physical and chemical properties of the feedstock. Excess or insufficient application of the initial charge can severely affect methanogenesis and biogas production in the long run. From the AD plant visits conducted by the author, it was observed that the rural farmer didn't put the amount of feedstock prescribed in the manual; instead the farmer used less than the optimum amount of feedstock required. Furthermore, the farmers in most of the farms visited did not apply the feed daily. Their feedstock application rate was irregular and 4 - 5 times a week. Secondary results of the initial charge of 3 domestic sized and one medium sized AD plants using both dung and poultry litter are given in the following table. The initial charge is also an important factor for impact assessment. For example a large amount of feedstock might require the transportation fuel consumption and embodied energy needs to be considered. The data on initial charge was collected from the rural entrepreneur and the Grameen Shakti biogas engineer. A 3.2 m^3 biogas plant was considered for the life cycle impact assessment and will be described in detail in chapter 8.

Table 6.2 Initial charge fed to digester for AD process (Barua, 2007).

Plant size (m^3)	**Initial charging (kg)**	
	Dung	**Poultry**
2.4	3000	1500
3.0	3750	1875
3.2	4000	2000
14	17500	9000

Daily charge

Primary data was collected on the daily charge for 9 domestic AD plants and two medium sized AD plants. Among the 11 AD plants only one of them was poultry based (3.2 m^3) with the remainder being dung based plants. Domestic AD plant range was from 2.4 m^3 - 3.2 m^3

and two medium AD plants were of 14 m^3 in size. All the biogas plants were operated by Grameen Shakti.

The daily charge was calculated by the researcher using the daily feedstock production per animal and the number of animals. Daily feedstock production capacity of each cattle, poultry bird and cattle market's cow is 10 kg, 0.10 kg and 35 kg respectively. According to this estimation, smallholdings of 5 cows were considered as 50 kg daily.

Table 6.3 An observation of the daily feedstock supply on-site of visited biogas plants and GS' manual.

Plant number	**Feedstock**	**Plant size (Gas-m^3)**	**Daily charge Primary (kg)**	**Daily charge (kg) GS manual**	**Location**
1	Cow dung	3.2	50	87	Barisal district
2	Cow dung	2.4	40	65	Barisal district
3	Cow dung	14	262.5	378	Dhaka district
4	Cow dung	14	262.5	378	Dhaka district
5	Cow dung	3	40	80	Manikgonj district
6	Cow dung	3.2	70	87	Manikgonj district
7	Cow dung	2.4	30	65	Manikgonj district
8	Cow dung	2.4	40	65	Manikgonj district
9	Cow dung	2.4	40	65	Manikgonj district
10	Cow dung	2.4	40	65	Manikgonj district
11	Poultry litter	3.2	45	45	Mymensingh

Comparing the on-site application of daily charge with the daily charge required according to the Grameen Shakti manual, it is clear that the farmers used a lower daily charge compared to the required dose. Calculation showed that they used 33% less manure from the manual dose. Inadequate number of cattle was the main reason for using less feedstock. It was also found during AD plant visit that the farmer didn't put daily charge properly. They supplied daily charge 3 - 4 times per week whereas it is essential to feed digester every day. Lack of knowledge might be the reason for such type of poor management.

Daily and initial charge of feedstock (3 experimental plants)

Three experimental plants of different sizes (2.4, 4.8 and 2 m^3) using dung, poultry and rice straw were considered for the further information. Those plants were selected by the author but the sizes of the plants were already in use by Grameen Shakti. The input material inventory of the three feedstocks is shown in Table 6.4. The initial and daily charge was taken as that prescribed by Grameen Shakti for cow dung and poultry litter. Daily charge to digester for cattle dung and poultry litter AD plant was intensive observed for 3 days and the initial charge was according to GS manual and operated by GS during AD plant start date. For the rice straw, the initial charge was 1,300 kg of which 900 kg was old dung slurry. 400 kg of rice straw and 1,600 litres water were added. The total initial charge (including water) was 2,900 kg mixed slurry and the daily charge was 90 kg (rice straw: water = 1:4) including water. The daily amount of feedstock needed for three types of feedstock and sizes were measured by weights during the experimental period as shown in Table 6.4.

Table 6.4 Initial and daily charge used in three farm feedstock AD processes.

Feedstock	**Plant size**	**Initial charge**	**Daily charge**
	m^3	Kg	Kg
Cow dung	2.4	3000	65 $\pm$ 2
Poultry litter	4.8	3000	67.67 $\pm$ 2.5
Rice straw	2	1300	17.67 $\pm$ 2

6.1.2 Anaerobic digester (plant construction materials)

During the primary data collection described above the types of AD plants seen were different. But only two types of digesters were found during farm visits in Bangladesh; mainly fixed dome and floating dome. Among three experimental plants, dung and poultry feedstock based plants were brick made fixed dome digesters and the plant using cattle market rice straw feedstock was a floating dome anaerobic digester. For LCA of an AD plant, it is necessary to obtain the inventory of the materials needed to construct them. Recently

Grameen Shakti (Gofran, 2011) introduced a portable glass fibre fixed dome and floating dome types of bio digester which is convenient for domestic AD system. The table below shows the digester types of 3 experimental biogas plants in this research work.

Table 6.5 Visited digester types with their location

Feedstock type	Plant size	Digester type	Digester materials	Location
Dung	2.4	Fixed dome	Brick digester	Manikgonj
Poultry litter	4.8	Fixed dome	Brick digester	Manikgonj
Cattle market rice straw	2	Floating dome	Brick + Plastic	Dhaka

Inventory of Materials: Fixed dome digester

The inventory of the materials used to construct a 3.2 m^3 AD plant is given in Table 6.6 (IDCOL, 2008). The list of the AD building materials was collected from Infrastructural Development Company Limited Bangladesh from their biogas plant construction manual published in Bengali. All the materials were calculated in kg by the information provider of IDCOL, Grameen Shakti and Advance Engineering Bangladesh.

Figure 6.1 Brick-cement fixed domes (left) and model of fibre glass fixed dome bio digester used in GS (right).

Table 6.6 Inventory of materials for 3.2 m^3 AD plant (translated by the author from the IDCOL biogas manual).

Materials	**Number/amount**	**Each weight in kg**	**Weight in kg**
Bricks (25x12.5x7.5 cm)	1747 number	3.5	6,115
Sand (Fine-medium) 1.2-1.5 mm	2.5 m^3		4,005
Khoa (Brick particle) 1.9cm	0.65m^3		971
Cement (50 kg bag)	21 bags	50	1050
Rod (10mm)	26 kg		26
Paint(Acrylic Emulsion paint)	2 Litre		1
Polythene	3 meter		0.5
Inlet PVC pipe (10 cm)	6 meter		1
GI Ware # 8	2 kg		2

Inventory of materials: Floating dome digester

Floating-drum plants consist of an underground digester and a moving gasholder. The gasholder floats either directly on the fermentation slurry or in a water jacket of its own. The gas is collected in the gas drum, which rises or moves down, according to the amount of gas stored. The gas drum is prevented from tilting by a guiding frame. If the drum floats in a water jacket, it cannot get stuck, even in substrate with a high solid content (UN-ESCAP report, 2007). A typical floating dome biogas digester is shown in Figure 6.2. The fixed dome plant materials in addition to plastic are needed for a floating dome digester.

Figure 6.2 Brick-cement-plastic floating domes (left) and model of a fibre glass floating dome bio digester used in GS (right).

6.2 Biogas parameters

Measurement of the result of biogas yield and composition of biogas are the main parts of this section. It also includes the composition of digestate.

6.2.1 Biogas yield

Biogas yields were determined using a digital gas flow meter from Bangladesh Council for Scientific and Industrial Research (BCSIR). Production of 24 hours worth of gas was loaded and then unloaded whilst adjusting the flow meter so that it can detect the gas flow. The entire amount of gas was unloaded until there was a steady level of gas flow. Biogas yield was measured by two ways. The detailed methodology is given in chapter 4 (methodology). The biogas yields from the feedstocks are given in Table 6.7. These results showed that the biogas yield of both cow dung and poultry feedstock is 0.021 m^3/kg of manure but the yield of cattle market rice straw feedstock is significantly higher at 0.099 m^3/kg of rice straw feedstock. Biogas yield per kilogram TS of dung, poultry and dung mixed rice straw is 0.11 m^3, 0.09 m^3 and 0.22 m^3 respectively.

Table 6.7 Biogas yield from farm feedstock (this study)

Feed stock	**%TS**	**Biogas yield (m^3/kg Feedstock)**	**Biogas yield (m^3/kg TS)**
Cow dung	19.23	0.021	0.11
Poultry	23.82	0.021	0.09
Rice straw	45.08	0.099	0.22

The recorded rates were lower than those according to the Grameen Shakti manual daily feed rate; biogas yield was 0.037 m^3/kg dung, 0.19 m^3/kg of TS dung feedstock and 0.071 m^3/ kg of poultry litter, 0.30 m^3/kg TS poultry feedstock. Section 6.3 explores the potential reasons for the variation.

Table 6.8 Data resources of 2 major used biogas feedstocks in Bangladesh (Grameen Shakti)

Feed stock	**%TS**	**Biogas yield (m^3/kg Feedstock)**	**Biogas yield (m^3/kg TS)**
Cow dung	19.23	0.037	0.19
Poultry	23.82	0.071	0.30

A research was conducted by Hu Rongdu et al. (2006) to investigate % TS and properties of biogas from poultry, pig and cattle manure feedstock. This result shows that the % TS is 17 and the biogas yield of dung and poultry litter is 0.25 and 0.33 m^3/kg TS respectively.

Table 6.9 Energy parameters of other researchers (Hu Rongdu (2006).

Manure source	**% TS**	**Gas yield (m^3/kg TS)**	**% Methane**
Cattle	17	0.25	50 – 77
Pig	18	0.27	50 – 77
Chicken	25	0.33	60 – 65

From this section it can be concluded that the biogas yield may differ with different feedstock, different amounts of feedstock application and different % TS of feedstock.

Existing biogas yield capacity

Biogas yield rate for cattle and poultry feedstock in this research was significantly lower compared to the Grameen Shakti published data. The current yield efficiency can be determined by comparing this result with the Grameen Shakti manual.

Table 6.10 Daily biogas yield and energy potential for each cattle.

	Feedstock (kg/cow)	**Yield (m^3/kg)**	**% CH_4**	**MJ/m^3 CH_4**	**m^3/cow**	**MJ/Cow**
This work(Chapter 6)	10	0.021	59.9	36.5	0.21	4.59
Grameen Shakti (Gofran, 2008)	10	0.037	60	36.5	0.37	8.10
Efficiency (this work/GS)					0.57	0.57

The result of this research shows that the biogas yield and energy capacity per cow is 0.21 m^3 and 4.59 MJ respectively. According to the GS manual biogas yield and energy capacity is 0.37 m^3 and 8.10 MJ respectively and is significantly higher than the primary data collected. A similar trend was observed for the biogas yield and composition from poultry. The result shows that the biogas yield and energy capacity per poultry bird is 0.0021 m^3 and 0.0472 MJ respectively. According to the GS manual biogas yield and energy capacity is 0.0071 m^3 and 0.168 MJ respectively.

Compared to the Grameen Shakti manual (biogas yield and composition rate) results show the cattle smallholding AD plant and poultry farm AD were 57% and 28% efficient (yield efficiency). This might be due to the improper management of biogas plants by the rural stakeholders. A brief discussion on the factors affecting biogas yield has been given in section 6.3 of this chapter. For the next calculation of this research it has been considered that the AD energy capacity of a cow is 8.10 MJ and a poultry bird is 0.168 MJ.

Table 6.11 Daily biogas yield and energy potential for each poultry bird.

	FS (kg/bird)	**Yield (m^3/kg)**	**% CH_4**	**MJ/m^3 CH_4**	**m^3/bird**	**MJ/bird**
This work (Chap-6)	0.1	0.021	61.6	36.5	0.0021	0.0472
Grameen Shakti (Gofran, 2008)	0.1	0.071	65	36.5	0.0071	0.168
Existing AD Efficiency of this work (%)						**29%**

Research was conducted into yields from cattle markets. The biogas yield and energy capacity of this source was much higher in comparison to cattle and poultry feedstock. The energy potential and biogas yield per cattle in a cattle market is 94.10 MJ and 3.5 m^3 respectively.

6.2.2 Composition of biogas

To determine the composition of the biogas, two gas samples from each plant were taken. The samples were collected for three days. These were collected using a balloon and were analysed in BCSIR laboratories in Dhaka. The amount of hydrogen sulphite and carbon dioxide was determined using a digital gas analyser. Volume percentage of methane and carbon dioxide was determined using an Orsat gas analyser. The detailed methodology to determine composition of biogas is given in section 4.3.2 of the methodology chapter.

Results showed that the methane percentage (by volume) in biogas produced from dung, poultry and cattle market rice straw was 59.80%, 61.59% and 74.43% respectively. The highest methane content was found in rice straw feedstock. Biogas yield composition of dung and poultry based plants is shown in Table 6.13 from Grameen Shakti published data. According to Grameen Shakti (Gofran, 2009) the methane percentage from cow and poultry manure are 60% and 65% respectively.

Table 6.12 Composition of dung, poultry and rice straw based biogas in volume percentage.

Biogas	**Cow dung**	**Poultry**	**Rice straw**
	% Volume	**% Volume**	**% Volume**
CH_4	59.90	61.6	74.43
CO_2	42.10	38.38	25.57
CO	0	0	0.0005
H_2S	0	0.02	0

Biogas contains traces of hydrogen sulphide (H_2S). Exposure to high concentrations of H_2S is harmful and may result in human fatality. The hydrogen sulphide content in biogas should be less than 200 ppm (parts per million) to ensure a long life for the power generators. Therefore, plant operators must be trained to handle H_2S hazards. Results also showed that 0.02% of H_2S was found in biogas produced from poultry feedstock. According to Grameen

Shakti H_2S of poultry biogas was 1000 ppm which is significantly higher than the present findings. Addition of $FeCl_3$ is an effective process to the removal of H_2S produced from dairy manure during anaerobic bioconversion process (Lar, 2009).

Table 6.13 Composition of dung and poultry based biogas in volume percentage (GS).

Biogas	**Cow dung (Volume percentage)**	**Poultry (Volume percentage)**
CH_4	60.00	65.00
CO_2	39.90	34.97
CO	0.00	0.00
H_2S	0.10	0.30

Biogas composition of cattle market rice straw

Cattle market rice straw is considered a new potential AD feedstock for Bangladesh which is an important finding of this research. It is basically cattle food rice straw mixed with cattle dung. It is particularly different from animal manure feedstock; dung and poultry feedstock. Composition of biogas is significantly affected by feedstock loading rate and the quality of feedstock. For example carbon nitrogen ratio of feedstock is a vital issue of biogas production. Carbon and nitrogen ratio (C/N ratio) of rice straw is 70 which is higher than that of cattle dung (24) and poultry litter (10) feedstock (Karki and Dixit, 1984). The optimum C/N ratio in anaerobic digesters is 20:1 – 30:1. The addition of animal dung with rice straw reduces the C/N ratio.

The C/N ratio is an important factor for biogas production. Nitrogen present in the feedstock has two benefits: (a) it provides an essential element for synthesis of amino acids, proteins and nucleic acids; and (b) it is converted to ammonia which, as a strong base, neutralizes the volatile acids produced by fermentative bacteria, and thus helps maintain neutral pH conditions essential for cell growth. An overabundance of nitrogen in the substrate can lead to excessive ammonia formation, resulting in toxic effects. Thus, it is important that the proper amount of nitrogen be in the feedstock, to avoid either nutrient limitation (too little nitrogen) or ammonia toxicity (too much nitrogen). The composition of the organic matter added to a digestion system has an important role on the growth rate of the anaerobic bacteria and the production of biogas.

Biogas composition at different durations (10, 15 and 30 days) after the first feeding of cattle market rice straw feedstock was determined for the cattle market rice straw feed AD plant. This was conducted because this feedstock was a new potential AD feedstock in Bangladesh and there were no available data on this unlike for other feedstock (cattle and poultry).

The AD used for the experiment had been used previously and had some residual slurry at the bottom from an experiment carried out a month before, using dung as feedstock. The AD had sat unused since and was cleaned up. In reusing the AD for the cattle market rice straw feedstock, 18 kg of the feedstock was diluted to give 8% total solid. Biogas composition on different days after initial charging was collected from the rice straw biogas plant. The initial charge was 1,300 kg of which 900 kg was old dung slurry. 400 kg of rice straw and 1,600 litres water were added. The total initial charge (including water) was 2,900 kg mixed slurry and the daily charge was 90 kg (rice straw: water = 1:4) including water shown in Table 6.14.

Table 6.14 Daily and initial feedstock loading rate of experimental rice straw biogas plant.

Charge	**Feedstock**	**Amount (kg)**
Initial charge	Old slurry	900
	Rice straw	400
	Water	1600
Total		**2900**
Daily charge	Rice straw	18
	Water	72
Total		**90**
Daily feedstock application		**15 days**

Daily charge was applied up to the 15th day after initial charge and after the 15th day the daily charge stopped being put in to digester. Biogas composition on the 10th day, 15th day and 30th day were observed. These days intervals observation was done due to look at the bacterial activity on feedstock availability. Moreover, because of a new potential AD feedstock more detailed experiments to investigate of biogas and methane yield on different days were done, using cattle market rice straw. The results are given in Table 6.15 and graphically represented in Figure 6.3.

Table 6.15 Biogas composition (% by volume) of cattle market rice straw showed in different days after charging.

Biogas	**10 days**	**15 days**	**30 days**
CH_4	74.18	74.92	62.50
CO_2	25.82	25.08	37.20
H_2S	0.00	0	0
CO	0.00	0.0005	0.004
O_2	0.00	0	0.30

On the 10th and 15th day the yield was around 75% CH_4. On the 30th day with little feedstock the digestion was hindered and the methane percentage was reduced (62.5%).

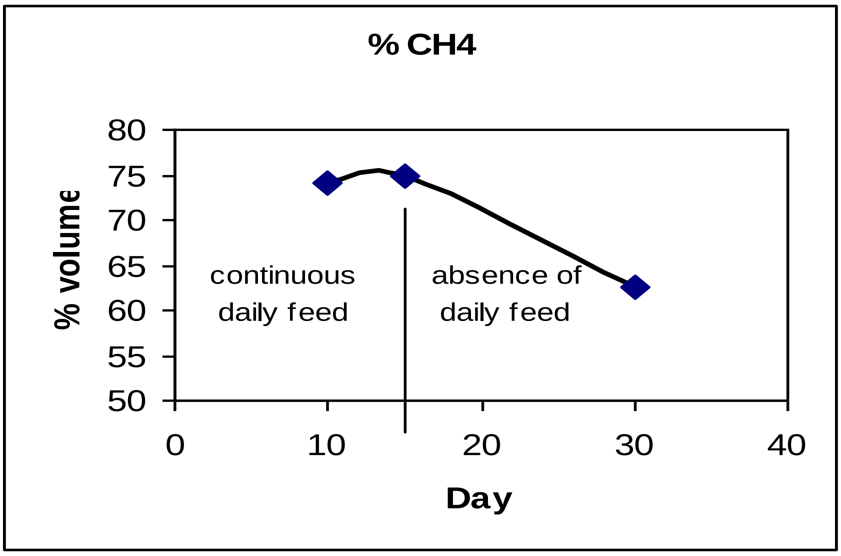

Figure 6.3 Percent methane on different days after charging.

For the reactor in the mesophelic range, the usual time of regeneration of the acedogenic anaerobic bacteria is 2 days, clostridia 2 - 3 days, acetogenic 4 - 5 days and the methanogenic bacteria 5 - 16 days (Cooper, 2010). In the absence of daily charge due to the variation of bacterial activities inside the digester causes impact on biogas and methane yield. At the early stage it could be a small rise in methanation and hence methane yield, but this would soon decline. For example, 10 days after there would have been very little microbial activity going on because the bacteria would have died off rapidly as soon as the reserve of substrate was used up in the reactor. Hence by 15 days the regeneration of methanogenic bacteria will be near a complete stop or very slow and in 20 days it may be a dead reactor. Consequently, by the 30th day after the initial charge (15 days without daily charge) methane yield reduced significantly. This change in composition is understood in terms of the process going on. Thus the existing data is a well explained and published idea which also confirms that it is appropriate to use the peak value observed in future calculation.

6.2.3 Composition of digestate

Digestate is an important product of the AD process and can be used as a soil conditioner. In order to conduct a whole Life Cycle Assessment the composition of digestate was also studied. Table 6.16 shows the nutrient percentage of cow dung and poultry litter digestate from a secondary source (Islam, 2006). Nitrogen, phosphorus, potassium, sulphur, calcium, magnesium and zinc is higher in poultry digestate compared to cow dung digestate and the organic matter percentage is higher in dung digestate compared to poultry digestate.

Table 6.16 Composition of dung and poultry digestate in % weight (Islam, 2006).

Nutrients in percentage	Cow dung digestate	Poultry digestate
Nitrogen (N)	1.29	2.73
Phosphorus (P)	2.8	3.29
Potassium (K)	0.71	0.85
Sulphur (S)	0.61	1
Calcium (Ca)	1.42	4.5
Magnesium (Mg)	0.66	2.52
Zinc (Zn)	0.06	0.071
Boron (B)	0.069	0.041
Organic Matter	26.04	21.58

This data will be considered in the LCA calculation presented in chapter 8. Data on cattle market rice straw digestate composition was not available for Bangladesh and hence is not mentioned here. Primary data on this parameter was not investigated because this research emphasized the potential AD energy capacity and LCA of AD which is related to biogas yield and composition. Moreover, digestate did not impact on GWP in its life cycle assessment. This is why further work on digestate was not done in this research.

6.2.4 Energy capacity

Due to the variation of biogas yield rate and methane percentage of different feedstock the energy capacity of different feedstock were different. Variation was also observed between the result of this experiment and the Grameen Shakti manual's based yield energy capacity.

Table 6.17 Energy capacity (MJ) of 1 kg of feedstock

	Energy capacity MJ/kg feedstock	
Feedstock	**This work**	**GS**
Cattle dung	0.46	0.81
Poultry litter	0.47	1.68
Rice straw	2.69	5.97 (Kalra, 2003)

Considering the yield rate of Grameen Shakti for dung and poultry manure and the yield rate of this experiment, the potential energy capacity of 1 kilogram dung, poultry and dung mixed rice straw feedstock is 0.80, 1.70 and 2.70 MJ respectively. The energy capacity was determined using the following formula.

Energy (MJ) = Biogas yield (m^3/kg FS) x % Methane (by volume) x D (kg/m^3) x CV

Here, D = Density of methane is 0.6565 (at 25^0 C) kg/m^3 and caloric value (CV) of methane is 55.6 MJ.

From this section on energy capacity, it can be concluded that the energy capacity of rice straw feedstock is higher than the same amount of dung or poultry litter feedstock.

6.3 Discussion of factors affecting biogas yield

According to this research's findings the biogas yield of cattle dung, poultry litter and cattle market rice straw is 0.021, 0.021 and 0.099 m^3/kg of feedstock. The biogas production rate according to the Grameen Shakti manual is 0.037 and 0.071 m^3/kg of feedstock for dung and poultry litter respectively. It clearly shows that the biogas yield is significantly less compared to the Grameen Shakti published data. This might be due to some operational factors and other general factors affecting biogas production. These factors will be discussed in more detail in this section.

6.3.1 Feedstock quality and amount of feedstock

The daily quantity of manure added must be sufficient, if too much or too little is added, very little or no gas will be produced as the bacteria does not have sufficient time to break down the manure. Under-feeding is the most commonly cited problem in rural Bangladesh (Gofran, 2010). Due to under-feeding and irregular feeding biogas yield was significantly less in dung and poultry based AD systems. Feedstock constituent also can cause a significant impact on biogas production. These were also noticed in this research during the survey.

From the 11 domestic biogas plants visited in this research it was found that only one plant (out of 11) was fed according to the required rate of feedstock. It means about 91% of biogas plants remain underfed. This result was justified by another survey result that was conducted by the Institute of Sustainable Development (2010) on a number of AD plants in Bangladesh. It was found that 83% of the plants were underfed with 50% of the plants receiving less than half of their required dung. According to the survey, under-feeding usually occurs when the biogas plant owners sell a cow after the biogas plant is constructed. In most of the cases lack of proper training is an important reason of under or improper feeding (i.e. excessive water/dung ratio). Other malfunctions were caused by poor workmanship or sub-standard construction materials (ISD, 2010). Proper mixing of slurry is also an important factor for proper bacterial activity. Occasional stirring is required to help mix the manure which will accumulate gas and prevent the forming of crust (cow dung) or slurry (poultry manure) in the digester chamber.

Another factor that might affect biogas production severely is the quality of the feedstock. In this result biogas yield of poultry litter was 0.021 m^3/kg of feedstock whereas the GS manual biogas yield rate is 0.071 m^3/kg of feedstock. It shows that the present yield rate is only one-third in comparison to the GS manual biogas yield rate. This was due to the composition of animal food. During the survey it was observed that the experimental poultry AD farmer used to feed poultry food mixed with crushed mussel’s shell which is rich in calcium. They do this to make the egg shells hard and increase egg production. Crushed mussel’s shells cause a compact layer inside the digester and affect bacterial activity and reduce biogas production in the long run.

6.3.2 Hydraulic Retention Time (HRT)

Suitable fermenting and breaking down time of manure is between 40 - 60 days. Grameen Shakti defines in its Biogas Technology Guide the retention time (duration that slurry should remain in the digester) required in agricultural digesters as 40 - 45 days. The mean retention time is approximated by dividing the digester volume by the daily influent rate. Depending on the vessel geometry, the means of mixing, etc., the effective retention time may vary widely for the individual substrate constituents. Selection of a suitable retention time thus depends not only on the process temperature, but also on the type of substrate used.

If the retention time is too short, the bacteria in the digester are "washed out" faster than they can reproduce, so the fermentation practically comes to a standstill. This problem rarely occurs in agricultural biogas systems. The retention time of liquid cow manure is 20 - 30 days, liquid pig manure 15 - 25 days, liquid chicken manure 20 - 40 days and the animal manure mixed with plant material 50 - 80 days (GTZ, 2007). The required retention time for completion of the AD reactions varies with differing technologies, process temperature, and waste composition. The retention time for wastes treated in a mesophilic digester range from 10 to 40 days. Lower retention times are required in digesters operated in the thermophilc range. A high solids reactor operating in the thermophilic range has a retention time of 14 days (personal communication with Gofran, 2010).

This research showed that the biogas yield was comparatively higher for cattle market rice straw feedstock than other two animal manures and the HRT of dung mixed rice straw was 15 days. Similar research was done using dung with an aquatic plant; Pistia stratiotes. It showed that the mixture of pistia stratiotes and cow dung (1:1) gave a biogas yield of 0.62 m^3/ kg TS. CH_4 percentage was 76.8%, and HRT 15 days (Zennaki et al. 1998).

The above discussion means that the hydraulic retention time has a vital role in biogas and methane production.

6.3.3 Temperature

The temperature factor is a critical value in the beginning of methane formation. The methanogens are inactive in extreme high and low temperatures. Once metabolism occurs exothermic reaction is helpful for methane production. In case of mesophilic digestion, the temperature range should be maintained between 37 to 42°C. Satisfactory gas production takes place in the mesophilic range, the optimum temperature being 37°C. Therefore, in cold climates the temperature of the digester area should be raised up to 37°C. Gas production can be increased significantly up to 55°C beyond which the production falls because of destruction of bacterial enzyme by elevated temperature. Thus, in case of thermophilic digestion, it should be between 45 to 55°C. On the other hand, when the ambient temperature goes down to 10° C, gas production virtually stops.

According to the Meteorological Department of Bangladesh (2010), the average minimum temperature of Bangladesh varies from 13°C to 26°C and the average maximum temperature is between 26°C to 34°C (Figure 6.4). Though it was called the mesophilic condition of an AD process, the temperature inside the digester remains at 20 - 25°C (Gofran, 2010). Temperature variation occurred due to the seasonal variation.

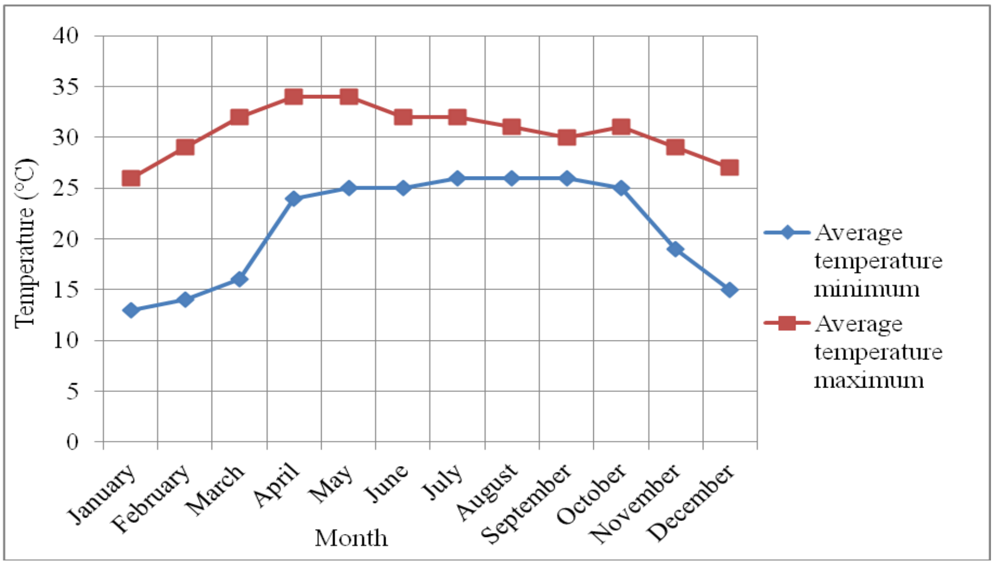

Figure 6.4 Average minimum and maximum temperature of Bangladesh (BMD, 2010).

The effective temperature for bacteria to grow is 37°C. If higher or lower than suggested the bacteria will not develop, decreasing gas production. For example less gas will be produced in summer or winter. It has been observed that higher temperatures in the thermophilic range reduce the required retention time (National Renewable Energy Laboratory, 1992).

In conclusion temperature plays an important role in biogas production and is also linked with HRT. For example, Zeeman (1991) found that there is limited knowledge and a lack of experience concerning psychrophilic digestion, but it is clear that lower temperatures need a longer HRT to achieve a similar gas production. Singh and Sooch (2004) mention Deenbandu biogas plant (fixed dome) operating in Punjab India at 25^{o}C with 40 days HRT. Hence, temperature influence HRT and biogas yield and HRT is directly linked with digester size. This is why temperature causes impact on life cycle assessment.

Sensitivity Analysis of Temperature on Biogas production

The process of bio-methanisation is very sensitive to changes in temperature. The degree of sensitivity, in turn, is dependent on the temperature range. Brief fluctuations not exceeding ± 1°C/h may still be regarded as un-inhibitory with respect to the process of fermentation. For example, a sudden fall in the slurry temperature by even 2°C may significantly affect bacteria growth and gas production rate (Lagrange, 1979). Furthermore, Methanogenesis bacteria are inactive in extreme high and low temperatures; thus the optimum temperature is 35°C (Lund *et al*, 1996).

The case of Tongliang in China is an example of biogas production at different temperatures. The daily production rate of biogas during winter (6 - 10°C) is 0.05 m^3; spring (16 - 22°C) is 0.1 - 0.2 m^3 and summer (22 - 23°C) is 0.2 - 0.33 m^3 (Daxiong et al, 1990). It shows in Table 6.18 how sensitive is temperature on biogas production and it cause impact on GWP finally.

Table 6.18 Sensitivity analysis of temperature variation on biogas yield and GWP

References	**Temperature**	**Biogas yield (m^3)**	**GWP (kg CO_2 equivalent)**
GS, 2009 (Bangladesh)	20°C	0.037	6
Daxiong, 1990 (China)	6 - 10°C	0.05	8
	16 - 22°C	0.15	23
	22 - 23°	0.26	39

6.3.4 Total solid (TS) and Organic Loading Rate (OLR)

Total solid and organic loading rate of feedstock has an important effect on biogas and methane production. The amount of fermentable material of feed in a unit volume of slurry is defined as solid concentration. Ordinarily 7 – 9% solids concentration is best suited (Zennaki et al., 1996). Baserja (1984) reported that the process was unstable below a total solids level of 7% (of manure) while a level of 10% caused an overloading of the fermenter.

It means TS and OLR are two important parameters that can affect biogas yield. In this research it was observed through the irregular application of feedstock and improper mixing of water with manure which influence the % TS of mixed slurry.

6.3.5 Other factors

There are a few more factors which can influence biogas production and the amount of methane directly or indirectly e.g. chemicals, leak from the digester, the C/N ratio and pH of feedstock. This research didn't investigate those factors. During data collection digester and gas pipe leak was found in case of two AD plant.

6.4 Conclusion

From the above result and discussion on anaerobic digesters, biogas parameters and factors can affect biogas yield. This chapter can be concluded as follows.

For AD plants

Biogas and methane yield are severely affected by initial and daily charge (feedstock) application, % TS of feedstock and mixed slurry. Fixed dome and floating dome: two types of biogas digesters are in operation in Bangladesh.

For biogas parameters

The biogas yield of dung, poultry and cattle market rice straw was 0.021, 0.021 and 0.099 m^3/kg of feedstock. This rate is significantly lower compared to the GS manual yield rates reported elsewhere. The reason was the improper management or poor management of biogas plants. Energy capacity as well as the biogas and methane yield is higher in cattle market rice straw compared to animal manures dung and poultry litter.

Biogas and methane yield vary with different feedstock AD facilities. Both parameters are accountable for the carbon footprint of anaerobic digestion. Methane yield of cattle dung, poultry litter and cattle market rice straw based biogas plants were 59.9%, 61.6% and 74.4% by volume respectively. In addition a few factors were identified that affect biogas production: amount of feedstock, % TS, temperature and HRT.

Chapter 7

Countrywide Anaerobic Digestion potential

7.0 Introduction

An aim of this thesis was to find out the anaerobic digestion (AD) potential for Bangladesh for the current and prospective feedstocks. Earlier chapters determined the common AD facility types potentially available for Bangladesh and their AD energy parameters. In order to determine the countrywide AD potential it is important to consult with respective government and non government institutes to scale up the survey results. During the scaling up process, data and information was collected whenever necessary from the Government Department of Livestock Services (DLS) Bangladesh and District Livestock Office (DLO) in Gazipur. Scaled up results has provided an indication of the AD potential of Bangladesh with the potential AD plant size. AD plant building materials are the main constituent of the financial involvement of AD. AD plant size estimation and financial involvement of AD provide a practical idea on AD systems. Determining the whole country’s AD potential from a representing district of Bangladesh helps to identify some scenarios suitable for rural people. Determining the most likely common scenarios could be domestic, community and commercial based AD plants. Scenarios are based on feedstock, plant size and sharing the gas to the adjacent household. Digester sizes and their required building materials are also important parameters for life cycle assessment. The objective of the chapter is to look at the AD energy potential of the country.

7.1 Background of scaling up

The Division of Livestock Services in Dhaka and District Livestock Office in Gazipur are the offices which hold data and information on poultry and livestock numbers in the country and the district respectively. Relevant information and data was collected through interviews and telecommunication with key personnel within those organizations.

Information from several different organizations was collected for comparison in order to get consistent data, and is summarised in Table 5.1 of Chapter 5. It was emphasised in consideration of the Government data and the consistency of data resources. This was done to allow the scaling up of the survey results to find out the countrywide AD potential in a realistic way. As mentioned in the overview part of the methodology, calculation would later be done to observe some specific uses of biogas energy.

Data on the total smallholding/farm animal population of both district and Bangladesh were collected from the Government Livestock Department as mentioned above. The number of domestic cattle, poultry birds and cattle markets was collected from that source as secondary data, and is summarised below in Table 7.1.

Table 7.1 Present status of 3 farm feedstocks (number of cattle, poultry and cattle markets of the district Gazipur and country Bangladesh according to two government sources (DLO-District Livestock Office DLS- Division of Livestock Service).

Area	**Number of cattle (million)**	**Number of domestic cattle (million)**	**Number of Poultry birds (million)**	**Number of Cattle markets**	**References**
Gazipur	0.86	0.74	24.82	30	DLO, Gazipur, 2010
Bangladesh	22.97	20.67	221.39	500	DLS, Dhaka, 2010

The total number of cattle in Bangladesh was 22.97 million whereas the domestic cattle were 20.67 million which was considered in this research as the total cattle population. This was because of the commercial dairy cattle were not considered during the smallholding survey.

7.2 Results of Country AD potential

This section will describe the AD potential of cattle smallholdings, poultry farms and cattle market rice straw according to their size categories. In the section 7.3 the countrywide AD potential by integrating the AD capacity of those feedstocks will be discussed.

7.2.1 Cattle

The total number of domestic cows in Gazipur was 743,680, and the data was provided by the Gazipur District Officer (DLO, Gazipur, 2009) and in the whole of Bangladesh is 20,673,000 (DLS, Dhaka, 2010) (see Table 7.2). The available total energy from cows is the number of cows times 8.1 MJ/cow (chapter 5). The potential for deployment of AD follows from Table 7.2. In Bangladesh, using cattle dung feedstock there is potential for 0.67 million small AD plants (< 2 m^3), 1.34 million domestic AD plants and 0.30 million medium AD plants with typical biogas yields of 1.5, 3 and 11 m^3 respectively (calculation is given in section 4.4.3 of chapter 4). Grameen Shakti already has standard 3 m^3 and 14 m^3 AD biogas units designed and available for the cattle sector. A total number of 2.31 million AD units of different sizes are feasible for the cattle sector of Bangladesh. According to the SNV survey (2005) Bangladesh has the potential of 3 million domestic biogas plants for cattle dung. Increasing the cattle number of bigger smallholdings and decreasing the cattle number of smaller smallholdings might be the reason for a lower number in AD potential. The possible reason and its effect are explained in section 5.2.1 of chapter 5 because it was also a prediction in that chapter of this thesis.

Table 7.2 Scale up of cattle sector energy pattern of Bangladesh.

Region	Gazipur	Bangladesh	Derived Outcome From Cattle Survey (this chapter)		
Number of cows	743,680	20,673,000			
Total Energy. MJ	6,015,996	167,234,130	Average		
AD Type (m^3)	Number of smallholding	Number of smallholding	Cow/ smallholding	MJ/ smallholding	AD Type m^3
Small domestic (< 2)	24,113	670,301	3.5	29	1.3
Domestic (2 - 5)	48,226	1,340,602	7	57	2.6
Medium (5 - 25)	10,809	300,480	28.6	232	11
Total	83,148	2,311,382			

7.2.2 Poultry

Based on the outcome of this survey and the reported number of birds in Gazipur District (DLO, Gazipur, 2009) as well as in the whole of Bangladesh (DLS, Dhaka, 2010), the results for the potential deployment of AD using poultry litter as a feedstock are shown in Table 7.3. For Bangladesh, there is potential for 4,400 domestic AD plants, 40,000 medium AD plants and 18,800 large AD plants with typical biogas yields of 4, 12 and 60 m^3, respectively. A total number of 63,000 different sized AD systems are feasible for the poultry sector of the country.

Table 7.3 Scale up of poultry sector energy pattern of Bangladesh

Region	Gazipur	Bangladesh	Derived Outcome From Poultry Survey (this chapter)		
Number of Birds	24,823,020	221,390,000	Average Values		
Total Energy. MJ	4,180,197	37,292,592			
AD TYPE (m^3)	Number of farm	Number of farm	Bird/farm	MJ/farm	AD TYPE m^3
Domestic (2 – 5)	494	4,403	572	93	4
Medium (5 – 25)	4,443	39,628	1614	270	12
Large (25 – 150)	2,116	18,871	8,305	1,399	59
Total	7,053	62,902			

Grameen Shakti already has standard 3.2 m^3 and 14 m^3 AD biogas units designed and available for the poultry sector. The country should look to develop large AD systems with the minimum capacity to produce 60 m^3 of biogas daily as this clearly shows the potential use for them. The outcome of the survey carried out suggests that these large facilities carry the potential for generating 64% of the energy available from poultry sourced feedstock.

7.2.3 Cattle market rice straw

There are 30 cattle markets in Gazipur and 500 cattle markets in Bangladesh (DLS, 2010). The cattle markets were divided into two categories according to biogas yield capacity. Average cattle of 390 per market was categorised as large and 1,150 as an extra large sized market. Results show that the average cattle number for large markets is 390 which produce a huge amount of rice straw feedstock hence the facility size needed is not domestic or medium but only large and extra large. Results indicate that a current large sized AD facility has the capacity to produce 1,350 m^3 of biogas daily and the extra large sized facility can produce 4,000 m^3 of biogas daily. In the whole of Bangladesh there are 500 cattle markets and their waste can produce about 35,000,000 MJ of energy through AD, with an average AD capacity from each cattle market of 70,000 MJ.

Table 7.4 Scale up of cattle market rice straw sector energy pattern of Bangladesh

Region		**Gazipur**	**Bangladesh**	**Derived Outcome From Survey (this chapter)**		
Number of Cattle markets		30	500			
Total Energy (MJ)		2098430	34973819	Average Values		
AD TYPE	Biogas m^3	Number of Cattle markets	Number of Cattle markets	Average cattle/market	Average MJ/market	AD TYPE m^3
Domestic/ Medium		0	0			
Large	1000 – 2000	16	265	390	36750	1350
Very Large	2000 – 7000	14	235	1150	108000	4000
Total		30	500		72,375	

The potential biogas energy from cattle market rice straw in Bangladesh is 35 x 10^6 MJ (35 TJ). This energy is equivalent to 35 x 10^6 x 0.2778 KWh or 9.723 x 10^9 Wh. From this calculation the biogas energy efficiency of a large and extra large sized rice straw based anaerobic digestion plant can be of a significant amount. Considering the cooking and lighting energy consumption of a family, this amount of energy can meet the energy requirement of a substantial number of people. It is also feasible to use for small to medium industrial needs. Generally the cattle markets take place in rural and urban areas of Bangladesh. Therefore this energy can play a vital role for the rural community.

It has been observed globally that renewable energy technologies are economically viable for distant rural electrification programs which upgrade the living standards of the rural people. The majority of energy-starved households are located in rural areas (Legros et al., 2009; World Bank, 2008). A large portion of the remote areas are not likely to be covered by the grid network due to inaccessibility and low customer density. Cattle market based biogas technologies could be considered viable alternatives for remote off-grid areas. The impact of the rural electrification in Bangladesh will be very large especially in the health care, education, family planning as well as female development and employment.

7.3 Countrywide AD potential

From the calculations above for Bangladesh, the potential available energy from AD biogas generation from the different sources is summarised in Table 7.5 and the feedstock contributions to AD presented graphically in Figure 7.1. An AD facility type with potential size distribution has been presented in chapter 5. This Chapter will emphasize the presentation of the total country AD potential and its possible contribution to the community.

The daily energy requirement for cooking purposes of a family in Bangladesh is 44 MJ of energy (Table 5.1, Chapter 5). According to this cattle smallholding is very feasible for domestic cooking. But the majority of poultry farms have a potential for medium AD systems with a capacity to generate 270 MJ of energy daily. This amount of energy is enough for 6 rural families. It implies that a number of families can benefit from an average sized poultry based AD system with a community based programme. As mentioned though, there are only 500 cattle markets in the country. These would power small electricity installations that could benefit education or small industry.

Table 7.5 The potential available energy contribution for cooking of AD biogas generation from the different sources.

	Energy Million MJ					
	Cattle	**Poultry**	**Rice straw**	**Total**	**Energy needed for cooking**	**Contribution for domestic cooking (%)**
Gazipur	6.02	4.2	2.1	12.3	19.8	62
Bangladesh	167	37	35	239.5	1325	18

The potential biogas energy from cattle smallholdings, poultry farms and cattle market rice straw in Bangladesh is 240 x 10^6 MJ (240 terajoules, TJ). This amount of energy is derived from 10.4 x 10^6 m^3 of biogas daily (1 m^3 biogas = 23 MJ energy). This energy is equivalent to 240 x 10^6 x 0.2778 KWh or 6.67 x 10^{10} Wh. The individual total potential contributions of cattle smallholdings, poultry farms and market rice straw feedstock is 167, 37, 35 million MJ respectively. These indicate that cattle smallholdings share 70% of the total AD capacity and poultry farms and cattle market rice straw contributes 16% and 14% of respectively. This energy (240 million MJ) is suitable for the cooking energy requirements of 30 million people in Bangladesh which is one-fifth of the total population of Bangladesh.

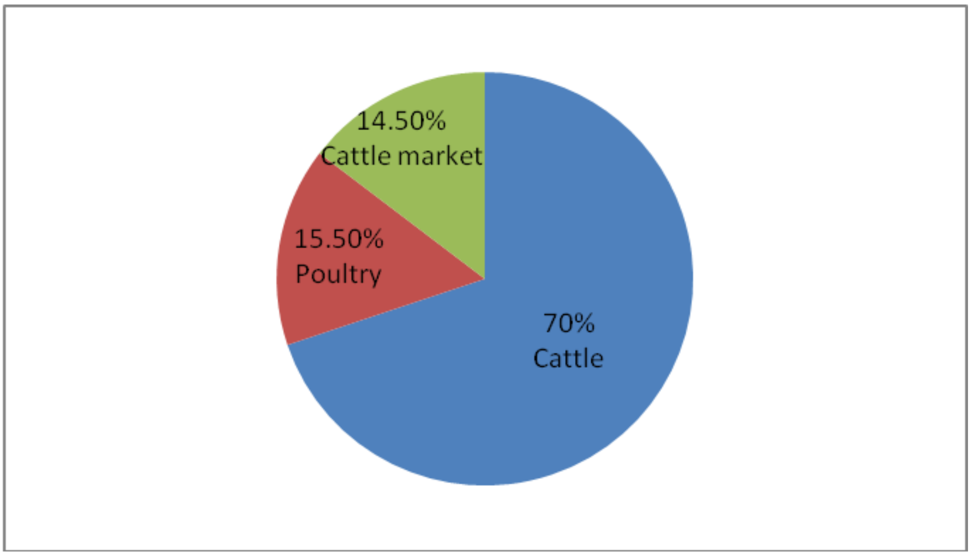

Figure 7.1 Percent (%) contribution of three potential AD feedstock in Bangladesh

Figure 7.1 shows the total AD energy derived from cattle is higher than any individual feedstock: cattle dung or poultry litter.

An average sized cattle market rice straw AD system can produce 72,375 MJ of energy. This amount of energy is equivalent to the energy derived from around 1000 cattle smallholdings with domestic cow dung fed AD or 120 poultry farms with medium poultry litter fed AD (Table 7.6).

Table 7.6 An AD size analysis of 3 farm feedstock AD systems.

Energy MJ	**Energy equivalent**	
1 cattle market	**Cattle smallholding**	**Poultry farm**
Rice straw	Domestic, 3 m^3	Medium, 12 m^3
72,375 MJ	1,000 unit domestic	120 unit medium

The results show that the energy derived from the three greatest potential feedstocks can contribute toward the energy requirement of a large portion of the population in Bangladesh. Especially, rural people would benefit from the AD energy facilities who are the main victims of the energy crisis of the country. Other than this, Bangladesh produces a significant amount of household waste, municipal solid waste, crop residue, water hyacinth, tannery waste and sewage sludge which are the prospective AD feedstocks for AD in Bangladesh. This amount of waste also has a capacity to produce a notable amount of energy through AD. Results of this research show that the biogas yield of combined feedstock is higher compared to individual animal manure feedstock. Having different feedstock facilities in Bangladesh, rice straw waste mixed with animal manure biogas production rate is the highest compared to other single AD feedstock.

From the above discussion it can be conclude that the countrywide AD potential could be improve utilizing all possible feedstock and technologies. There is a huge scope of further work on AD and AD feedstock. For example, determination of the combination of feedstock uses for biogas production and assess their biogas and methane yields.

7.4 Detailed concept of 3 representative sized AD digesters

Results show that the energy capacity of an average sized dung, poultry and rice straw AD plant are 72, 562 and 72,375 MJ respectively. The proposed digester size of those three feedstocks is shown in Table 7.7.

Table 7.7 Biogas yield and energy capacity of an average sized dung, poultry and rice straw based biogas plant in Bangladesh (Averaged across all categories: domestic, medium and large)

	Cattle smallholdings	**Poultry farms**	**Cattle market rice straw**
Biogas energy capacity			
Average animal numbers of a farm	9	3520	796
Feedstock (kg)	90	352	27,860
Biogas (m^3)	**3**	**25**	**2,758**
Energy capacity (MJ)	72	562	74,500

From this result three different sizes of biogas digester could be recommended for three feedstocks according to their biogas yield capacity. To produce 3 m^3, 25 m^3 and 2750 m^3 of biogas from cattle dung, poultry litter and cattle market rice straw the plant sizes needs to be 9 m^3, 53 m^3 and 7000 m^3 (Table 7.8).

Table 7.8 Digester volume of an average sized dung, poultry and rice straw based biogas plant in Bangladesh

Digester size	**Cattle smallholdings**	**Poultry farms**	**Cattle market rice straw**
Animal manure (kg)	90	352	27,860
Water added (Lit/kg)	90	704	111,440
Daily mixed slurry (kg)	180	1056	139,300
Total mixed slurry (kg) (HRT=40 days)	8100	47520	6268,500
Volume of mixed slurry (m^3)	8	48	6,269
Additional 10% free space	1	5	627
Digester volume (M^3)	**9**	**53**	**6,895**

According to Grameen Shakti, the equipment and labour cost of a domestic (up to 5 m^3) biogas plant is 20,000 TK (£200) to 60,000 TK (£600) and a medium sized AD plant cost is 250,000 TK (£2500). The cost of different sized biogas plants is shown in Table 7.9. There is no price list for large or extra large biogas plants as none currently exist in Bangladesh.

Table 7.9 Cost of different yield capacity biogas plants in Bangladesh (Gofran, 2011).

Biogas yield capacity (m^3)	Total cost (Taka)	Total cost (£)
1	20,000	200
2	30,000	300
3	**40,000**	**400**
4	50,000	500
5	60,000	600
20	200,000	2000
25	**250,000**	**2500**

This means the recommended cattle dung 3 m^3 AD plant will cost £400 and poultry based 25 m^3 AD will cost £2,500. Considering the present financial status of Bangladesh the establishment of domestic sized biogas plant might be affordable but cost will be a barrier to developing bigger facilities. The biogas beneficiaries could take the initiative to build those medium sized plant as a community based AD system.

Table 7.10 Percent energy contribution of three feedstock based on AD plant size.

Feedstock	**Potential AD energy capacity (%) in different sizes and types of feedstock**						
	Small domestic (<2m^3)	**Domestic (2-5 m^3)**	**Medium (5-25 m^3)**	**Large (25-150 m^3)**	**Very large (>150 m^3)**	**Total (million MJ)**	**% contribution**
Cattle	12	46	42	0	0	167	70
Poultry	0	1	29	70	0	37	16
Cattle market rice straw	0	0	0	28	72	35	14
Total						**240**	**100**

Table 7.10 summarises the percentage AD energy contribution of cattle dung, poultry litter and cattle market rice straw with their size distribution (on the basis of yield capacity). Among the categories, cattle smallholdings are suitable for domestic and medium sized plants only which provide 70% of the total potential. Poultry farms contribute 16% of AD energy capacity of which a major portion (70%) comes from large AD and rest of the energy from medium sized AD plants. In practice, the maximum dung and poultry based AD in

Bangladesh is domestic in size and a very few of them are medium sized plants. But this research shows that the prospective AD size is medium to large for cattle and poultry farms. Cattle market rice straw which contributes 14% of AD energy capacity is suitable for large and extra large AD only.

7.5 Consideration of potential uses of the different AD facility types

The motive and size of representative AD plants in Bangladesh from three farm feedstocks is indicated after the result analysis of this research. Three typical potential plant sizes are found after investigation of every individual feedstock. Availability of feedstock, current energy situation and socio-economical impact was considered for categorization of anaerobic digestion. The categories of the plants are domestic, community based (medium) and commercial (large).

7.5.1 Domestic-based AD plants

Results from Chapter 5 showed that 87% of cattle smallholdings are suitable for a domestic sized biogas plant. It means that cattle smallholdings domestic based biogas plants are the main option and individual rural families are the beneficiaries. The energy capacity of those plants is sufficient to meet the energy requirements of a rural family. The results also indicate that, there is the potential for 2.31 million domestic AD plants in Bangladesh from cattle smallholdings. Bangladesh is an agro-based country. According to interviews with SNV, GTZ and Grameen Shakti there are 8.44 million households in Bangladesh that keep 22.29 million cattle/buffalo. From this about 952,000 households keep more than 5 heads of cattle whereas another 2 million households keep 3 - 4 cattle per household. This figure indicates that about 3 million small sized biogas plants are technically feasible from dung only. The range of plant size is 2 m^3- 4.2 m^3 (SNV, 2008). This research shows that the average AD size of a cattle smallholding is 3 m^3 (8 x 10 x 0.037) which is defined as a domestic anaerobic digestion plant. From a domestic biogas plant the primary product is biogas and it is used for cooking mainly and in very few cases used for lighting additionally. Slurry is used as fertilizer in domestic farm management.

The digester construction materials, maintenance and labor costs are the key factor that affect the AD program in rural Bangladesh. This is where microfinance (MF) intervention could overcome a barrier and provide micro-energy loans in order to enable poor households and small enterprises, especially in rural areas, to finance access to energy (Aron et al., 2009; Beck & Martinot, 2004; Urmee et al., 2009). Grameen Shakti also operates a microfinance policy with their biogas program in rural Bangladesh.

Most of the digesters of this type of plant are brick-cement built fixed dome and a few of them are brick-plastic made floating dome types. The infrastructural materials are bricks, cement, iron rods, sand and plastic. There is no embodied energy to be considered for feedstock in this case as the feed stock comes from animal stomachs directly. Embodied energy need to be consider for the anaerobic digester construction. It is an important record to do life cycle impact assessments of the vast potential AD. Eventually it could be an important sector that can work with Clean Development Mechanism (CDM) which allows emission reduction projects in developing countries to earn certified emission reduction (CER) credits (IPCC, 2007).

7.5.2 Community-based AD plants

The results from poultry farms in Bangladesh show that the average sized AD plant is 25 m^3, a medium sized AD plant. 63% of poultry farms are feasible for a medium sized AD plant.

This type of plant is neither beneficial for a single family (domestic) use nor enough for industrial (commercial) use. The best option would be to share the amount of gas in between the village community where 5/6 families live in a cluster in rural Bangladesh. According to an interview with the Chairman of the Bangladesh Biogas Association, less than 1% of poultry farms of Bangladesh have their in ground biogas plants. Out of those only 8% of poultry farms are running their biogas plants using their total potential feedstock. The range of the farms using their total potential varies from 800 birds to 2,000 birds. Farmers having enough feedstock for medium or even larger sized AD plants also have the tendency to build domestic sized plants. For example, all of the poultry farms having more than 5,000 birds are using less than 20% of their potential feedstock for biogas production. It was also found on the Bangladesh visit in 2009 that Grameen Shakti has constructed a biogas plant in a poultry farm of 48,000 birds which is located in Mymensingh district. The aim was to produce electricity for back up during power cuts. The existing capacity of that biogas plant was 70 m^3 which is designed to use the poultry droppings of 10,000 birds only. With the total potential the size would be 340 m^3. That means it is going to use only about 20% of its total potential feedstock.

Bangladesh is one of the most densely populated countries in the world. A large portion of rural people in Bangladesh do not have any poultry farms but have a severe energy crisis. Similarly there are a numbers of rural farmers who have big farms producing a surplus amount of feedstock daily. So, it is very possible and feasible to introduce a community based anaerobic digestion plant to meet the energy needs of neighbouring households. It can be beneficial in two ways. One is the use of potential level of feedstock of a farm to produce the maximum amount of yield and another is to meet the energy requirement of the neighbouring households. It could be medium to large sized plants ranging from 10 m^3 to 340 m^3. A number of farmers can be involved as a cooperative program.

7.5.3 Commercial-based AD plants

Survey results for cattle market rice straw feedstock show that for all the cattle markets, either large or extra large sized plants are feasible. An average sized cattle market can produce 2,700 m^3 of biogas with 72,375 MJ energy capacities from 796 cattle of a cattle market. This amount of energy can be used on a large scale commercial basis. There are about 22.29 million cattle and 500 cattle markets in Bangladesh. On the basis of the cattle population the cattle markets are different in size. According to these results cattle markets were divided into two types: large and very large markets. Average cattle of 390 per market were categorised as large and 1,150 were categorised as very large sized markets. Results show that a large and very large market produces 13.65 and 40.25 tonnes of rice straw feedstock respectively with an average of 28 tonnes. Hence the facility size needed is large and very large. Results from cattle markets indicate that a current large sized AD facility has the capacity to produce 1,350 m^3 of biogas daily and a very large sized facility can produce 4,000 m^3 of biogas daily.

Rice straw is the main food for cattle in the cattle markets in Bangladesh. After eating, a significant amount of straw becomes waste. Normally there is 10-15% of dung mixed with the cattle market rice straw (Jalil, 2010). Thus, rice straw becomes a potential raw material for biogas production. A commercial scale biogas plant is possible integrating 2 - 3 cattle markets waste according to the size of the cattle market. It has multiple benefits where wide ranges of people could be benefit at the same time. It can replace national grid electricity with the hazak light (hazak-locally used lighting device) or with electricity production through generators. Proper utilization of cattle market waste also keeps the market pollution free. This type of plant has a significant commercial value as it causes both energy and financial savings for the community. A large and very large sized biogas plant is feasible in this scenario.

Most of the cattle markets utilize energy from the national grid for their needs. Energy production from cattle markets could meet their own energy requirements as the primary benefit. But in reality it can contribute more with the surplus potential energy. Fuel, power and good quality organic fertilizer make biogas investment a commercially viable venture (IDCOL, 2009). Moreover, economic benefits derived from such large scale biogas plants in terms of fuel and chemical fertilizer savings can have notable impact on the national economy. In the future, the commercial biogas technology is expected to be the driving force for ongoing growth the cattle and poultry industry in Bangladesh.

7.6 Conclusion for this chapter

Currently 55% of rural people in Bangladesh use biomass for their cooking purposes. It is not only an inefficient source of energy but also causes environmental pollution, health hazards, depletion of soil organic matter, deforestation and flood propensity in the long run through green house gas emission. Potential utilization of cattle smallholding, poultry farm and cattle market rice straw AD systems can make a significant contribution to the energy sector in Bangladesh. Especially the ordinary rural people can benefit from this renewable energy. This is justified in this research through the determination of the country’s AD potential.

The potential biogas energy of cattle smallholdings in Bangladesh is 167 x 10^6 MJ. This amount of energy comes from 7.3 x 10^6 m^3 of biogas daily (1 m^3 biogas = 23 MJ energy). This represents 70% of the total prospective AD energy share.

The potential biogas energy of poultry farms in Bangladesh is 37 x 10^6 MJ. This amount of energy is produced from 1.6 x 10^6 m^3 of biogas daily. This represents 16% of the total prospective AD energy. 63% of poultry farms have a potential of medium type AD systems and have the capacity to generate 270 MJ of energy. This amount of energy is enough for 6 rural families. It implies that a number of families can benefit from an average sized poultry based AD system with a community based programme.

The potential biogas energy of cattle market rice straw in Bangladesh is 35 x 10^6 MJ. This amount of energy is produced from 1.5 x 10^6 m^3 of biogas daily. This energy is equivalent to 35 x 10^6 x 0.2778 KWh or 9.723 x 10^9 Wh. The study showed that an average sized cattle market waste AD biogas energy plant can contribute a significant amount of energy to the rural community. This represents 14% of the total prospective AD energy. As mentioned, though, there are only 500 cattle markets in the country; these can power small electricity installations that can benefit education or small industry. An average sized cattle market rice straw AD system can produce 72,375 MJ of energy daily. This amount of energy is equivalent to the energy derived from 1,000 cattle smallholdings of domestic cow dung fed AD or 120 poultry farms of medium poultry litter fed AD. The cattle markets are take place in rural and urban areas of Bangladesh. Therefore this energy can play a vital role in the rural community. The below table shows the country's AD potential from the prospective feedstocks.

Table 7.11 Total potential number of AD plants in different sizes of cattle, poultry and cattle market rice straw feedstock.

Feedstock	Potential number of AD plants in different sizes from different feedstock					
	Too small ($<2m^3$)	**Domestic (2-5 m^3)**	**Medium (5-25 m^3)**	**Large (25-150 m^3)**	**Extra large (>150 m^3)**	**Total**
Cattle	670,000 (29%)	1,341,000 (58%)	300,000 (13%)	0	0	2,311,000 (100%)
Poultry	0	4,403 (7%)	39,628 (63%)	18,871 (30%)	0	62,902 (100%)
Cattle market rice straw	0	0	0	265 (53%)	235 (47%)	500 (100%)
Total	670,000	1,345,403	339,628	19,136	235	2,374,402

The potential biogas energy of cattle smallholdings, poultry farms and cattle market rice straw in Bangladesh is 240 x 10^6 MJ (240 TJ). This amount of energy is derived from 10.4 x 10^6 m^3 of biogas daily (1 m^3 biogas = 23 MJ energy). This energy is equivalent to 240 x 10^6 x 0.2778 KWh or 6.67 x 10^{10} Wh. Energy derived from 3 farm feedstocks can meet the cooking energy requirements of 30 million people in Bangladesh.

A cattle smallholding in Bangladesh is mainly appropriate for a domestic sized AD. An average sized dung based AD plant has 3 m^3 biogas yield capacity and the cost of setting it up is £400. A poultry farm in Bangladesh is suitable for a medium sized AD plant and an average sized poultry AD plant can produce 25 m^3 of biogas daily and the cost is £2,500 (Gofran, 2011). The 400,000 (796 x 500) cattle population of 500 cattle market produce 14,000 tonnes of rice straw waste which is feasible for large and very large sized biogas plants. Such an AD plant is still a vision for Bangladesh and requires enough funds and technologies for its installation.

Funding is one of the most important factors for AD installation because the primary cost of AD is to build a digester. Being a developing country, the AD program is badly affected in

Bangladesh due to this initial cost. Individual or combined participation of government and non-governmental organizations and their modern financial tools (e.g. microfinance) could be helpful for the AD programme in Bangladesh. In addition, the Clean Development Mechanism (CDM) could be a potential source of funding to help develop the AD infrastructure in Bangladesh. There are strict criteria for CDM including clear demonstration of the environmental benefits of the technologies. A life cycle assessment of anaerobic digestion was undertaken as set out in Chapter 8.

Chapter 8

Life Cycle Assessment of anaerobic digestion and GHG mitigation

8.0 Introduction

This chapter will present the environmental impacts of anaerobic digestion of cattle manure from farm-based holdings in Bangladesh from a life-cycle perspective. The results of the evaluation are presented here. For Life Cycle Assessment, the software for analysis used was SimaPro 7 and its Eco-invent database. This chapter will be described in three sections; LCA of a domestic AD facility type, social and economic impacts of AD technology and the scope of AD.

8.1 LCA of a typical AD facility type

A Life Cycle Assessment of a domestic (3.2 m^3) biogas plant was undertaken as it is the most common system operated by Grameen Shakti in Bangladesh. This section will describe (1) the results of the LCA calculations to determine the GWP impact parameter associated with the installation, operation, and end-of-life disposal of a domestic farm-based AD plant, (2) the methods used to quantity the GHG emissions avoided through the use of AD systems, and (3) a discussion on the implications in terms of energy available from AD installations. It will discuss the results as to (1) GWP derived from an AD plant, (2) GWP derived from the AD process using primary and secondary data and (3) discussion of results including application of the data in:

i) Comparison between a domestic (3.2m^3) and medium (25 m^3) cow dung AD plants, ii) comparison between a cow dung and poultry feedstock to a domestic AD iii) comparison between a fixed dome and floating dome digester and (4) discussion of the energy attributes of the biogas.

8.1.1 GWP derived from an AD plant

This section will describe the impact of anaerobic digesters and also interpret the results of the impact assessment.

8.1.1.1 Impact Assessment

The process map, Figure 8.1, is reproduced below with all the non-contributing phases except the production of materials. The phases which do not cause any emission in an AD system are identified as non-contributing phases. The production of materials was considered for environmental impact calculations. The functional unit for this analysis is a 3.2 m^3 brick constructed fixed dome AD plant. The analysis uses the Eco-invent database corrected for Bangladesh production conditions as discussed in Chapter 4. The GWP attributed to materials used to build the AD plant is also shown in the Table 8.1.

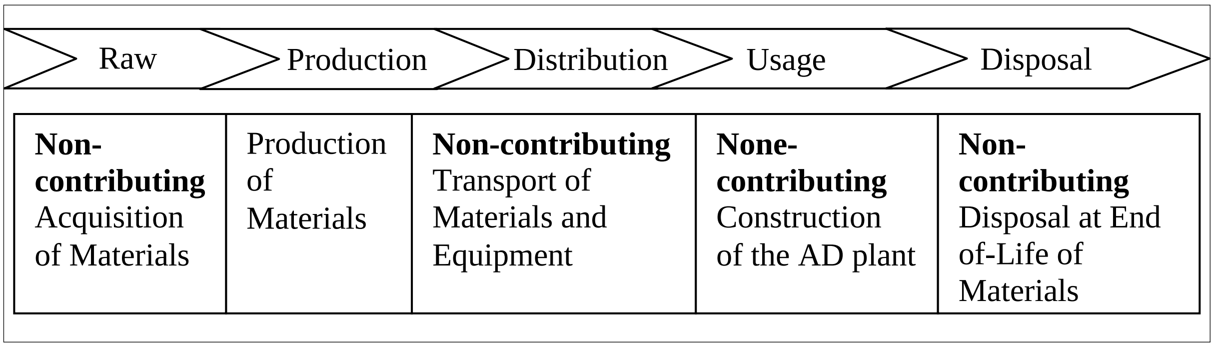

Figure 8.1 Non-contributing phases shown in the AD plant.

Table 8.1 Inventory of materials for 3.2 m^3 AD plant.

Materials	**Amount**	**GWP/unit**	**GWP**
	unit	**kg CO_2 equivalent/unit**	**kg CO_2 equivalent**
Bricks (25x12.5x7.5 cm)	1,747 bricks	0.58	1,019
Brick particle	277 bricks		161
Cement (50 kg bag)	1050 kg	.03250	34
Total			**1,214**

The GWP from materials that principally make up a 3.2 m^3 digester plant is 1,214 kg CO_2 equivalent. This impact comes from fixed dome anaerobic digester materials. The results for the other impact indicators are given in Appendix 1.

8.1.1.2 Interpretation of results

The current designs are small AD structures below the ground and are not heated to maintain the optimum temperature for reactivity. In the future, with larger sized fixed dome ADs more bricks and cement may be needed. The information in Table 8.1 will be useful for future AD designs. A floating dome digester is built with both bricks and plastic materials. For the total GWP of a 3.2m^3 AD system, the contribution from the plant derived from this section will be added to the contribution from the process given below.

8.1.2 GWP derived from an AD process

This section will present the impact assessments of the AD process and interpret the results. Biogas and digestate impact assessment will be done in this section.

8.1.2.1 Impact Assessment

Life cycle assessment of anaerobic digestion in Bangladesh will be described in this section. The process map for AD operation is shown in Figure 8.2 and defines the boundary condition for the LCA analysis of anaerobic digestion. The material manure input is cow dung as AD feedstock. The functional unit for this analysis is the conversion of 1 kg of manure to biogas. Following from Chapter 4, the manure is mixed with water to form slurry and fed into the anaerobic digester. There is no energy required for the operation of a domestic sized AD. The treatment produces biogas as the principal product and a digestate as the secondary product.

There is no further waste or emission. The biogas is used as fuel, mainly for cooking and the digestate as fertiliser.

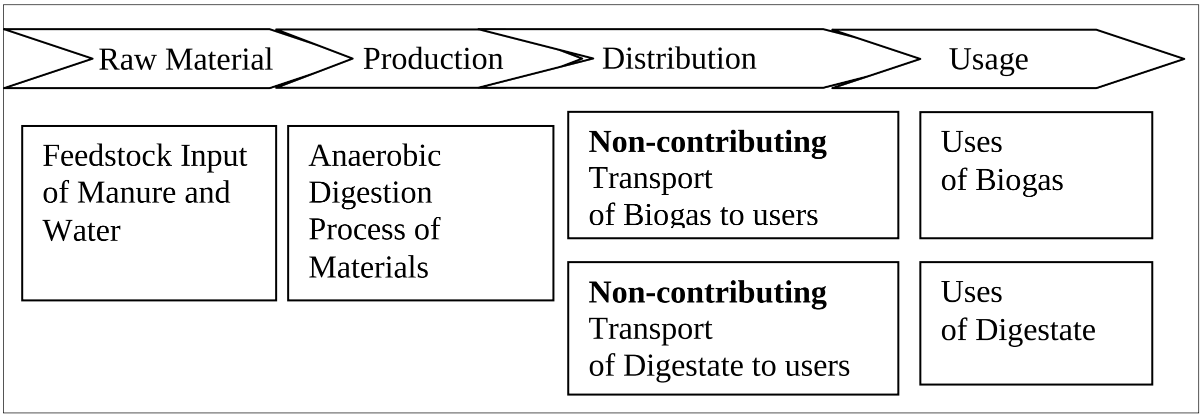

Figure 8.2 Non-contributing phase shown in AD process (3rd step).

Before the operation of an AD plant, it is given an initial charge of slurry to promote the reaction process. The slurry is cow dung mixed with an equal amount of water (1:1). The anaerobic digester is fed the initial charge and after 5 - 7 days the reactor is ready for daily charge once gas starts to be produced (Gofran, 2010). From here, the AD reactor is given a daily feed of slurry to generate the daily supply of biogas.

The data of daily and initial charge of feedstock, biogas yield and composition of biogas, have been presented in Chapter 6. For the LCA study, a common domestic plant size of 3.2 m^3 was selected with an initial charge of 4,000 kg and a daily charge of 87 kg. Although this research investigated the average plant size is 3 m^3 and it comes from 8 cows. Embodied energy is an important issue to be considered for the AD product and process during an LCA. However, this research assessed life cycle impact of a domestic AD plant and its feed is animal dung. The feedstock is considered waste and no embodied energy to be considered here, the embodied energy associated with feeding and upkeep of the cows is assigned to the principal products such as dairy, meat, crop production through tillage, crop harvesting and of transport in some cases in rural areas.

According to Grameen Shakti the biogas yield is 0.037 m^3/kg for dung and the biogas composition is principally CH_4 (60%) and CO_2 (39.90%). By way of comparison commercial natural gas contains 87 - 96% methane and a few other gases like ethane, propane, N_2 and CO_2 (EPA reports, 2007).

SimaPro is a mass-based software. Table 8.2 shows the corresponding conversion to weight of gas per kg of cow dung for input to SimaPro. The conversion calculation is mentioned in appendix 5.

Table 8.2 Corresponding conversion to weight of gas per kg of cow dung.

Biogas	**Density**	**Wt gas/kg dung**	**Wt gas in 87 kg dung**
	kg/m^3	**grams**	**Kg**
CH_4	0.657	16.714	1.454
CO_2	1.811	18.092	1.574
CO	1.145	0.000	0.000
O_2	1.309	0.145	0.013
H_2S	1.410	0.052	0.005
H_2	0.082	0.079	0.007
N_2	1.146	0.051	0.004
TOTAL		**35.133**	**3.057**

It means, the total gas produced from the daily charge (87 kg of dung) is 3.057 kg by weight where methane produces 1.454 kg.

8.1.2.1.1 Impact of Biogas

Environmental impact using the categories in SimaPro CML 2000 was determined for the gases listed in Table 8.3. Gases O_2, N_2 and H_2 have no impacts. Table 8.3 shows the impacts for the gases CH_4, CO_2 and H_2S. CH_4 and CO_2 are greenhouse gases with global warming potential (GWP) of 23:1, respectively. Methane also has a photochemical oxidation impact indicated by kg C_2H_4 equivalent. H_2S does not have any global warming effect but has a 0.22 kg 1, 4-DB equivalent toxicity effect on humans.

Table 8.3 GWP Impacts per kg gas (Using SimaPro).

Impacts per kg of gas				
Impact category	**Unit**	**CH_4**	**CO_2**	**H_2S**
Abiotic depletion	kg Sb equivalent	0	0	0
Acidification	kg SO_2 equivalent	0	0	0
Eutrophication	kg PO_4 equivalent	0	0	0
Global warming (GWP100)	kg CO_2 equivalent	23	1	0
Ozone layer depletion (ODP)	kg CFC-11 equivalent	0	0	0
Human toxicity	kg 1,4-DB equivalent	0	0	0.22
Fresh water aquatic ecotox.	kg 1,4-DB equivalent	0	0	0
Marine aquatic ecotoxicity	kg 1,4-DB equivalent	0	0	0
Terrestrial ecotoxicity	kg 1,4-DB equivalent	0	0	0
Photochemical oxidation	kg C_2H_4 equivalent	0.006	0	0

Using the process map in Figure 8.2, for material feedstock input of 87 kg of dung there is no embodied energy associated with dung as it is considered waste, no extraction or embodied process due to water as it is taken from the nearby pond or tube well and the mixing of dung and water is done manually. GWP from material and resource input into the AD process is zero; GWP from raw material is also zero.

For the digestion itself, the reaction proceeds in the mesophilic regime without any source of added heating. The GWP from supporting the reaction process is zero; the GWP for the actual reaction is also zero. The AD process produces two products: the biogas and the digestate. The impact due to the biogas is calculated as follows.

Table 8.4 The GWP of per kg dung

Biogas	**GWP (from Table 8.3)**	**Wt gas/kg dung (from Table 8.2)**	**GWP/kg dung**
Gas	**Kg CO_2 equivalent/kg gas**	**grams**	**Kg CO_2 equivalent/kg dung**
CH_4	23	16.71	0.38
CO_2	1	18.09	0.02
CO	0	0.00	0.00
O_2	0	0.15	0.00
H_2S	0	0.05	0.00
H_2	0	0.08	0.00
N_2	0	0.05	0.00
TOTAL			**0.403**

The GWP per unit kg of dung is 0.403 kg CO_2equivalent. The initial charge is the amount of dung added at the start of life of the digester to activate the reactions. For a 3.2 m^3 digester this is 4000 kg. The GWP due to the initial charge is 1.61 tonnes CO_2 equivalent.

The daily charge is the amount of feedstock added every day to maintain the operation of the digester. For a 3.2 m^3 plant, this is 87 kg so a daily biogas production yielding a GWP of 35.0 kg CO_2 equivalent.

Assuming a lifetime of an AD plant is 10 years and for a lifetime yield production required lifetime dung =daily x 365days/year x 10years =317550 kg. This gives a GWP of 128 tonnes CO_2 equivalent. The total impact is the sum of contribution from the initial charge and lifetime charge. The GWP impact due to the biogas for a 3.2m^3 plant operating for 10 years is 130 tonne CO_2 equivalent (including impact of initial charge). The data is summarised in Table 8.5 below.

Table 8.5 Life time (10 year) impact of the main output of a 3.2 m^3 dung based biogas plant (before methane combustion)

Impact category	Unit	Initial charge	Daily charge	Lifetime charge	Total
Weight of dung	1 kg	4 tonnes	87 kg	317.55 tonnes	321.55 tonnes
Global Warming Potential (GWP-CO_2 equivalent)	0.403 Kg	1.6 tonne	35.0 kg	128 tonne	130 tonne

The methane rich biogas is used as fuel for cooking thus converting methane to CO_2. Assuming 100% conversion, each molecule of methane is converted to a molecule of CO_2. For every molecule of methane burned, a molecule of CO_2 is produced.

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_20$$

The weight of CO_2 evolved per molecule of methane oxidised is given in Box 1 and 2 of appendix 5. For a daily amount of 1.27 kg methane produced, 3.99 kg CO_2 is produced.

Table 8.6 shows the global warming saving through the use of biogas in combustion where the GWP attributed to biogas used drops from 0.40 kg CO_2 equivalent/kg dung to 0.064 kg CO_2 equivalent/kg dung.

Table 8.6 GWP per kg of dung before and after combustion of methane.

	Biogas	**GWP (from Table 5.12)**	**Wt gas/kg dung (from Table 5.11)**	**GWP/kg dung**
	Gas	**kgCO_2eq/kg gas**	**grams**	**kgCO_2eq/kg dung**
Before Combustion	CH_4	23	16.71	0.38
	CO_2	1	18.09	0.02
After Combustion	CH_4	23	0	0
	CO_2	1	18.09 + 45.95 (16.71x2.75=45.95)	.064

This table indicates that the life time (10 year) GWP impact of a 3.2 m^3 biogas plant before combustion of methane is 130 tonnes CO_2 equivalent but it goes to only 21 tonnes of CO_2 equivalent after combustion of methane. Results showed that the use of biogas as fuel can reduce 109 tonnes of CO_2 equivalent GWP. This represents an 84% reduction in GWP.

Table 8.7 Global warming saving through methane combustion ($CH_4+2O_2=CO_2 + 2H_2O$).

Impact category	**Initial charge**	**Daily charge**	**Lifetime charge**	**Total**
	4000 kg	**87 kg**	**318 tonne**	**322 tonne**
GWP before burning (Kg CO_2 equivalent)	1610	35.0	127818	130 tonne
GWP after burning (Kg CO_2 equivalent)	256	5.57	20339	21 tonne
Reduction in GWP from CH_4 combustion	1353	29.4	107478	109 tonne

According to the manual of Grameen Shakti, the daily charge of a 3.2 m^3 biogas plant is 87 kg. But from this study and farm visits to 10 cow dung based AD plants, the feedstock material input used on average is 65 kg of dung daily, representing a GWP of 97 tonnes of CO_2 equivalent before usage and 15 tonnes of CO_2 equivalent after usage, again an 84% reduction.

8.1.2.1.2 Impact of Digestate

Daily digestate production of a 3.2 m^3 plant is 13.05 kg and 78.75 kg in the case of a 14 m^3 plant (Gofran, 2009). Basically the digestate is a good fertilizer and soil conditioner. The impact of digestate (specifically nutrient element) was analysed in soil and water. The results of digestate impact analysis are given in appendix 6. There is no contribution to GWP from the digestate. So this assumes the digestate is completely stabilised.

Eutrification, human toxicity, fresh water aquatic ecotoxicity, marine aquatic ecotoxicity and terrestrial ecotoxicity was observed. Out of the nutrient content of digestate, eutrification is caused by nitrogen and phosphorus. Zinc causes human toxicity, fresh water aquatic ecotoxicity, marine aquatic ecotoxicity and terrestrial ecotoxicity (Table 8.8).

Table 8.8 Impact of 1 kg digestate in soil

Impact category	**Unit**	**N**	**P**	**Zn**
Eutrophication	kg PO_4 equivalent	0.42	3.06	0
Human toxicity	kg 1,4-DB equivalent	0	0	63.7
Fresh water aquatic ecotox.	kg 1,4-DB equivalent	0	0	47.7
Marine aquatic ecotoxicity	kg 1,4-DB equivalent	0	0	7210
Terrestrial ecotoxicity	kg 1,4-DB equivalent	0	0	24.6

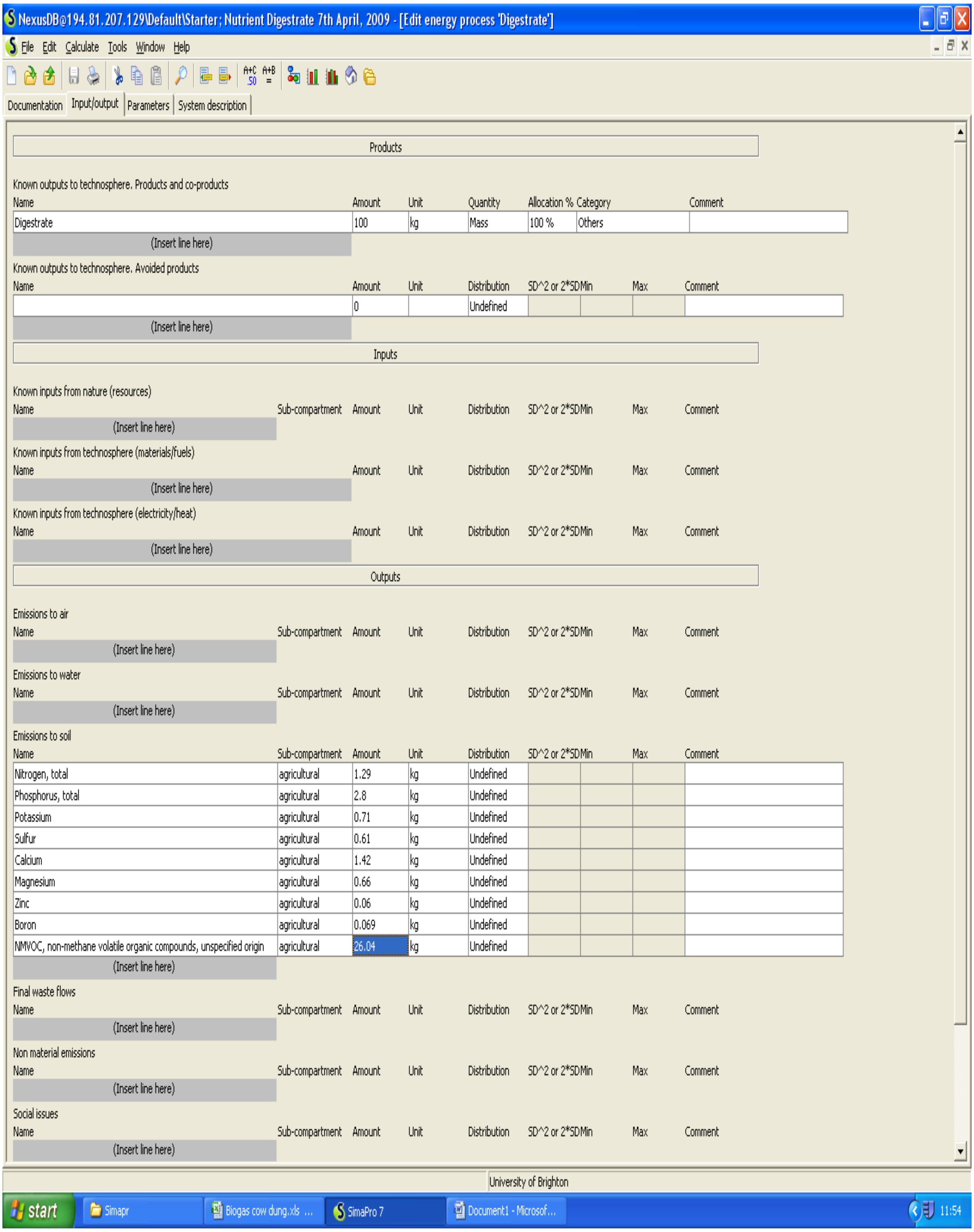

Figure 8.3 An example of Simapro model sheet used to measure impact of digestate.

8.1.2.2 Interpretation of Results

The results are summarised in the map below which can be called the Life Cycle Assessment of a domestic anaerobic digestion plant.

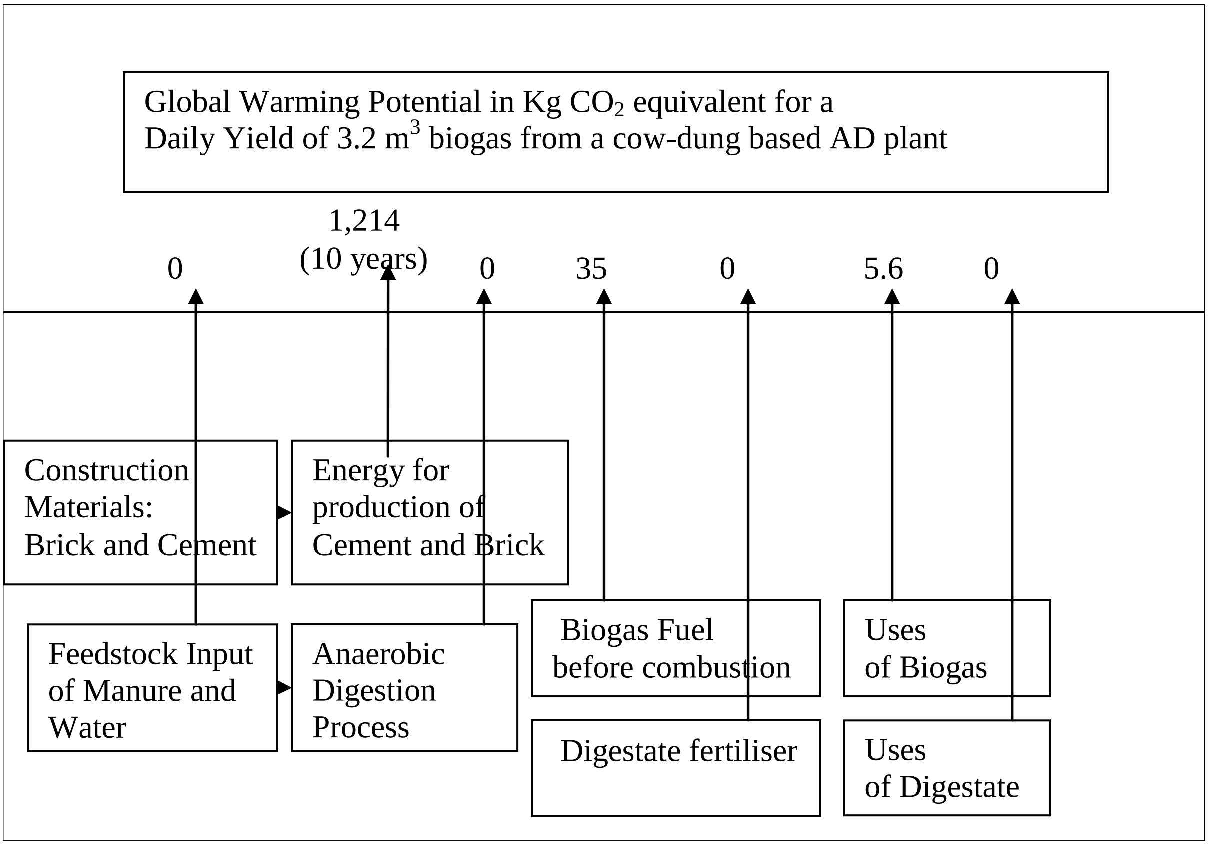

Figure 8.4 GWP of product and process of AD.

From the analysis above the GWP from bricks and cement used to build up a 3.2 m^3 biogas plant was 1,214 kg CO_2 equivalent. The daily accounting of the GWP is shown in the map. It is mostly from the biogas. For fuel the GWP is 35 kg CO_2 equivalent and after usage it is 5.6 kg CO_2 equivalents, an 84% reduction in GWP. The lifetime GWP on the basis of a ten year lifetime of a 3.2 m^3 biogas plant is shown in Table 8.9.

Table 8.9 GWP of a 3.2 m^3 biogas plant of different parameters.

Parameters	**CH_4 before combustion**	**CH_4 after combustion**
Biogas	130,000	20,596
Digestate	0	0
Structural materials	1214	1214
Total	131,000	22,000
Yearly GWP		**2200 kg CO_2 eq.**
Emission reduction from CH_4 combustion		**84%**

The GWP in 10 years is 22,000 kg CO_2 equivalent. The contribution from digestate is zero and from structural material ~1%. On the basis of a year, the GWP of a 3.2 m^3 biogas plant is ~ 2,200 kg CO_2 equivalent per year, deriving principally from the production of the biogas. When the biogas is used as a fuel then the GWP will reduce by 84%.

To determine the GWP of an AD plant, the information needed is the daily volume of biogas produced per weight of feed and the composition of the biogas. The next section describes the results obtained from data collected to obtain these parameters.

8.1.3 GWP derived from an AD process using primary data

In the previous section a life cycle impact assessment was undertaken of a domestic (3.2 m^3) anaerobic digestion plant in Bangladesh. Secondary data provided from Grameen Shakti was used for the LCA. This section will describe the LCA of anaerobic digestion using the primary data. It will look at the Global Warming Potential of every single plant that was visited and of the data collected on daily charge of feedstock. A total number of 11 plants will be considered for this. Biogas and methane yield of primary results will be considered when determining GWP.

8.1.3.1 Impact Assessment

It was observed from earlier results that the impact of an AD system is mainly influenced by the biogas and methane yield. During initial AD facility visits 11 AD plants were visited and there were two types of feedstock: cattle dung and poultry litter. During determination of AD biogas parameters the feedstock were cow dung, poultry litter and cattle market rice straw at the experimental AD plants. The practical result shows that the methane and biogas yields differ from the Grameen Shakti references shown in the table below.

Table 8.10 Biogas yield from different feedstock compared with GS

	Biogas Yield		**% Methane (by volume)**	
	This work	**Grameen Shakti**	**This work**	**Grameen Shakti**
Feedstock	**m^3/kg manure**	**m^3 /kg manure**		
Cattle dung	0.021	.037	59.9	60
Poultry litter	0.021	.071	61.6	65
Cattle market rice straw	0.099	0.22 (Kalra, 2003)	74.4	--

Due to the variation of biogas and methane yield and the application of daily feedstock, the assessed impacts differ from the earlier impact assessment. For example, below Table 8.11 shows that how the GWP can differ due to the biogas yield variation. The GWP for a cattle dung AD plant was 45% less and for the poultry based AD plant was 70% less than the GWP observed using the secondary data shown in Table 8.11. This variation is due to the biogas yield from cattle and poultry feedstock AD plants as these were less than the reference (Grameen Shakti). The daily charge and improper management was another reason for that. The Global Warming Potential per kilogram of feedstock of a 2 m^3 sized cattle market rice straw AD plant was 1.159 kg CO_2 equivalent which was higher compared to any other feedstock. This indicates that the GWP mainly differs due to the biogas and methane yield.

Table 8.11 Variation of GWP of different feedstock (kg CO_2/kg feedstock).

GWP in kg CO_2 equivalent/kg feedstock		
Feed stock	**This work**	**Other (GS)**
Cattle dung (2.4 m^3)	0.205	0.365
Poultry litter (4.8 m^3)	0.210	0.712
Cattle market rice straw (2 m^3)	1.159	

Ultimately the GWP of existing biogas plants was less than the manually operated AD systems. Figure 8.5 shows the comparative analysis. The first 10 biogas plants were dung based and their yields and GWPs were lower than the manually operated plants. Biogas plant number 11 was poultry litter based and the farmer followed instructions and added the required amount of daily charge. The result for that poultry based plant showed the GWP as the same as the GS reference.

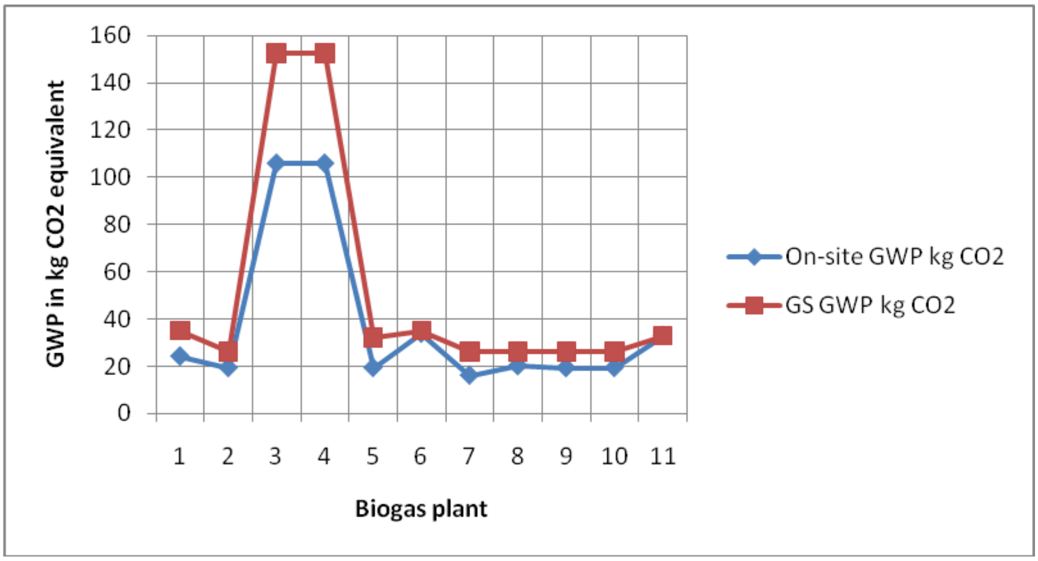

Figure 8.5 A comparison of GWP of in-site visit and Grameen Shakti.

8.1.3.2 Interpretation of Results

From the analysis of the result it is noticeable that feedstock rate affects yield and yield influences GWP. A comparison of biogas yield and GWP is shown in the Table below for the farms visited. On the basis of farm visits, the existing AD plants mostly use feeds in amounts lower than prescribed by the reference and the biogas yields can be much lower as given by the primary data.

Table 8.12 Comparison of biogas yield and GWP of existing and Grameen Shakti (manually operated) AD system.

Plant Number		**This work**		**GS**	
	Feedstock	**Biogas yield**	**GWP kg CO_2**	**Biogas yield**	**GWP kg CO_2**
1	**Cow dung**	1.3	24	3.2	35
2		1.0	19	2.4	26
3		5.5	106	14.0	152
4		5.5	106	14.0	152
5		1.0	19	3.0	32
6		1.8	34	3.2	35
7		0.8	16	2.4	26
8		1.1	20	2.4	26
9		1.0	19	2.4	26
10		1.0	19	2.4	26
11	**Poultry litter**	**3.2**	**33**	**3.2**	**33**

Nonetheless, when the biogas is used as fuel, the GWP will decrease by 84% in comparison to the biogas product generated by the AD.

8.1.4 Discussion of impact assessment

During the field trip to Bangladesh a total number of 11 anaerobic digestion plants were visited. All the plants were different in sizes, feedstock and digester type. Two plants among them were 14 m^3 which are defined as medium sized plant. One of them was a poultry based 3.2 m^3 plant. The results presented in the above sections suggest the GWP originates principally from the biogas produced. These results can be used to predict the GWP of other AD plants characterised by type of feedstock and size. In this discussion examples of the applications of data to a change in size and later to change in feedstock will be discussed.

8.1.4.1 Comparison GWP in variation of plant size

A 3.2 m^3 biogas plant is a standard example of a domestic biogas plant that can meet the energy requirement of an average sized family (5/6 person) and a minimum of 5 cows are needed to get the required amount of feedstock. A 14 m^3 biogas plant is a medium sized plant. In the first field visit comprising of 11 AD plants, only two AD plants were medium-sized. This type of plant is suitable for small commercial purposes. This amount of biogas could be shared among 6 - 7 families. The biogas produced from these plants is always surplus after meeting the family and daily requirements.

Biogas yield is 0.037 m^3 biogas/kg dung and GWP is 0.403 kg CO_2 equivalent/kg dung. These are the values derived using the maximum expected yield and methane content from Grameen Shakti (Table 8.13). The GWP contained in 14 m^3 biogas sourced from cow dung fed AD will be 161 kg CO_2 equivalent. The results are summarised in the table below.

Table 8.13 Comparison of GWP between a domestic (3.2m^3) and medium (14m^3) sized AD plant.

Daily Biogas Produced	**Biogas yield**	**Amount of Feed Needed**		**Biogas Produced GWP**	**Impact Parameter GWP**
		Calculated	Rounded		
m^3	m^3/kg dung	Kg dung	Kg dung	kg CO_2 equivalent per kg dung	kg CO_2 equivalent
3.2	0.037	86.5	90	0.403	35
14	0.037	378.4	400	0.403	161

After the use of biogas for fuel, the GWP will drop by 84% and the post combustion GWP for the 14m^3 of biogas will be 26 kg CO_2 equivalent. It was observed in this research that a few medium sized plants which were operated produced more biogas yield but were used for a single family. This was due to two main reasons. The first reason is the wrong site selection for an AD plant and the second is the lack of technical knowledge. For example, out of 11

AD plants visited, 2 of them had a daily biogas yield capacity of 14 m^3 which produced more biogas than they need. It is clearly not cost-effective at all in aspect of GWP and can be majorly polluting. Incentives to develop pipelines or collected communities are needed to maximise the use of biogas for those communities.

The design of a digester plant for the fixed dome type depends on the amount required for the reactor volume and the gas reservoir volume. For the 14m^3 biogas plant the gas reservoir volume is 14m^3 and the reactor volume is always larger than the gas reservoir volume (detailed in section 7.4 of Chapter 7). The reactor volume is obtained from the amount of feedstock needed, the dilution required and the hydraulic retention time (Chapter 2, Section 2.2). For cow dung, the dilution required to reduce the received dung containing 15% TS to 8% TS is done with addition of water. The density of dung is approximately the same as that of water and in practice the farmer adds the amount of water in litres equal to the required weight of feedstock in kg. Hence the total volume of the daily feed to the digester is simply 2 x Weight/1000 in m^3. The volume required for the reactor is volume x HRT where HRT is the hydraulic retention and is taken as 40 days for Grameen Shakti designs. The calculation for the total capacity of the digester needed is shown in Table 8.14.

Table 8.14 Total volume of the digester of two common sized AD plants.

Volume for Daily Biogas	**Weight of Daily Feed**	**Volume of Daily Feed**	**HRT**	**Volume for Reactor**	**Total Volume for Digester**
m^3	Kg	m^3	days	m^3	m^3
3.2	90	0.18	40	7.2	10.4
14	400	0.80	40	32	46

There are additional constructions for the overflow of the digestate but the table above demonstrates the scaling up in terms of requirements of bricks and cement. The GWP for brick and cement is given in Table 8.1. The digestate does not contribute to GWP but does contribute to other indicators such as eutrofication. Daily digestate production of a 3.2 m^3 plant is 13.05 kg and 78.75 kg in the case of a 14 m^3 plant (Gofran, 2009). There is a 6-fold increase in amount of digestate recovered. The impact parameters from the appendix can be adjusted accordingly to reflect the increase in output digestate yield.

8.1.4.2 Comparison of GWP in variation of feedstock type

The plant size assumed is 3.2 m^3 and the biogas yield from Chapter 5 is reproduced here for a comparative analysis. This is because GWP is closely related with the biogas and methane yield.

Table 8.15 Biogas yield of dung and poultry biogas (GS).

Feedstock source from	**Biogas Yield m^3 biogas/kg manure**
Cattle dung	0.037 (GS)
Poultry litter	0.071 (GS)

For the same sized AD plant, the amount of initial and daily charge using poultry litter is half in comparison to cattle dung. Using the information from Chapter 5 on biogas yield and biogas composition comparing cow dung and poultry litter and the gas densities, then the following Table 8.16 can be generated.

Table 8.16 Comparison biogas production from per kg dung and poultry litter.

Biogas	**Weight Gas Per kg Dung (g)**	**Weight Gas Per kg poultry litter (g)**
CH_4	16.714	30.068
CO_2	18.092	38.960
CO	0.000	0.000
O_2	0.145	0.372
H_2S	0.052	0.300
H_2	0.079	0.163
N_2	0.509	1.220
		0.000
TOTAL	**35.59**	**71.08**

The weight of gas per kg of poultry litter is almost twice that of cow dung. Making the substitution for the gas composition in poultry in Table 8.16 then the calculation as above applied to a poultry litter 3.2m^3 plants will produce about the same GWP as a cow dung plant.

Table 8.17 GWP of per kg dung and poultry litter biogas feedstock.

Feedstock	**GWP kg CO_2 equivalent/kg feedstock**
Cow dung	0.403
Poultry litter	0.731

Table 8.18 GWP Impact of dung and poultry feedstock.

Daily Biogas Produced	**Biogas yield**	**Amount of Feed Needed**		**Biogas Produced GWP**	**Impact Parameter GWP**
	m^3/kg	**Calculated**	**Rounded**	**kg CO_2 equivalent**	**kg CO_2**
m^3	**feed**	Kg feed	Kg feed	**per kg feed**	**equivalent**
3.2 Cow	0.037	86.5	90	0.403	36
3.2 Bird	0.071	45.1	50	0.731	37
4.8 Bird	0.071	67.6	70	0.731	51

The 3.2 m^3 designs for cow dung are not optimum for poultry so Grameen Shakti has another design which has a gas reservoir for 4.8 m^3 for poultry farm use. The GWP on account of the increase in feed and yield is 51 kg CO_2 equivalent.

However, the material requirements are not that different than for a 3.2 m^3 biogas plant as shown in the table below and therefore the GWP from the construction material of the biogas will be similar to that of the 3.2 m^3 design given in Table 8.19.

Table 8.19 Digester volume for different sizes plant.

Volume of daily biogas	Weight of daily feed	Volume of daily deed	HRT	Volume of reactor	Total volume for digester
m^3	Kg	m^3	days	m^3	m^3
3.2 Cow	90	0.18	40	7.2	10.4
3.2 Bird	50	0.10	40	4	7.2
4.8 Bird	70	0.14	40	5.6	10.4

8.1.4.3 Comparison between a fixed dome and floating dome digester

A fixed dome digester is made of bricks and cement whereas floating dome is made of bricks and plastic. The GWP of a 3.2 m^3 fixed dome digester was found to be 467 kg CO_2 equivalent. A floating dome also needs bricks, sand, cement and in addition a plastic gas reservoir. GWP of major AD construction materials were estimated from secondary data use based on Bangladesh. The details of this calculation are shown in Chapter 4 and Table 8.1 of this chapter.

8.1.5 Discussion on energy attributes of AD plant

Another output of this study is an estimation of the energy capacity of biogas as a fuel. The heat from the combustion of 1 kg of methane is 55.6 MJ. Based on calculations a 3.2 m^3 biogas plant can produce 1.45 kg of methane. As a result the heat energy of 1.45 kg methane is (55.6 x 1.45) =80 MJ. This is based on a biogas produced from 87 kg of dung feed in a 3.2 m^3 plant. The GWP is 5.57 kg CO_2 equivalent after combustion of the daily yield of biogas. Some conversion terms can be defined accordingly.

The caloric value per m^3 of biogas derived from cow dung is 23.5 MJ/m^3, caloric value per kg feed of cow dung is 0.87 MJ/kg dung and GWP energy is 0.074 kg CO_2 equivalent/MJ. The boiling of one litre of water needs 0.31MJ of heat. The total methane generation per day can boil (=80/0.31) 258 litres of water (from room temperature to 100°C).

8.1.5.1 Replacing biomass with biogas

Combustion of 1 kg of wood produces only 15.5 MJ. A 3.2 m^3 domestic sized biogas plant produces 80 MJ. This indicates that this biogas plant can save more than 5.2 kg of wood daily (Table 8.20). This means in the 10 year life time of a 3.2 m^3 domestic biogas plant, the use of biogas will save more than 15 tonnes of biomass fuel. The following table summarises these points.

Table 8.20 Calculation shows efficiency of biogas over traditional biomass fuel.

Factors	**Units**
Heat from combustion of methane	55.6 MJ/kg
Daily methane production from 3.2 m^3 plant	1.45 kg
Heat from combustion of daily methane production	80 MJ
Heat combustion of wood	15.5 MJ/kg
Daily methane production of a 3.2 m^3 plant can save	5.2 kg wood daily
A 3.2 m^3 domestic biogas plant can save in its life time (10 year)	20 tonnes of wood
Boiling 1 litre of water needs	0.31 MJ heat
Methane produced daily in a 3.2 m^3 plant can boil	258 Litres of water
To boil an amount of water needs 5.2 kg of wood daily	

Biogas is used mostly for cooking and lighting. Biogas replaces wood biomass with cooking and kerosene with lighting. Biomass fuel stoves are a significant source of pollution in the form of products from incomplete combustion (PIC), i.e., much fuel carbon is diverted into non-CO_2 airborne emissions such as CO, CH_4, NMHC, and particles which are major health-damaging pollutants (Edward, 2002).

The burning of renewably harvested fuel wood (and other biomass) has often been assumed to be GHG neutral as eventually all the CO_2 will be recycled and taken up by vegetation in the next growing season. This picture is flawed as most PIC emitted from incomplete combustion has higher global warming impact per carbon atom than CO_2 (Kirk et al, 2000). Thus inefficiently burned biomass fuels have a global warming contribution even if renewably harvested. In China, for example, considering only CO_2 and CH_4, the burning of renewable brushwood and crop residues appears only marginally worse than emissions from LPG (Liquefied Petroleum Gas), even though LPG releases fossil carbon. For wood, even if only a small fraction is harvested non-renewably, it becomes worse than LPG (Edward, 2002).

Daily production of biogas from a 3.2 m^3 plant can save 5.2 kg of firewood. According to this research there are 2.3 millions of potential domestic AD plants in Bangladesh from cattle smallholdings. Biogas from cattle smallholding can save 12,000 tonnes of traditional biomass fuel daily and total saving of firewood is 17,000 tonnes. Firewood is widely used in developing countries. PIC of firewood causes indoor air pollution and increase propensity of diseases. Of the commercial fuels, coal and kerosene are two of the most common fuels. They are both fossil fuels contributing to climate change and can be expensive to use. (Gautam *et al* 2009; Li *et al* 2005). Dry dung is also used for cooking in rural Bangladesh and it is an inefficient fuel when burned. The better way of raising the efficiency in the burning of biomass fuels is by converting it or replacing it with biogas. Burning dried dung has a heat efficiency of about 10% when burned. But if biogas is first produced from the dung then used the heating efficiency would be raised to 60%. (Mirza et al. 2008). As a result, the use of biogas for cooking in well designed gas stoves is highly desirable.

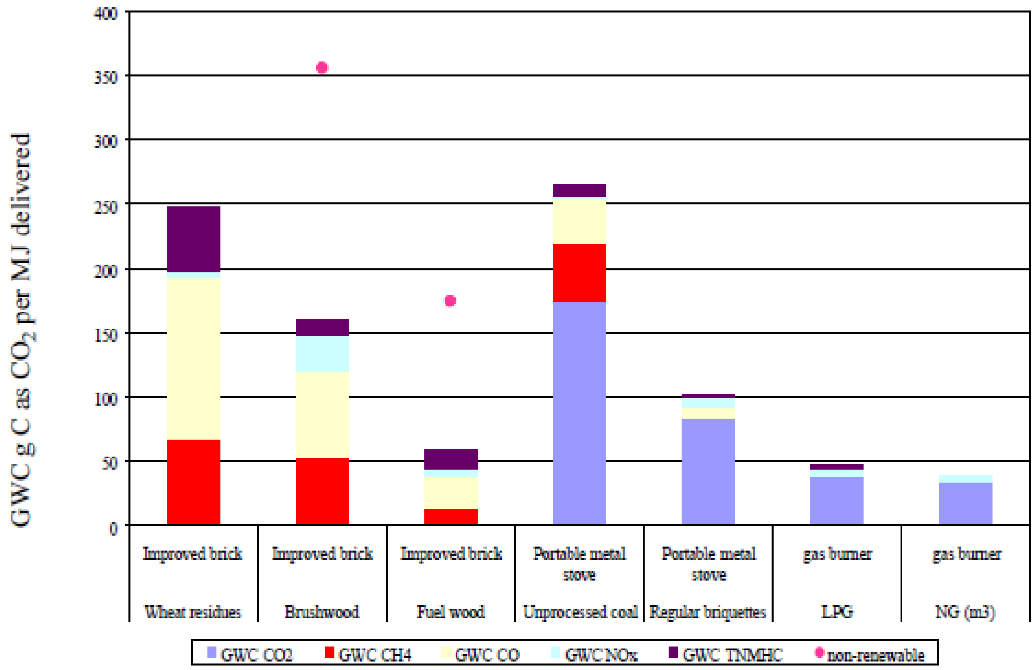

Figure 8.6 Global Warming Contribution as gram carbon per MJ from different stoves and fuel types in China (Edward, 2002).

8.1.5.2 Replacing kerosene with biogas

The traditional energy source for rural Bangladesh is kerosene. Biogas can replace kerosene for lighting. Used 4 hours/day, a kerosene lamp emits 100 kg of CO_2 annually and 100 kg CO_2 is produced from burning 28.9 kg kerosene (Atul Raturi, 2008). Comparing these research results with this report it can prove that the GWP of kerosene and biogas are similar per energy. The caloric value of kerosene and methane is 46.2 (The National Institute of Standards and Technology, NIST) and 55.6 MJ/kg respectively. The daily average kerosene requirement of a rural family in Bangladesh is 0.15 kg which is equivalent to 6.93 MJ. To produce this amount of energy emits 0.52 kg CO_2 equivalent. So for kerosene per MJ emission is 0.075 kg CO_2 equivalent. According to research conducted in this thesis, to produce 80 MJ of energy from a 3.2 m^3 biogas plant emits 5.6 kg CO_2. It means for biogas, per MJ emission is 0.070 kg CO_2 equivalent. It means that replacing kerosene with biogas is quite logical in the aspect of GWP.

8.2 Discussion of benefits

The initial investment cost for an anaerobic digester consists of the costs of construction, piping, and stoves. The main benefits are the replacement costs of fuels substituted by biogas and fertilizer by digester slurry. Villagers do not appreciate the monetary value of biogas production because there are adequate supplies of biomass at no cost and householders put little or no value on time spent gathering biomass. On the other hand, benefits derived from fermented slurry have immediate monetary value since the slurry replaces commercial fertilizer. The slurry contains some of the nutrients (sodium, potassium and phosphate) found in chemical fertilizers like urea, potash and superphosphates (Parikh, 1985).

This part will explain how the social and economic factors affect biogas technology in Bangladesh. It will represent the advantages of biogas in Bangladesh influencing the social status. It will also briefly describe how the AD construction cost affects this technology.

8.2.1 Saving of conventional fuel

Saving fuel like wood fuel, Liquid Petroleum Gas (LPG) etc. are a direct economic benefit of biogas. Wood fuel is the main source of rural energy supply. So, saving wood fuel is the important issue for protecting deforestation. Moreover fuel wood is becoming scarce and its price increasing day by day. Biogas replaces the use of kerosene as described in an earlier section. Kerosene is a fossil fuel that is widely used in many developing countries for cooking and lighting. It is expensive and often needs to be imported. In areas where biogas has been utilized the use of kerosene has dropped considerably (Gautama *et al* 2009).

8.2.2 Impact of use of digestate

The deterioration of the rural environment and ecological system has become a worldwide problem mainly caused by the excessive utilization of land and forest, excessive use of chemical fertilizers and pesticides and the careless discharge of livestock waste (Sasse, 1988). Research has shown that digestate from AD plants can be used successfully in growing crops. Therefore the digestate can be sold thereby helping the AD plant become more financially viable.

The use of digestate as an organic fertilizer not only reduces the dependency of chemical fertilizers but can also improve soil structure. The slurry that has been digested is a high grade fertilizer. In fact the processed substrates are a better fertilizer than before the digestion procedure. Digestate from 1 kg of digested dung can yield up to an extra 0.5 kg of nitrogen compared to fresh manure (Sasse, 1988). This can solve problems of soil degradation in areas where earlier dung has been used as a burning fuel. It can also mean that less artificial fertilizer has to be bought thereby economic savings to the household (Li et al., 2005). Moreover, the finished digestate from AD does not have any GWP when applied to land.

Excessive farming and the use of chemical fertilizers has damaged the soil fertility of Bangladesh. Digestate has the ability to safeguard organic materials such as nitrogen, phosphorous, and potassium, which increases it’s standard as a fertilizer and ensures higher agricultural production. Digestate produced from poultry litter is very good for acidic soil and helps to reduce acidity and aluminium poisoning. A 3 m^3 cow dung based biogas plant can produce more than 8 tonnes of slurry which is equivalent to 224 kg of urea, 1.1 tonnes of Triple Super Phosphate (TSP) and 114 kg of Muriate of Potash (MoP) fertilizer. An entrepreneur can earn Tk 16,000 from selling this slurry which is the equivalent to £150

(Grameen Shakti, 2005). According to this estimation the potential of 2.4 million AD plants could save the use of a substantial amount of chemical fertilizer.

8.2.3 Save time

Women and children would have more time for education when they don't have to spend as much time collecting firewood and other biomass fuels. The daily time spent in feeding a small biogas digester could be as little as 15 minutes compared to several hours collecting biomass. Time consumed cleaning pots and other kitchen equipment can also be lowered since biogas won't create as much soot as biomass generally does. Biogas can also be used for lighting which means it would be possible to study during the dark hours as well (Bajgain, Shakya, 2005).

On an average, biogas enables approximately 1 hour and 5 minutes of saved time per day per family mainly due to the reduction of time used for collecting biomass, cooking and cleaning of utensils; whereas an increase in time has also been incurred for some additional works such as collection of water, feeding and caring for livestock (SNV/IDCOL, 2005).

Traditional biomass fuel is not only hazardous to health, but the use of it is also a big waste of time. The use of biogas can save time which can directly and indirectly influence the economy and social status of the user community. Overall it improved income from diversified activities. It also generates new employment.

8.3 Scope of AD

8.3.1 Carbon benefit/mitigation of GHG emission

Biogas technology takes part in the global effort against the greenhouse effect by reducing the release of CO_2 from burning fossil fuels in two ways. Firstly, biogas is a direct substitute for gas or coal for cooking, heating, electricity generation and lighting. Secondly, the reduction in the consumption of artificial fertiliser avoids carbon dioxide emissions that would otherwise come from the fertiliser-producing industries. By helping to counter deforestation and degradation caused by overusing ecosystems as sources of firewood and by melioration of soil conditions, biogas technology reduces CO_2 releases from these processes and sustains the capability of forests and woodlands to act as a carbon sink (ibid). GWP impact of a life time (10 years) of 3.2 m^3 biogas plants before combustion of methane is 131 tonnes of CO_2 equivalent but it drops to only 22 tonnes of CO_2 equivalent after combustion of methane. It means that the use of biogas as a fuel can reduce the GWP by 109 tonnes of CO_2 equivalent. This represents an 84% reduction in GWP. Developing countries of Asia account for most of the world's animal population. The animal wastes produced annually in these countries constitute a major source of methane and other greenhouse gases (GHG). For 23 countries in Asia, Bhattacharya et al, 1997 estimated that 17,730 Gg of CH_4, 1,290,000 Gg of CO_2 and 179 Gg of N_20 are emitted from animal wastes. Using the biogas that can be produced from recoverable animal wastes as a substitute for fuel wood and kerosene in cooking and lighting will reduce the net GHG emissions by 53.1, 19.5 and 61.1% for CH_4, CO_2 and N_20, respectively (Bhattacharya *et al*, 1997).

Management of animal dung prevents methane gas emissions. When dung is naturally digested methane gas is produced and released into the atmosphere. Instead of these if the substrates are digested in a biogas plant where the methane gas (biogas) is collected and thus avoiding release into the atmosphere. When the biogas is then combusted most of it is converted into CO_2. Methane gas is a 21 times more aggressive GHG than CO_2 in a hundred year perspective so biogas plants can be effective means of mitigation (Yua *et al* 2008). The net saving of GHG for an average sized biogas plant has been estimated to be 4.6 tonnes of CO_2 equivalents per year. (Bajgain , Shakya, 2005).

In 2005, Bangladesh emitted 0.053 to 0.045 billion tons of CO_2 equivalent which is less than 0.20% of the world's total GHG emissions. It reflects the low per capita energy consumption in the country. Although the contribution of GHG emission is very low, the government of Bangladesh wishes to play its role in reducing emission now and in future. The government wants to develop a strategic energy plan to ensure national energy security and lower GHG emissions.

The Clean Development Mechanism (CDM) of the UNFCCC can be used for biogas projects. This flexible mechanism makes it possible for Annex 1 (developed) countries to displace emission reductions to developing countries. The avoided GHG emissions from the CDM projects will generate CERs (Certified Emission Reductions) that can be bought by Annex 1 countries. This can help finance further biogas growth in developing countries. (Bajgain, Shakya, 2005).

8.3.2 Pollution reduction

The open dumping of waste is the common scenario for both rural and urban areas of Bangladesh. It causes different types of diseases by polluting both air and water. AD facilities can reduce pollution. The use of biogas also improves indoor air quality. Replacing biomass energy with biogas could help to solve a lot of the problems that are typically found with biomass fuels. The indoor climate would be dramatically improved as a result of using clean biogas stoves instead of burning firewood, straw and dung cakes. This would mean that a lot of the problems with hazardous smoke particles would be avoided. (Li *et al* 2005).

8.4 Conclusion for this chapter

This chapter has used Life Cycle Analysis and PAS 2050 methods to count carbon of domestic biogas plants in a developing country like Bangladesh in order to indicate the potential for carbon reduction schemes. Results show that the use of biogas produced by anaerobic digestion minimizes a significant amount of global warming compared to the traditional practices. The other product of anaerobic digestion which is the digestate does not contribute to GWP but is a big source of plant nutrient.

From the LCA results it follows that the contribution from materials such as bricks and cement that make up the digester have some GWP embodied through the production of them but will probably make up about 1% of the GWP of a biogas LCA system when taken over a 10 year lifetime. The feedstock is a mixture of waste manure and pond water and both have no embodied energy so their contribution to GWP is nil. There is no heat or energy applied to the digester to maintain its operation in the mesophilic regime so the contribution to GWP from reactor operation is also zero.

The products of the AD process are biogas and digestate. There is no GWP associated with the digestate and so the major source of GWP is the biogas. As a fuel it can have methane content as high as 69% but once used as fuel, combustion oxidises CH_4 to CO_2, a gas with lower GWP than methane in the ratio of GWP of CH_4:CO_2 is 23:1. The use of the biogas as fuel will reduce the GWP of the fuel by 80-84 % depending on the methane content of the biogas.

The use of biogas significantly reduces the expenses on fuel for cooking and lighting. The slurry obtained from biogas plants can be used as organic manure thereby substituting the costly inorganic fertilizers. This manure is more effective and of higher quality than farmyard manure. The accumulation of these savings from biogas plants makes it possible to recover the total plant construction cost within five years. These multiple benefits are the main motivating factors for rural households towards the adoption of biogas technology (SNV/IDCOL, 2005).

Since the vast majority of rural households have no access to modern energy and the use of commercial fuels is limited, the opportunities of renewable energy used by rural households are potentially large. The relation between energy access in rural areas and indicators for rural development is well established. Utilization of renewable energy technology may be directly linked to social, economic, environment and energy security issues like jobs, income level and poverty, access to agricultural production, social services, health, climate change and environmental quality. Biogas technology development is at a very early and growing stage in rural Bangladesh and there are mainly policy and institutional barriers that hinder this sector from being able to achieve reasonable progress to get benefits.

The results of this work can be used to estimate the GWP of an AD system based on feedstock and size variables. This work can also be used to quantify the energy available from the biogas fuel. The information is useful for decision making in terms of the kind of AD systems that should be built within a local farm, a community or a commercial centre.

The information can be entered into future applications to grants for development of facilities such as the CDM (Clean Development Mechanism).

Results at a glance

For the 10 year life time of a 3.2 m^3 biogas plant the following conclusions can be drawn

1. The GWP is about 22 tonnes CO_2 equivalent after combustion
2. Combustion of methane reduces GWP by 109 tonnes of CO_2 equivalent
3. Use of biogas replaces more than 15 tonnes of wood
4. Digestate is a nutrient rich fertilizer causing zero GWP

Chapter 9

Conclusion and Future work

9.1 Overview of aims and objectives

This research was to determine the anaerobic digestion (AD) potential and green house gas mitigation of small and medium anaerobic digester systems in Bangladesh. This final chapter provides an overview of the conclusions from the completed study. The results are presented in terms of key findings and areas suitable for future work. Cattle smallholdings, poultry farms and cattle market rice straw wastes are shown to provide significant potential AD feedstocks for Bangladesh. The daily potential AD capacity of Bangladesh from these three AD feedstocks is 240 million MJ which could be coming from 2.4 million potential AD plants. This energy can meet the cooking energy requirements of up to 6 million households or 30 million people, which is 20% of the total population of Bangladesh.

This was achieved through field work, identification of representative AD facility types, determination of the key energy parameters and surveys of cattle and poultry. Primary data was collected where there were any data missing. A life cycle impact assessment of a common sized digester AD plant was undertaken to calculate the GHG mitigation of a domestic anaerobic digester system in Bangladesh.

Dung and poultry litter were found to be the two most common and major AD feedstock types available in Bangladesh. A new feedstock with significant potential was identified, namely cattle market waste, which is dung mixed with the rice straw which is used as bedding for animals while stationed in the market place. Cattle market rice straw waste was investigated as a third major potential feedstock. The daily potential AD capacity of Bangladesh and the potential biogas yield for these three feedstock types was determined.

The potential AD capacity and the different characteristics of the contribution of these three feedstock types was presented with appropriate AD unit useful sizes – Domestic (2-5 m^3), Medium (5 - 25 m^3) and large (25 - 150 m^3), as well as two further sizes found to be useful during the research (small domestic (< $2m^3$) from cattle smallholdings and extra large (> $150m^3$) from cattle market rice straw), as shown in the key findings section below. These five categories provide very useful information for understanding how to maximize financial returns, environmental returns and energy provision returns on investments.

9.2 Key findings

The result from the unique feedstock showed that 87% of cattle smallholdings are suitable for domestic sized AD plants and 13% of them are feasible for medium sized AD. 63% of the poultry farms are suitable for medium sized AD plants, 30 % for large and only 7% for domestic sized AD plants. All of the cattle markets with rice straw waste are suitable for large (53%) or extra large (47%) sized AD plants.

Table 9.1 shows the percentage of AD plants of different sized AD potential in Bangladesh. 28% of potential AD plants are small domestic AD for cattle smallholdings with 3 - 4 cattle. It means a substantial number of small families can use those amounts of biogas for their daily requirement. The potential shares of domestic, medium and large sized AD plants are 57%, 14% and 1% respectively.

Table 9.1 The percentage (%) of different sized AD units (measured by volume) that could potentially be set up in Bangladesh (total absolute number = 2 million).

	Small domestic ($<2m^3$)	**Domestic (2-5 m^3)**	**Medium (5-25 m^3)**	**Large (25-150 m^3)**	**Extra large (>150 m^3)**	**Total**
Cattle	28.22	56.48	12.63	0.00	0.00	97.33
Poultry	0.00	0.19	1.67	0.79	0.00	2.65
Cattle market rice straw	0.00	0.00	0.00	0.01	0.01	0.02
Total	**28**	**57**	**14**	**0.81**	**0.01**	**100.00**

Table 9.2 presents the same data in a different way, showing AD energy contributions from the different sized potential AD biogas units in Bangladesh. Only 8% of total potential AD energy comes from small domestic AD facilities (which are only suited for cattle smallholdings). Most of the potential AD energy of Bangladesh comes from domestic, medium and large sized AD with 32%, 34% and 15% respectively. The rest (11%) of the potential energy comes from the new category - extra large AD plants.

Table 9.2 The percentages to the total potential energy contribution of different sized AD potential units in Bangladesh.

	Very small ($<2m^3$)	**Domestic (2-5 m^3)**	**Medium (5-25 m^3)**	**Large (25-150 m^3)**	**Extra large (>150 m^3)**	**Total**
Cattle	8	32	29	0	0	70
Poultry	0	0.2	5	11	0	16
Cattle market rice straw	0	0	0	4	11	14
Total	**8**	**32**	**34**	**15**	**11**	**100**

Table 9.3 illustrates the results categorised by feedstock source, the result shows that the potential number of AD plants from cattle smallholdings, poultry farms and cattle market rice straw are 97%, 3% and 0.02% respectively. The energy contributions of those three feedstocks are 70%, 16% and 14% respectively.

Table 9.3 Potential AD in Bangladesh categorised by potential feedstock and (i) by AD plant number and ii) by energy contributions.

Feedstock	**Percentage (%) of AD plants**	**Percentage (%) AD energy contribution**
Cattle	97	70
Poultry	3	16
Cattle market rice straw	0.02	14
Total	**100**	**100**

Bangladesh is a densely populated agro-based country that produces a huge amount of household waste, energy crops and crop residue waste. These can also be the prospective feedstock for future AD installations. As a result, the proposed energy contributions of the three animal feedstocks could increase, and the total potential AD capacity could also be increased by adding other feedstocks (e.g. food waste, water hyacinth, MSW) to supplement units running primarily on animal manure feedstock.

Combining the AD capacity of three potential AD feedstocks, the daily potential AD capacity of Bangladesh is 240 million MJ which comes from 10.43×10^6 m^3 of biogas. This means the annual AD potential for Bangladesh from those potential feedstocks is 3.8×10^9 m^3 of biogas. This is equivalent to 8.76×10^{10} MJ or 2.4×10^{10} KWh (2.4×10^7 MWh).

The work in this thesis has also provided the information needed to calculate the net environmental impact of these AD facilities by obtaining primary data on key parameters such as realistic biogas yield, methane content, anaerobic digester construction materials and feedstock demands. An LCA of a common (domestic) sized AD plant was conducted in this research to find the GHG mitigation capacity of such an AD plant. The global warming saving through the use of biogas in combustion where the GWP attributed to biogas used drops for per kg of dung were from 0.40 kg CO_2 equivalent to 0.064 kg CO_2 equivalent. The lifetime GWP impact of a 3.2 m^3 biogas plant (before combustion of methane) is 130 tonnes

CO_2 equivalent but it decreases to 21 tonnes of CO_2 equivalent (after combustion of methane) with the utilization of biogas. This shows that the use of biogas as a fuel can reduce GWP by 109 tonnes CO_2 equivalent. This represents an 84% reduction in GWP. The use of biogas also significantly reduces the expenses of fuel for cooking and kerosene for lighting. Daily energy capacity of a 3.2 m^3 domestic biogas plant is 80 MJ. Accordant to this yearly savings of fuel wood and kerosene from a 3.2 m^3 domestic AD plant is 1.6 tonnes and 635 litres respectively. The digestate obtained from biogas plants can be used as fertilizer thereby substituting the costly inorganic fertilizers with no GWP impact.

9.2.1 Possible application of findings

Altogether, this information provides a very good overview and detail for the balance of energy production and environmental impact to be considered. This is particularly important for Bangladesh because such information is needed to obtain access to large scale extended funding such as through the CDM process.

Cattle smallholding

There are a potential of 2.3 million AD plants with cattle smallholdings in Bangladesh. The majority (97%) of the cattle smallholdings are suitable for domestic sized AD plants. It also contributes 70% of the total potential energy. This result provides crucial information for short and long term planning for policy making. For example, the government or any development organization should emphasize the importance of this type of plant to ensure a large future number of domestic sized AD plant from cattle smallholdings are set up. Since they all have in common the fact that they are linked to cattle ownership, this suggests that one pathway to provide advice and regulation could be via veterinary surgeons and the related legislative and governmental bodies associated with them. Microfinance would obviously be an important tool for implementation of this category because the rural smallholder would probably not be able to afford AD construction on his own. It is also important to note that development of the potential of this category of AD plant would have a big impact on a large number of rural poor families can benefit from the biogas energy, both in financial savings and convenience e.g. of fuel for lighting for studying.

Poultry farm

There are a potential of 63,000 AD plants based on poultry farms in Bangladesh. They could provide 3% of the total potential number of AD plants which and would be either medium or large sized plants. Poultry farms would provide 16% of total AD energy of the units proposed here. The AD energy that comes from these sources is not appropriate for domestic AD plants nor extra large plants; a medium sized AD plant is mostly feasible from this fuel source and its energy is thus sufficient for a cluster of families. The biogas could be supplied neighbouring households through a pipeline. A small community with a few families could benefit from a poultry farm AD facility. Another possibility to consider is not to use the gas at the poultry farm but to transport the litter to a nearby village or cluster of households and use it there so that the gas produced can be used more easily. This type of information is very important because it can maximise the use of existing feedstock, and make the most sensible use of the potential fuel, in the most sustainable and socially and financially useful manner.

Cattle market rice straw

Only 0.02% of the number of potential AD plants is suitable with cattle market rice straw but they contribute 14% of the total potential AD energy capacity which is almost in the same as the energy capacity of the poultry farms. A comparatively small number of large and extra large AD plants are thus suitable for cattle market rice straw. The locations of the cattle market are in both rural and urban areas of Bangladesh. The amount of energy from cattle markets rice straw is sufficient for electrification. Investment of a few large sized AD plants could ensure a significant amount of energy contribution at sites where that energy can be immediately used in more densely populated areas. However, more investment and expertise will be needed for these types of AD constructions. AD plant site selection would be an important factor to be considered because it could have positive and negative impact to the local community. For example, energy issues and availability of fertilizer would be the positive impact and AD operational activities, build of AD plant near residence might cause negative impact to the community.

Overview

The government target is to generate 5% of its total electricity using renewable energy technologies by 2015 and 10% by 2020 (Renewable Energy Policy, 2008). Ensuring the potential AD biogas production can play a vital role with this target. A comparison between the potential AD capacity and the present reality is shown in Table 9.4.

Table 9.4 Potential AD capacity is compared with the current status of AD.

Feedstock/Factor	**Potential number of AD plants**	**Current status**
Cattle dung	2,310,000	35,000
Poultry litter	63,000	5,000
Cattle market rice straw	500 (Large and Extra large)	0
Total	2,400,000	40,000
Present AD plant capacity (%)		**1.67**
Present AD energy capacity (%)		**0.67**

All of the results in the sections above provide crucial information for planning for businesses, civic authorities and national policy making. By considering these results and information, the government can plan, NGOs (Grameen Shakti) and international development organizations can take initiatives, monetary organizations (e.g. banks) can see the relevance of funding, and the documentation of the GWP impact can assist in getting CDM credit. Integration of all these efforts could make a realistic opportunity for AD energy generation with sustainable management.

9.2.2 Contribution to knowledge

In this thesis primary and secondary data has been analysed in a rigorous manner to assess the potential for AD to contribute to meeting Bangladesh's energy needs. This is a key contribution to knowledge as there have previously been few studies investigating the AD potential in Bangladesh. This is also the first study that undertakes an LCA to determine the potential impact of AD which shows the mitigation of Greenhouse gas emissions - this is a further contribution to knowledge.

The determination of the most appropriate AD feedstock and facility types is another contribution to knowledge of this research. Traditionally AD plants have been small or medium using cow dung and poultry litter as a feedstock. A key contribution to knowledge has been determination of the biogas and methane yield of cattle market rice straw and its energy potential - no previous studies have assessed this in Bangladesh. A further contribution has assessing the role of large commercial plants using cattle market rice straw.

Primary data was collected on animal populations on cattle small holdings, poultry farms and cattle markets. Few studies have looked at animal populations in Bangladesh previously and this data helps to understand potential AD capacity. Primary data has also been collected on actual gas yields from AD plants and therefore this is a further contribution to knowledge.

In addition, LCA of AD; a carbon estimation, is an important tools for CDM. An understanding of what types of facilities would contribute the most to energy and social changes and thus how they can be supported best e.g. with microfinancing for domestic and community based AD, and large investment for others. This has an impact on 6 million rural household (30 million people) of Bangladesh. This is an indirect contribution to knowledge of this research work.

Any district or area of Bangladesh can use these results as a footprint for developing AD systems in their territory/district of Bangladesh or as a template in the design of future legislation or costing for deployment of AD nationwide. The LCA of an AD plant develop an estimation of the potential mitigation of GHG emissions and have a scope to justify the socio economic benefit of the AD facilities.

This research determined the difference between the current AD status from the potential AD capacity and also identified factors that can significantly affect AD biogas yield. It also estimated the AD energy capacity and traditional fuel replacement, clarifying the social economic and environmental return of investment. Implementation of every single output of this research could act as a potential catalyst to the improvement of AD technology in Bangladesh.

9.3 Recommendations for further work

The background of this research is based on a developing country, Bangladesh that has significant energy and public health issues and generates a huge amount of organic waste. On the basis of the analysis, discussion, and interpretations of this research several recommendation can be drawn for further work.

A more critical analysis of realistic factors affecting biogas and methane yield should be undertaken for cattle market rice straw. Biogas and methane yield was determined in this research for rice straw that contained 15 - 20% of dung. The yield could be investigated using this feedstock with different percentages of cattle dung mixed with it. A significant amount of cow urine is mixed with cattle market rice straw waste. Further research on cattle market rice straw might be useful to investigate any further impact on biogas and methane yield while utilizing that feedstock.

Some factors affect biogas and methane yield and these are temperature, pH, C/N ratio, %TS and %VS of feedstock. Biogas and methane yield cause a significant impact on LCA. Therefore an advanced sensitivity analysis of those factors can assess exactly how sensitive those factors are to the biogas production and GWP through LCA.

Analysis of other feedstock types should be undertaken such as food waste, water hyacinth, municipal waste and wastes mixed with animal manure. Research could look at mixing the feedstocks to increase biogas yields. A feasibility study could be undertaken to find out the barriers and bottlenecks of implementing AD for different feedstocks in Bangladesh.

This thesis has focused on evaluating the lifecycle impact of AD but it is important to consider the economic and social impacts and related issues. Increased knowledge of these issues will provide a complete understanding on the role AD has to play in meeting the energy requirements of Bangladesh. Further research could look at financing of AD plants and see what realistically could be achieved.

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Appendix

Appendix 1 – Details of Simapro categorization Impact

The impact categories are Global warming potential (GWP), Acidification, Eutrophication (nutrification), Abiotic depletion Ozone layer depletion (ODP) Human toxicity, Fresh water aquatic ecotoxicity, Marine aquatic ecotoxicity, Terrestrial ecotoxicity and Photochemical oxidation

Global warming potential (GWP)

Climate change due to gases like carbon dioxide, methane which emissions increase greenhouse effect into the atmosphere means global warming. It is the greenhouse effect, equivalent to carbon footprint

Acidification

The acidifying effect of SO2 is called acidification. It means forest lakes destruction by acid rains caused by acid air emissions.

Eutrophication (nutrification**)**

Eutrophication is the impacts due to excessive levels of macro-nutrients in the environment. It means lack of oxygen and algae development in water streams or soil due to too high nitrogen and phosphorus concentration.

Abiotic depletion - extraction of minerals and fossil fuels.

Ozone layer depletion (ODP) - causes UV-B radiation reaching the earth surface.

Human toxicity - effects of toxic substances on the human environment

Fresh water aquatic ecotoxicity - impact on fresh water ecosystems,

Marine aquatic ecotoxicity - impacts of toxic substances on marine ecosystems.

Terrestrial ecotoxicity - impacts of toxic substances on terrestrial ecosystems.

Photochemical oxidation - potential capacity of a volatile organic substance to produce ozone.

Impact of individuals gas (CH_4, CO_2 and H_2S) - No impact of H_2, O_2 and N_2

Title:	**Analyzing 1 kg 'methane'**
Method:	CML 2 baseline 2000 V2.04 / World, 1995
Indicator:	Characterization
Skip categories:	Never
Relative mode:	Non

Impact category	**Unit**	**Total**	**methane**
Abiotic depletion	kg Sb eq	0	0
Acidification	kg SO_2 eq	0	0
Eutrophication	kg PO_4--- eq	0	0
Global warming (GWP100)	kg CO_2 eq	23	23
Ozone layer depletion (ODP)	kg CFC-11 eq	0	0
Human toxicity	kg 1,4-DB eq	0	0
Fresh water aquatic ecotox.	kg 1,4-DB eq	0	0
Marine aquatic ecotoxicity	kg 1,4-DB eq	0	0
Terrestrial ecotoxicity	kg 1,4-DB eq	0	0
Photochemical oxidation	kg C_2H_4	0.006	0.006

Title:	**Analyzing 1 kg 'CO_2'**
Method:	CML 2 baseline 2000 V2.04 / World, 1995
Indicator:	Characterization
Skip categories:	Never
Relative mode:	Non

Impact category	**Unit**	**Total**	**CO_2**
Abiotic depletion	kg Sb eq	0	0
Acidification	kg SO_2 eq	0	0
Eutrophication	kg PO_4--- eq	0	0
Global warming (GWP100)	kg CO_2 eq	1	1
Ozone layer depletion (ODP)	kg CFC-11 eq	0	0
Human toxicity	kg 1,4-DB eq	0	0
Fresh water aquatic ecotox.	kg 1,4-DB eq	0	0
Marine aquatic ecotoxicity	kg 1,4-DB eq	0	0
Terrestrial ecotoxicity	kg 1,4-DB eq	0	0
Photochemical oxidation	kg C_2H_4	0	0

Title:	**Analyzing 1 kg 'H_2S'**
Method:	CML 2 baseline 2000 V2.04 / World, 1995
Indicator:	Characterization
Skip categories:	Never
Relative mode:	Non

Impact category	**Unit**	**Total**	**H_2S**
Abiotic depletion	kg Sb eq	0	0
Acidification	kg SO_2 eq	0	0
Eutrophication	kg PO_4--- eq	0	0
Global warming (GWP100)	kg CO_2 eq	0	0
Ozone layer depletion (ODP)	kg CFC-11 eq	0	0
Human toxicity	kg 1,4-DB eq	0.22	0.22
Fresh water aquatic ecotox.	kg 1,4-DB eq	0	0
Marine aquatic ecotoxicity	kg 1,4-DB eq	0	0
Terrestrial ecotoxicity	kg 1,4-DB eq	0	0
Photochemical oxidation	kg C_2H_4	0	0

No impact of H_2, O_2 and N_2 (Example given for H)

Title:	**Analyzing 1 kg 'Hydrogen'**
Method:	CML 2 baseline 2000 V2.04 / World, 1995
Indicator:	Characterization
Skip categories:	Never
Relative mode:	Non

Impact category	**Unit**	**Total**	**Hydrogen**
Abiotic depletion	kg Sb eq	0	0
Acidification	kg SO_2 eq	0	0
Eutrophication	kg PO_4--- eq	0	0
Global warming (GWP100)	kg CO_2 eq	0	0
Ozone layer depletion (ODP)	kg CFC-11 eq	0	0
Human toxicity	kg 1,4-DB eq	0	0
Fresh water aquatic ecotox.	kg 1,4-DB eq	0	0
Marine aquatic ecotoxicity	kg 1,4-DB eq	0	0
Terrestrial ecotoxicity	kg 1,4-DB eq	0	0
Photochemical oxidation	kg C_2H_4	0	0

Appendix 2 – Details of the Orsat gas analyser

An **Orsat gas analyser** is a piece of laboratory equipment used to analyse a gas sample (typically fossil fuel flue gas) for its oxygen, carbon monoxide and carbon dioxide content. Although largely replaced by instrumental techniques, the Orsat remains a reliable method of measurement and is relatively simple to use.

Construction

The apparatus consists essentially of a calibrated water-jacketed gas burette connected by glass capillary tubing to two or three absorption pipettes containing chemical solutions that absorb the gasses it is required to measure. For safety and portability, the apparatus is usually encased in a wooden box. The absorbents are: Potassium Hydroxide (Caustic Potash), Alkaline pyrogallol and ammoniacal Cuprous chloride. The base of the gas burette is connected to a levelling bottle to enable readings to be taken at constant pressure and to transfer the gas to and from the absorption media. The burette contains slightly acidulated water with a trace of chemical indicator (typically methyl orange) for colouration.

Method of analysis

By means of a rubber tubing arrangement, the gas to be analyzed is drawn into the burette and flushed through several times. Typically, 100 mls is withdrawn for ease of calculation. Using the stopcocks that isolate the absorption burettes, the level of gas in the leveling bottle and the burette is adjusted to the zero point of the burette. The gas is then passed into the caustic potash burette, left to stand for about two minutes and then withdrawn, isolating the remaining gas via the stopcock arrangements. The process is repeated to ensure full absorption. After leveling the liquid in the bottle and burette, the remaining volume of gas in the burette indicates the percentage of carbon dioxide absorbed.

The same technique is repeated for oxygen, using the pyrogallol, and carbon monoxide using the ammoniacal cuprous chloride.

$KOH + CO_2 \dashrightarrow KCO_3 + H_2O$

Here KOH absorb CO_2. Biogas pass through KOH and CO_2, Pyrogallic acid absorb O_2, and amonical $Cucl_2$ absorb CO.

Orsat Gas analyser

Appendix 3 – Smallholdings/Farms survey sheet

Location : Gazipur Sadar. **Date:** **SL No:**

Name of the Poultry / Cattle Farm	
Location (in detail)	

(a)The number of Cattle population (25 house hold / Dairy random survey)

Number of Cattle			
1-2		11-20	
3-4		21-50	
5-6		51-100	
7-8		101-200	
8-10		More than 200	

Give tick mark (✓) for suitable box and Specify total numbers.

1. Food of Cattle:…………………..…………………………………………………..……
2. Biogas Operating (Yes / No) :……………………………………...……………………………
3. If Yes then what is the size of Biogas (m^3 per day) :……………………………………………….
4. Are they use Slurry as Fertilizer (Yes / No) :…………………….……………………...………

Name of Data Collector	
Signature and Date	

(b) Poultry farm random survey (25 samples)

Type	**Layer**		**Broiler**	
Size of Farm (Base on total Bird)				
Less than 500		5001-6000		
500-1000		6001-7000		
1001-2000		7001-8000		
2001-3000		8001-9000		
3001-4000		9001-10000		
4001-5000		More than 10000		

Give tick mark (✓) for suitable box and Specify total numbers.

1. Food of Poultry Bird ………………………………………………………………………………
2. Electricity Lighting per day (hours)………………………………………………………………….
3. Biogas Operating (Yes / No) ………………………………………………………………………
4. If Yes then what is the size of Biogas (m^3 per day)……………………………………………….
5. Use of biogas (Cooking/Hazak Lighting/Electricity Lighting)...
6. Are they use Slurry as Fertilizer (Yes/No)……………………….……………………

7.

(c)The number of Cattle Market

Size of Cattle market	**Number**	**Name of market**
Small (50-249 cow)		
Medium (250-449 cow)		
Large (500-999 cow)		
Very large (1000=1999)		
Extra large (more than 2000)		
Total		

Appendix 4 - 11 AD plant Visit to Bangladesh in January, 2009

An example of interview with AD entrepreneur (Barisal District)

The survey is given bellow as was done in the same day (12th January, 2009) in Barisal

Q1 Assalamualaikum
Ans Walaikum assalam
Q2 What is your name?
Ans Amit Sing
Q3 How many members do you have in your family?
Six
Q4 What advantages do you get from your domestic biogas plant?

a. I use gas for cooking purpose and it can meet up my purpose.
b. It can fulfil my fertilizer requirement
c. I got a clean environment after build up the plant
d. My medical expenses have been reduced recently
e. Life became easier
f. We don't need to collect biomass fuel and now we can save our time.

Q4 Do you have any comments against your biogas plant? If yes what are they?
Yes, A few

a. Gas supply is very less and some time stopped in winter season
b. It is difficult to rotate the feedstock by the conventional method, some time it can make the chest pain

Q5 Any more disadvantage?
No Sir
Q6 What are the impressions of your neighbours about your plant?
They are happy and show positive attitude
Q7 So, having advantages and disadvantages what are your final comments about the plant?
Having few problems in winter season for few days I am very happy and winner to have such a plant.

Thank you very much for answering my question having patient.

Detailed information of visited 11 AD plants

AD Plant 1 (Barisal District)

Location : William para, Baptist Mission Road, Barisal, Bangladesh
Owner : Amit Sing (01712-745853)

No of parameter	Parameter	Data to be collected	Amount/value	Measurement unit
1	Feedstock	Number of Cattle	5	
		Amount of dung production	50	Kg/day
		Pipe to deliver to digester	Sand, Cement	
		Transport to digester	manually	
2	Water	Quantity of water	50	Litre
		Transport	manually	
3	Digester	Materials needed for digester	Sand, Brick, Cement	
		Size of digester (biogas yield)	3.2	m3
		Thickness of digester	10	inches
		Replacement of digester	Fix for 10 years	
		Cost to build up plant	40000 TK(£400)	Taka/Pound
4	Gas pipe output	Materials	Plastic pipe	
		Length of pipe	40	Ft
		Replacement	10 year	
5	Process	Temperature	20	°C
		Control temperature	No controller	
		Time of processing	45 days	
6	Products	Amount of biogas	.037	m3/kg feedstock
		Solid materials	50	Kg
		Liquid residue	50	Litre
		Trace element		
7	Social issue	Consumer satisfaction		
		Social survey	Done	

AD plant 2
Location : Hawlader Bari, North Sagordi, Barisal, Bangladesh
Owner : Rajab Ali Hawlader (03742001262)

No of parameter	**Parameter**	**Data to be collected**	**Amount/value**	**Measurement unit**
1	Feedstock	Number of Cattle	4	
		Amount of dung production	40	Kg/day
		Pipe to deliver to digester	Sand, Cement	
		Transport to digester	manually	
2	Water	Quantity of water	40	Litre
		Transport	manually	
3	Digester	Materials needed for digester	Sand, Brick, Cement	
		Size of digester (biogas yield)	2.4	m3
		Thickness of digester	10	inches
		Replacement of digester	Fix for 10 years	
		Cost to build up plant	30000 TK(£300)	Taka/Pound
4	Gas pipe output	Materials	PVC	
		Length of pipe	40	Ft
		Replacement	10 year	
5	Process	Temperature	20	°C
		Control temperature	No controller	
		Time of processing	45 days	
6	Products	Amount of biogas	.037	m3/kg feedstock
		Solid materials	40	Kg
		Liquid residue	40	Litre
		Trace element		
7	Social issue	Consumer satisfaction		
		Social survey	Done	

Biogas plant 1 and 2 was visited on 12th January, 2009

AD plant 3
Location : Hemayetpur, Savar, Dhaka, Bangladesh
Owner : Tarikul Haque

No of parameter	**Parameter**	**Data to be collected**	**Amount/value**	**Measurement unit**
1	Feedstock	Number of Cattle	35	
		Amount of dung production	525	Kg/day
		Pipe to deliver to digester	Sand, Cement/10ft	
		Transport to digester	manually	
2	Water	Quantity of water	525	Litre
		Transport	manually	
3	Digester	Materials needed for digester	Sand, Brick, Cement	
		Size of digester (biogas yield)	14	m3
		Thickness of digester	10	inches
		Replacement of digester	Fix for 10 years	
		Cost to build up plant	200000 TK(£2000)	Taka/Pound
4	Gas pipe output	Materials	PVC	
		Length of pipe	70	Ft
		Replacement	10 year	
5	Process	Temperature	20	°C
		Control temperature	No controller	
		Time of processing	45 days	
6	Products	Amount of biogas	.037	m3/kg feedstock
		Solid materials	525	Kg
		Liquid residue	525	Litre
		Trace element		
7	Social issue	Consumer satisfaction		
		Social survey	Done	

AD plant 4
Location : Hemayetpur, Savar, Dhaka, Bangladesh
Owner : Tarikul Haque

No of parameter	**Parameter**	**Data to be collected**	**Amount/value**	**Measurement unit**
1	Feedstock	Number of Cattle	35	
		Amount of dung production	525	Kg/day
		Pipe to deliver to digester	Sand, Cement/10ft	
		Transport to digester	manually	
2	Water	Quantity of water	525	Litre
		Transport	manually	
3	Digester	Materials needed for digester	Sand, Brick, Cement	
		Size of digester (biogas yield)	14	m3
		Thickness of digester	10	inches
		Replacement of digester	Fix for 10 years	
		Cost to build up plant	200000 TK(£2000)	Taka/Pound
4	Gas pipe output	Materials	PVC	
		Length of pipe	70	Ft
		Replacement	10 year	
5	Process	Temperature	2o	°C
		Control temperature	No controller	
		Time of processing	45 days	
6	Products	Amount of biogas	.037	m3/kg feedstock
		Solid materials	525	Kg
		Liquid residue	525	Litre
		Trace element		
7	Social issue	Consumer satisfaction		
		Social survey	Done	

AD plant 5
Location : Joymondop, Singair, Manikgong, Bangladesh
Owner : Nurul

No of parameter	**Parameter**	**Data to be collected**	**Amount/value**	**Measurement unit**
1	Feedstock	Number of Cattle	4	
		Amount of dung production	40	Kg/day
		Pipe to deliver to digester	Sand, Cement/10ft	
		Transport to digester	manually	
2	Water	Quantity of water	40	Litre
		Transport	manually	
3	Digester	Materials needed for digester	Sand, Brick, Cement	
		Size of digester (biogas yield)	3	m3
		Thickness of digester	10	inches
		Replacement of digester	Fix for 10 years	
		Cost to build up plant	25000 TK(250)	Taka/Pound
4	Gas pipe output	Materials	PVC	
		Length of pipe	60	Ft
		Replacement	10 year	
5	Process	Temperature	22	°C
		Control temperature	No controller	
		Time of processing	45 days	
6	Products	Amount of biogas	.037	m3/kg feedstock
		Solid materials	40	Kg
		Liquid residue	40	Litre
		Trace element		
7	Social issue	Consumer satisfaction		
		Social survey	Done	

AD plant 6
Location : Joymondop, Singair, Manikgong, Bangladesh
Owner : Ashraful Jamal

No of parameter	**Parameter**	**Data to be collected**	**Amount/value**	**Measurement unit**
1	Feedstock	Number of Cattle	7	
		Amount of dung production	70	Kg/day
		Pipe to deliver to digester	Sand, Cement/10ft	
		Transport to digester	manually	
2	Water	Quantity of water	70	Litre
		Transport	manually	
3	Digester	Materials needed for digester	Sand, Brick, Cement	
		Size of digester (biogas yield)	3.2	m3
		Thickness of digester	10	inches
		Replacement of digester	Fix for 10 years	
		Cost to build up plant	25000 TK(250)	Taka/Pound
4	Gas pipe output	Materials	PVC	
		Length of pipe	40	Ft
		Replacement	10 year	
5	Process	Temperature	22	°C
		Control temperature	No controller	
		Time of processing	45 days	
6	Products	Amount of biogas	.037	m3/kg feedstock
		Solid materials	70	Kg
		Liquid residue	70	Litre
		Trace element		
7	Social issue	Consumer satisfaction		
		Social survey	Done	

AD plant 7
Location : Kamta, Saturia, Manikgong, Bangladesh
Owner : Shohrab Hossain

No of parameter	Parameter	Data to be collected	Amount/value	Measurement unit
1	Feedstock	Number of Cattle	3	
		Amount of dung production	30	Kg/day
		Pipe to deliver to digester	Sand, Cement/10ft	
		Transport to digester	manually	
2	Water	Quantity of water	30	Litre
		Transport	manually	
3	Digester	Materials needed for digester	Sand, Brick, Cement	
		Size of digester (biogas yield)	2.4	m3
		Thickness of digester	10	inches
		Replacement of digester	Fix for 10 years	
		Cost to build up plant	20000 TK(200)	Taka/Pound
4	Gas pipe output	Materials	PVC	
		Length of pipe	40	Ft
		Replacement	10 year	
5	Process	Temperature	22	°C
		Control temperature	No controller	
		Time of processing	45 days	
6	Products	Amount of biogas	.037	m3/kg feedstock
		Solid materials	30	Kg
		Liquid residue	30	Litre
		Trace element		
7	Social issue	Consumer satisfaction		
		Social survey	Done	

AD plant 8
Location : Kamta, Saturia, Manikgong, Bangladesh
Owner : Abdul Malek

No of parameter	Parameter	Data to be collected	Amount/value	Measurement unit
1	Feedstock	Number of Cattle	4	
		Amount of dung production	40	Kg/day
		Pipe to deliver to digester	Sand, Cement/10ft	
		Transport to digester	manually	
2	Water	Quantity of water	40	Litre
		Transport	manually	
3	Digester	Materials needed for digester	Sand, Brick, Cement	
		Size of digester (biogas yield)	2.4	m3
		Thickness of digester	10	inches
		Replacement of digester	Fix for 10 years	
		Cost to build up plant	20000 TK(200)	Taka/Pound
4	Gas pipe output	Materials	PVC	
		Length of pipe	60	Ft
		Replacement	10 year	
5	Process	Temperature	20	°C
		Control temperature	No controller	
		Time of processing	45 days	
6	Products	Amount of biogas	.037	m3/kg feedstock
		Solid materials	40	Kg
		Liquid residue	40	Litre
		Trace element		
7	Social issue	Consumer satisfaction		
		Social survey	Done	

AD plant 9
Location : Kamta, Saturia, Manikgong, Bangladesh
Owner : Antor Ali

No of parameter	**Parameter**	**Data to be collected**	**Amount/value**	**Measurement unit**
1	Feedstock	Number of Cattle	4	
		Amount of dung production	40	Kg/day
		Pipe to deliver to digester	Sand, Cement/10ft	
		Transport to digester	manually	
2	Water	Quantity of water	40	Litre
		Transport	manually	
3	Digester	Materials needed for digester	Sand, Brick, Cement	
		Size of digester (biogas yield)	2.4	m3
		Thickness of digester	10	inches
		Replacement of digester	Fix for 10 years	
		Cost to build up plant	20000 TK(200)	Taka/Pound
4	Gas pipe output	Materials	PVC	
		Length of pipe	60	Ft
		Replacement	10 year	
5	Process	Temperature	20	°C
		Control temperature	No controller	
		Time of processing	45 days	
6	Products	Amount of biogas	.037	m3/kg feedstock
		Solid materials	40	Kg
		Liquid residue	40	Litre
		Trace element		
7	Social issue	Consumer satisfaction		
		Social survey	Done	

AD plant 10
Location : Kamta, Saturia, Manikgong, Bangladesh
Owner : Ramjan Ali

No of parameter	**Parameter**	**Data to be collected**	**Amount/value**	**Measurement unit**
1	Feedstock	Number of Cattle	4	
		Amount of dung production	40	Kg/day
		Pipe to deliver to digester	Sand, Cement/10ft	
		Transport to digester	manually	
2	Water	Quantity of water	40	Litre
		Transport	manually	
3	Digester	Materials needed for digester	Sand, Brick, Cement	
		Size of digester (biogas yield)	2.4	m3
		Thickness of digester	10	inches
		Replacement of digester	Fix for 10 years	
		Cost to build up plant	20000 TK(200)	Taka/Pound
4	Gas pipe output	Materials	PVC	
		Length of pipe	40	Ft
		Replacement	10 year	
5	Process	Temperature	20	°C
		Control temperature	No controller	
		Time of processing	45 days	
6	Products	Amount of biogas	.037	m3/kg feedstock
		Solid materials	40	Kg
		Liquid residue	40	Litre
		Trace element		
7	Social issue	Consumer satisfaction		
		Social survey	Done	

Biogas plant 3-10 was visited on 14 January, 2009

AD plant 11
Location : Fulpur, Mymensingh, Bangladesh
Owner : Customer number 150 (Mohammad)

No of parameter	**Parameter**	**Data to be collected**	**Amount/value**	**Measurement unit**
1	Feedstock	Number of Poultry	1000	
		Amount of Excreta production	100	Kg/day
		Pipe to deliver to digester	Sand, Cement/10ft	
		Transport to digester	manually	
2	Water	Quantity of water	20	Litre
		Transport	manually	
3	Digester	Materials needed for digester	Sand, Brick, Cement	
		Size of digester (biogas yield)	3.2	m3
		Thickness of digester	10	inches
		Replacement of digester	Fix for 10 years	
		Cost to build up plant	25000 TK(250)	Taka/Pound
4	Gas pipe output	Materials	PVC	
		Length of pipe	60	Ft
		Replacement	10 year	
5	Process	Temperature	20	°C
		Control temperature	No controller	
		Time of processing	45 days	
6	Products	Amount of biogas	.037	m3/kg feedstock
		Solid materials	10	Kg
		Liquid residue	20	Litre
		Trace element		
7	Social issue	Consumer satisfaction		
		Social survey	Done	

Biogas plant 11 was visited on 26th January, 2009

Appendix 5 Calculation

Box 1: Conversion of volume to mass

Example for CH_4, Methane

Production of Biogas	A = 0.037 m^3/kg dung
Volume % of CH_4 in biogas	B = 60 %
Volume of CH_4 per kg dung	V = A*B
	= 0.0222 m^3 per kg dung
Density of CH_4	D = 0.6565 kg / m^3 (Miller)
Weight	W = Density * Volume
	= D*V
Weight of CH_4	= 0.0146 kg / kg dung
CH_4 production from 1 kg dung	= 0.0146 kg
CH_4 production of 87 kg (daily)	= 1.27 kg

The daily charge of dung is 87 kg for a 3.2 m^3 biogas plant operated by Grameen Shakti. So the daily CH_4 production from a 3.2 m^3 biogas plant is 1.27 kg.

Box 2: Conversion of weight of CO_2 per known weight of CH_4

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_20$$

Using the molecular ratio equation

$$W_{CO2}/ MW_{CO2} = W_{CH4}/ MW_{CH4}$$

$$W_{CO2} = W_{CH4} * MW_{CO2}/ MW_{CH4}$$

Where

W = weight

MW = molecular weight, MW_{CH4} = 44 and MW_{CO2} = 16

Then for W_{CH4} = 1.45 kg CH_4

$$W_{CO2}= 1.45 *44/16= 3.99 \text{ kg } CO_2 \text{ daily}$$

Appendix 6 - Impact of digestate using Simapro

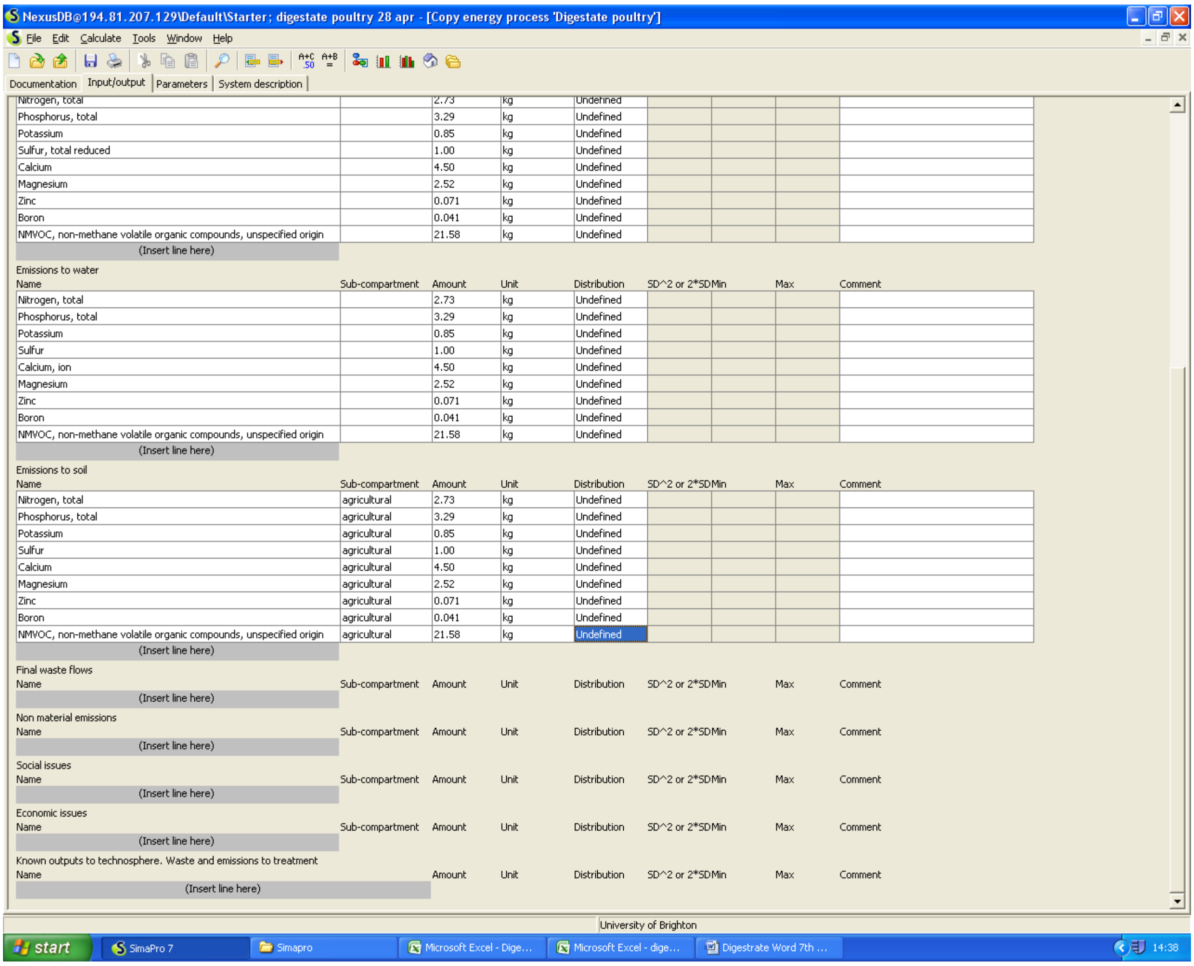

Figure An example of Simapro model sheet to put data input of digestate components

Title:	**Analyzing 1 kg 'Digestate nitrogen'**
Method:	CML 2 baseline 2000 V2.04 / World, 1995
Indicator:	Characterization
Skip categories:	Never
Relative mode:	Non

Impact category	**Unit**	**Total**	**Digestate nitrogen**
Abiotic depletion	kg Sb eq	0	0
Acidification	kg SO_2 eq	0	0
Eutrophication	kg PO_4--- eq	0.42	0.42
Global warming (GWP100)	kg CO_2 eq	0	0
Ozone layer depletion (ODP)	kg CFC-11 eq	0	0
Human toxicity	kg 1,4-DB eq	0	0
Fresh water aquatic ecotox.	kg 1,4-DB eq	0	0
Marine aquatic ecotoxicity	kg 1,4-DB eq	0	0
Terrestrial ecotoxicity	kg 1,4-DB eq	0	0
Photochemical oxidation	kg C_2H_4	0	0

Title: **Analyzing 1 kg 'Digestate phosphorus'**
Method: CML 2 baseline 2000 V2.04 / World, 1995
Indicator: Characterization
Skip categories: Never
Relative mode: Non

Impact category	Unit	Total	Digestate phosphorus
Abiotic depletion	kg Sb eq	0	0
Acidification	kg SO_2 eq	0	0
Eutrophication	kg PO_4 eq	3.06	3.06
Global warming (GWP100)	kg CO_2 eq	0	0
Ozone layer depletion (ODP)	kg CFC-11 eq	0	0
Human toxicity	kg 1,4-DB eq	0	0
Fresh water aquatic ecotox.	kg 1,4-DB eq	0	0
Marine aquatic ecotoxicity	kg 1,4-DB eq	0	0
Terrestrial ecotoxicity	kg 1,4-DB eq	0	0
Photochemical oxidation	kg C_2H_4	0	0

Title: Analyzing 1 kg 'Digestate Zinc'
Method: CML 2 baseline 2000 V2.04 / World, 1995
Indicator: Characterization
Skip categories: Never
Relative mode: Non

Impact category	**Unit**	**Total**	**Digestate Zinc**
Abiotic depletion	kg Sb eq	0	0
Acidification	kg SO_2 eq	0	0
Eutrophication	kg PO_4 eq	0	0
Global warming (GWP100)	kg CO_2 eq	0	0
Ozone layer depletion (ODP)	kg CFC-11 eq	0	0
Human toxicity	kg 1,4-DB eq	63.7	63.7
Fresh water aquatic ecotox.	kg 1,4-DB eq	47.7	47.7
Marine aquatic ecotoxicity	kg 1,4-DB eq	7210	7210
Terrestrial ecotoxicity	kg 1,4-DB eq	24.6	24.6
Photochemical oxidation	kg C_2H_4	0	0

Academic output of this research

Workshop report on “Promotion of renewable energy technologies to rural stakeholders” Mymensingh, Bangladesh, January 26, 2009. Published in Journal Global Build Environment Review, GBER Vol. 7 No. 1 pp 71-74 (http://www.edgehill.ac.uk/gber/pdf/vol7/issue1/ WorkshopReportMizanurRahman pdf).

Presented research result in London Imperial College on 9th February, 2011 organized by CIWM, DEFRA and London Imperial College, UK (http://www.ciwm.co.uk/web/FILES/ LondonandSouthernCentre/K_M_R_Presentation_ CIWM_ -_ Final.pdf)

Presented research work in Nottingham Conference, 29-30 June, 2009 held in the Jubilee Campus, University of Nottingham. Sixth annual conference showcasing novel and innovative approaches to tackling waste, WARMNET conference, 2009. Organised by The University of Northampton and the University of Notttingham, UK.

Presented research findings in the First International Conference on Microfinance and Renewable energy (University Meet Microfinance, 2009) organized by Planet Finance and European Union in ULB, Brussels, 5th June, 2009