KTH Industrial Engineering and Management

FEASIBILITY ANALYSIS OF BIOGAS BASED POLYGENERATION FOR RURAL DEVELOPMENT IN BANGLADESH

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To Fariduddin Ahmed Chisty (my grandfather),
my beloved parents, my lovely wife Prianka and
daughter Tamanna for showing the true meaning of love

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Abstract

Around three-quarters of Bangladeshis (total population 164 million) live in rural areas: only 25% of these households have access to grid electricity with non-reliable supply despite the country's successful rural electrification program, kerosene is the predominant source for lighting, and woody biomass is virtually the only option available for cooking. Aside from this energy service challenges the rural population also struggles with unsafe drinking water in terms of widespread arsenic contamination of well water. Access to electricity, clean cooking gas, and safe drinking water services are genuine needs of the rural poor and are essential to improving welfare. These needs can be addressed individually or using an integrated approach. Anaerobic digesters are now a proven technology and remain economically promising in the rural setting, where connection to the public electric and gas grids are not available/either not cost effective or feasible, and where energy and water scarcity are severe. As the technologies continue to improve, and as energy and safe water becomes scarce and fossil fuel energy prices rise, renewable energy based services and technological integration becomes more viable techno-economically. In these circumstances, the integration of biogas digester with power generation and water purification unit is an innovative concept that could be applied in remote areas of Bangladesh.

This work presents a new concept for integrated polygeneration and analyzes the techno-economic performance of the scheme for meeting the demand of electricity, cooking energy and safe drinking water of 30 households in a rural village of Bangladesh. This study considers a holistic approach towards tackling both of these issues via integrated renewable energy-based polygeneration employed at the community level. The polygeneration unit under consideration provides electricity via cow dung-fed digester, which in turn is coupled to a gas engine. Excess digester gas is employed for cooking, while waste heat from the process drives a membrane distillation unit for water purification. The specific technologies chosen for the key energy conversion steps are as follows: plug-flow digester; internal combustion engine; and air-gap membrane distillation. The technical features, energy consumption, and potential of renewable energy use in driving the main integrated processes are reviewed and analyzed in this thesis. This study also examines one approach by investigating the application of suitable membrane technologies, specifically air gap membrane distillation (AGMD), as a promising method for small-scale, low cost deployment.

Experimental results show that the tested AGMD prototype is capable of achieving high separation efficiency, as all product water samples showed arsenic levels below accepted limits. Mass flows and energy balance, life cycle cost (levelized cost) of producing electricity, cooking gas and safe drinking water as well as the payback period of such a polygeneration system were studied. The results indicate that this polygeneration system is much more competitive and promising than other available technologies when attempting to solve the energy and arsenic-related problems in Bangladesh. One of the main encouraging issues of this integrated system is the levelized cost of the three major services: cooking gas (0.015 USD/kWh), electricity (0.042 USD/kWh–an orders of magnitude lower than comparable photovoltaic or wind systems) and safe drinking water (0.003 USD/liter). Additionally, the payback period is between 2.6 to 4 years.

Keywords: Anaerobic digester; polygeneration; cooking gas; gas engine; electricity; membrane distillation; arsenic safe water

Sammanfattning

Ungefär tre fjärdedelar av alla Bangladeshs invånare (totalt 164 miljoner) bor på landsbyggden. Endast 25 % av dessa hushåll har tillgång till elnätet med osäker eltillgång, trots landets framgångsrika elektrifieringsprogram. Fotogen är den huvudsakliga källan till ljus, medan träbaserad biomassa är praktiskt taget det enda tillgängliga alternativet för matlagning. Bortsett från dessa utmaningar i energisystemet kämpar även befolkningen mot förgiftat dricksvatten på grund av en utbredd arsenikförgiftning av grundvattnet. Tillgång till elektricitet, ren gas till matlagning och säkert dricksvatten är sanna behov bland de fattiga på landsbyggden, och grundläggande för att öka välfärden. Dessa behov kan tillgodoses individuellt eller genom ett integrerat tillvägagångssätt. Anaerobiska rötkammare bygger på beprövad teknik, och är fortsatt ekonomiskt lovande på landsbyggden som saknar tillgång till de allmänna gas- och elnäten, av antingen praktiska eller ekonomiska skäl, och där energi- och vattentillgången är mycket begränsad. I takt med att teknikerna fortsätter att utvecklas begränsas samtidigt tillgången till energi och rent vatten ytterligare, på grund av att priserna på fossila bränslen ökar. Detta gör förnyelsebara energitjänster och teknisk integrering mer techno-ekonomiskt gångbart. I denna situation är integrering av biogasrötkammare med kraftproduktion och vattenrening ett innovativt koncept som skulle kunna tillämpas i avlägsna områden i Bangladesh.

Detta arbete visar ett nytt koncept för integrerad polygenerering och analyserar den techno-ekonomiska prestandan av systemet i fråga om att uppnå efterfrågan av elektricitet, gas för matlagning, och rent dricksvatten för 30 hushåll i en avlägsen by i Bangladesh. Studien antar ett holistiskt tillvägagångssätt för att tackla alla dessa problem genom integrerad förnyelsebar energibaserad polygenerering, utförd på lokal nivå. Den aktuella polygenereringsenheten genererar elektricitet genom en gödselmatad rötkammare, som i sin tur är kopplad till en förbränningsmotor. Överflödig gas används till matlagning, medan överskottsvärmet driver en membrandestillationsenhet för vattenrening. De specifika teknikerna valda för varje steg i processen är följande: plug-flow-rötkammare, förbränningsmotor, luftspallt membrandestillering. Tekniska aspekter, energiåtgång, samt potential för att driva processen med förnyelsebar energi har undersökts och analyserats genom arbetet. Studien undersöker också tillämpningen av olika membrantekniker. Särskilt luftspallt membrandestillering (AGMD) framstår som en lovande metod för småskaliga tillämpningar, med låg investeringskostnad.

Experimentella resultat visar att den testade AGMD-prototypen kan nå hög avskiljningsgrad, då alla vattenprov visade godkända arseniknivåer, under gränsvärdena. Massflöden, energibalans och livscykelkostnad (levelized kostnad) har undersökts för kraftproduktion tillsammans med framställning av gas och rent dricksvatten. Även återbetalningstiden för av polygenereringsanläggningen har undersökts. Resultaten visar att denna typ av anläggning är mycket mer konkurrenskraftig och lovande än andra tillgängliga tekniker, i avseende att lösa energi- och arsenikproblemen i Bangladesh. En av de främsta fördelarna med det integrerade systemet är levelized kostnad av de tre huvudsakliga produkterna: gas (0.015 USD/kWh), elektricitet (0.042 USD/kWh) (en storleksordning lägre än motsvarande solcell- eller vindkraftssytem), samt rent dricksvatten (0.003 USD/liter). Dessutom är återbetalningsperioden 2.6 till 4 år.

Nyckelord: Rötkammare; polygenerering; matlagning gas; gasmotor; elektricitet; membrandestillering; arsenik säkert vatten

Preface

The present thesis is based on the following publications:

I. **Khan Ershad Ullah,** Mainali Brijesh, Martin Andrew, Silveira Semida, 2014 "Techno-Economic Analysis of Small Scale Biogas Based Polygeneration Systems: Bangladesh case study", *Sustainable Energy Technologies and Assessments 7(2014) 68-78*.

II. **Khan Ershad Ullah,** Martin Andrew, 2014, "Water purification of arsenic-contaminated drinking water via air gap membrane distillation (AGMD)", *Periodica Polytechnica, Mechanical Engineering*, 58 (2014), 47-53. *http://www.pp.bme.hu/me/article/view/7422*.

Other publications related to this research but not included in the thesis:

III. **Khan Ershad Ullah,** Martin Andrew, 2014. Integrated Renewable Energy with Membrane Distillation Polygeneration for Rural Households in Bangladesh, accepted to the 6th International Conference on Applied Energy-ICAE2014, Taipei, Taiwan.

IV. **Khan Ershad Ullah,** Martin Andrew, 2014. Biogas from anaerobic co-digestion for energy off-grid rural households in Bangladesh, abstract accepted to World Bioenergy Conference 2014, Jönköping, Sweden.

Contribution of the thesis author:

Paper I: First author was main author; research idea, technical analysis, mass and energy balance and system integration were done by the first author. Second author has partly involved with economic analysis and levelized costs of energy, payback time and IRR calculations. Third author acted as the main mentor and reviewer and fourth author also acted as reviewer.

Paper II: First author was main author; experimental work, analysis have been performed by the first author. System analysis and parametric studies were also done by the first author. The second author acted as mentor and reviewer for the experimental works, results and articles.

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Abbreviations and Nomenclature

AD	Anaerobic Digester
AGMD	Air-Gap Membrane Distillation
BCSIR	Bangladesh Council of Scientific and Industrial Research
BBS	Bangladesh Bureau Statistics
BPDB	Bangladesh Power Development Board
CHP	Combined Heat and Power
CH_4	Methane
CDM	Clean Development Mechanism
CER	Emission Reduction Credits
CO_2	Carbon Dioxide
DCMD	Direct Contact Membrane Distillation
DESCO	Dhaka Electric Supply Company Ltd
DPDC	Dhaka Power Distribution Company Ltd
HRSG	Heat Recovery Steam Generator
EHRS	Exhaust Heat Recovery System
FHC	Feedstocks Handling Costs
FAOSTAT	Food and Agriculture Organization of the United Nations
GS	Grameen Shakti
GIZ	German Technical Cooperation
GHG	Greenhouse Gas
H_2S	Hydrogen Sulphide
IDCOL	Infrastructure Development Company Limited
IEA	International Energy Agency
IRR	Internal Rate of Return
IAEA	International Atomic Energy Agency
IEA	International Energy Agency
LCOE	Levelized Cost of Energy
LHV	Lower heating value of a fuel
LGED	Local Government Engineering Department
MD	Membrane Distillation
MSF	Multi-Stage Flash
MSW	Municipal Solid Waste
$\dot{m}$	Mass flow rate
NDBMP	National Domestic Biogas and Manure Programme
NPV	Net Present Value
NGO	Non-government Organization
O&M	Operation and Maintenance
PPM	Parts Per Million
PV	Photo Voltaic
PSMP	Power System Master Plan
PBS	Palli Bidyut Samity
BREB	Bangladesh Rural Electrification Board
RET	Renewable Energy Technology
RO	Reverse Osmosis
SIDA	Swedish International Development Cooperation Agency
SO_2	Sulphur Dioxide

SNV	Netherlands Development Organization
SED	Sustainable Energy for Development
TRR	Thermal recovery rate
VMD	Vacuum Membrane Distillation
WHO	World Health Organization
WZPDCL	West Zone Power Distribution Company Limited

1. Introduction

1.1 Study background and motivation

Energy is one of the key and basic ingredients required to alleviate poverty, improved standard of life and socio-economic development and environmental sustainability. The future economic development of Bangladesh is likely to result in a rapid growth in the demand for energy with accompanying shortages and problems. Though, Bangladesh has been facing a severe energy crisis for about two decades and third among the top twenty countries where people lack access to electricity [SE4ALL, 2013]. Eventually, rural areas of the country have faces severe crisis often have limited or no public energy supply. Only theoretically 30% of the rural population has access to national grid electricity while about 75% of the total population (164.2 million, 2012) in the country live in this area, though the quality of service is quite unreliable and the availability of electricity is only 23% [Chakrabarty et al., 2013; BREB, 2010]. Only 6-8% of households have natural gas connection mostly in urban and semi-urban areas through national pipeline for cooking purposes but unfortunately remote and rural areas have no natural gas access [Chakrabarty et al., 2013]. Most recent estimate shows that 58 percent of rural households in Bangladesh are officially “energy poor (the consumption of modern energy per capita in these regions is very low),” and lack of access to even basic energy services [Barnes et al., 2011]. In such regions energy needs are met with traditional biomass fuels. Biomass fuel is estimated to cover about 62% of the country’s energy consumption [Al-muyeed and Shadullah, 2010] and cover most of energy consumption mainly for cooking. Some 95 percent of Bangladeshi households collect or purchase biomass energy with which to cook all or part of their meals, mainly using fixed clay stoves [Asaduzzaman et al., 2010]. Conventional cooking stoves based on biomass burning, however, have a very low energy efficiency of 5–15% [Hossain, 2003] which may lead to high pressure on forest resources, and increased air pollution from smoke, resulting in public health problems (e.g., eye infections and respiratory diseases). Traditional energies also impose both personal and social costs to end-user as the time spent for collecting traditional fuels by family members, the considerable quantity of fuel and associated labour needed and the distance of fuel-sources from home often travelled by foot [Bhattacharya, 2006; Sarkar et al., 2003].

Though, the electrification of rural villages in remote areas requires large investment and leads to power losses associated with transmission and distribution networks. Therefore, it is very clear that many villages and isolated areas may not be connected in the near future to conventional electricity generation and distribution networks [Mondal et al., 2010]. Moreover, intensive energy demand with economic development and population growth and lack of fossil fuel availability, limited power generation and infrastructure capacity, increasing the import fuel price and fuel security, vulnerable of environment due to fossil fuel combustion, the renewable energy could be an inevitable option and play a significant rule in order to achieve sustainable development as a whole for rural Bangladesh. The main renewable energy resources in Bangladesh are biomass, solar, wind and hydropower [Hossain and Badr, 2007]. Though, hydropower potential is limited due to the relatively flat land topography and wind power generation has certain limitations due to the lack of reliable wind speed data and seasonal variation, another potential source is solar energy but capital investment costs are very high [Al-Muyeed and Shadullah, 2010]. The combination of increasing energy demand, limited amount of natural resources available, and lack of clean renewable energy has led to a burgeoning interest in biogas technology in Bangladesh. Anaerobic digestion (AD) and biogas technology provides an effective and efficient method for turning residues from agriculture and livestock farming into biogas, useful fibers and liquid fertilizer. Especially in less developed countries such as Bangladesh, AD has seen resurgent interest due to its potential for manure stabilization, sludge reduction, odor control, and energy production [Cantrel et al., 2008]. Several studies such as [Bala and Hossain, 1992; Bhat et al., 2001; Biswas and Lucas, 1997; Biswas, 2011; Ghimire, 2012; Kandpal et al., 1991; Katuwal and Bohara, 2009] have reported on the techno-economic viability of biogas plants in rural areas of South Asian countries. It provides clean and efficient fuels that can be used for several end uses, including cooking, water heating and cooling applications. Another important application of biogas is power generation through internal combustion engines to drive electric generators in rural areas. If properly treated, biogas can be used in such engines to generate electricity [Monterio et al., 2011]. There is mature, reliable high quality technology available on the global market. Whereas using biogas for only cooking is more common, generating electricity is relatively rare in Bangladesh. In developed countries, power generation is the main purpose of biogas plants and conversion of biogas to electricity has become a standard technology.

Not only lack of electricity but also safe water scarcity is threatening social and economic growth in rural areas of developing countries like Bangladesh. Although Bangladesh has a plenty of surface and underground water, unfortunately water-borne diseases in surface water and recent arsenic contamination in underground (ACU) water have posed a great challenge [Stephan et al., 2008]. In urban areas large cities, the only option tap water which is supply through pipe line network where surface and groundwater are treated in central water treatment plants. But, the rural water supply is highly decentralized and depends on potable groundwater because of the surface water has greater risk of pollution with pathogens and other inorganic pollutants. Before 1970s people of rural Bangladesh used to use surface water as major source of water for drinking and cooking purposes. Presently, 97% of the rural population drinks underground water through 12 millions of hand-pump tubewells from depth of 15-60 meters [Stephan et al., 2008]. But this success was challenged by the discovery of widespread arsenic contamination in groundwater exceeding the Bangladesh drinking water local standard of 50 microgram per liter. Though, the World Health Organization (WHO) recommends a safe limit for As in drinking water of 10 microgram per liter. A recent survey looked that the contamination extents very rapidly all over the country since its first identification in 1993 and presently 61 districts out of 64 (except hilly regions) are affected by excessive level of arsenic in groundwater [Khan et al., 2006; Khan et al., 2003]. The concentration of arsenic in groundwater ranges less than 0.25 µg/L to more than 1600 µg/L [Smedley and Kinniburgh, 2002]. The impact of arsenic in drinking water in Bangladesh is huge and complex. This has resulted in a major public health crisis with as many as 70 million people possibly at risk [IAEA, 2011]. A number of alternative arsenic-free water supply technologies are identified and tested in several affected areas of Bangladesh [Howard et al., 2006; Hoque et al., 2000] by government agencies aided by international organizations. Unfortunately all these options are limited by one or more problems like seasonally varies bacterial contamination, high health risks, less acceptance, difficulties in maintenance due to cost, time and labour and uncertainty [Howard et al., 2006; Hoque et al., 2004; Hoque et al., 2000]. Additionally, in coastal regions people face more challenges due the salt intrusion in surface water and shallow aquifers. Lack of appropriate technologies has complicated and inhibited mitigation initiatives. The government and its national and international development partners developed various arsenic mitigation technologies for water supply, but most of the arsenic removal technologies were promoted without sound testing and showed poor, questionable and/or confusing performance in real situations. Also, use of most of the arsenic removal technologies was discontinued after a few to several months of installation [Manna et al., 2010; Chakraborti et al., 2010; Figoli et al., 2010; Uddin et al., 2007].

Considering these variety and magnitude of the problem, efforts have been made separately by the government, as well as by non-governmental and international organizations, to address the widespread rural energy problem and the natural catastrophe of arsenic contamination in drinking water. Some national and international agencies together with the government organizations and NGOs have distributed hundreds of different types of filters for the removal of arsenic from drinking water. There are programs supporting the dissemination of biogas digesters to rural inhabitants. These efforts have not been very successful in reaching the poorer and more remote sections of the country, largely due to limitations in affordability, and technical and economic viability. In sum, it appears that most of the options are not completely sustainable from the socio-technical, economic and environmental perspectives. The efforts made so far remain fragmented, and a holistic approach is often missing in addressing the multiple service needs of the rural areas (clean cooking, energy, electricity and safe drinking water). An integrated biogas based polygeneration system with gas production unit, electricity generation unit, and water purification unit could be a promising technological option to address such multiple rural needs.

1.2 Polygeneration

A few researchers [Maraver et al., 2012; Maya et al., 2011; Serra et al., 2009; Rubio et al., 2008; Uche et al., 2004; Foronda et al., 2003] have been trying to look into different integrated polygeneration systems in order to achieve better energy efficiency compare to conventional power plants by recovering waste heat through additional cooling and heating. A set of alternatives of polygeneration systems are studied with diverse combination of technologies, but they rarely provide the appropriate results for each particular situation. Energy and thermo-economic analysis were presented by the authors [Colella and Uche, 2007] in other polygeneration schemes, but in the proposed polygeneration system, we configured some different and very unique integration such as renewable energy, cooking gas, electricity and arsenic free safe drinking water. Clearly there is scope for investigating new concepts for tackling this multifaceted problem.

While energy is an essential indicator of techno-economic development and social welfare but it also exemplifies one of the most important sources of environmental pollution and greenhouse gas emissions [WWF, 2006] which is hamper the overall sustainable development of society. In this context, polygeneration or also called multigeneration came into light, which for instance refers to renewable energy systems that produce several useful outputs from one single or several kinds of primary energy input (viz. fuel). Polygeneration reproduce the advantages of cogeneration and trigeneration [Chicco et al., 2009; Serra et al., 2009]:, a reliable energy supply, energy and economic saving and reduction of the process losses [Hernandez and Sanchez, 2003; Fumo et al., 2009; Desideri et al., 2009]. With the aim of using renewable energy, increasing overall system efficiency and reducing energy and distillation costs, several researchers have proposed the concept of polygeneration [Rubio et al., 2008; Serra et al., 2009; Maraver et al., 2012]. The purpose of polygeneration is to improve the utilization of primary resources (fuels) more effectively and efficiently through wasted energy recovery system. This is a method of improving the efficiency of energy generation processes for better sustainability. For example, less fuel is required to produce a given amount of electrical and thermal energy in a single unit than is needed to generate the same quantities of both types of energy with separate, conventional technologies (e.g., gas generator sets and steam boilers). The current rural energy circumstances and subsequent socio-economic problems require the utilization of non-fossil fuel based and innovative polygeneration system. Apart from generating "energy products" through a polygeneration system, one can also fabricate by-products with added value, such as pure water, fertilizer etc. In water scarce rural and coastal areas, fresh water obtained from a local purification unit could be that additional product which, integrated in the polygeneration plant, also reduces the strong dependency of that critical resource with respect to climate conditions [Maya et al., 2010]. Water purification technologies are very much energy intensive and it requires large quantities of energy, are mostly driven by fossil fuels but it is no longer sustainable practice. So, it is crucial to develop processes that are renewable and sustainable for freshwater production. Plants where electricity (use gas turbine or internal combustion engines) is generated in combination with desalted water have been widely studied by previous authors [El-Nashar, 2008; Fath et al., 2004; Darwish and Al Najem, 2004; Bruno et al., 2008; Alarcon and Garcia, 2007; Delgado and Garcia, 2007; Kamal, 2005; Eltawil et al., 2009; Yari and Mahmoudi, 2010; Bouzayani et al., 2007; Cardona and Piacentino, 2004; Almulla et al., 2005; Mussati et al., 2005; Rubio et al., 2008; Mathioulakis et al., 2007; Cardona et al., 2007; Ophir and Lokie, 2005]. One common characteristic in combined power and desalination is the use of low grade heat or waste heat from one top cycle. One approach to these types of combined systems might combine a power plant, a desalination system to supply fresh water. The study incorporates a membrane distillation (MD) unit where the MD is maintained at the design temperature by a flue gas waste heat recovery system (EHRS). In biogas-cogeneration installations, the MD draws the motive energy for membrane distillation from the waste heat recovered from the exhaust gases system of a gas generator power plant. This waste energy brings the operating costs of the MD unit down to a minimum and the efficiency of the integrated system up from approximately 50% to over 80% [Maya et al., 2011; El-Nashar, 2008; Eltawil et al., 2009; Cardona et al., 2007]. The following options are available for managing the water and energy crisis in a sustainable manner:

- Utilize renewable energy local sources
- Employ low-cost and energy-efficient technologies
- Implement process integration in order to maximize the system waste energy recovery

1.3 Objectives of the thesis

In rural areas of Bangladesh, family size biogas digesters are well known and cooking is the dominating pathway for small and medium scale biogas plants. However, utilization biogas for only cooking is not economically attractive compared to what can be produced in individual, farm-based biogas plants. Moreover, there are different approaches to increase the volume of biogas from locally made farm-scale plants, for example change the digester type, increase digester temperature and improve the monitoring system etc. Thus, improving the energy supply situation and, in particular, increasing access to clean electricity and facilitating more sustainable use of traditional energies, are important in addressing energy related impacts. On the other hand, the rural poor are the ultimate victims of arsenic poisoning and saline groundwater consumption. In these circumstances, an alternative utilization pathway for community-based biogas is the production of electricity, heat and safe water. From a technological point of view it is feasible to co-produce heat and power simultaneously using biogas as a feed and very few studies on technical and economic aspects of this combined technology have been carried out or explored specifically in Bangladesh but no integrated (CHP along with membrane distillation) system study has been done. However, whether the proposed polygeneration (biogas digester, gas engine and membrane distillation unit) system is very distinctive (new and innovative) and can be adopted and applied in local rural community mostly depends on whether the system is techno-economically feasible and profitable. Therefore techno-economic evaluation of integrated polygeneration system needs to be performed.

This work presents an innovative energy and drinking water solution via a small scale biogas based polygeneration system designed for deployment in rural Bangladesh. The concept encompasses a gas engine and cooking stove integrated with a digester; waste heat from the engine drives a thermally-driven water purifier (membrane distillation unit). The study estimates the size and cost of a biogas based polygeneration system, its feedstock requirements and the necessary outputs to meet the cooking energy, electricity and safe drinking water demands. The thesis also investigated experimentally whether the MD is suitable in the integrated system for handling the arsenic contaminate feedwater in terms of separation efficiency and thermal energy consumption. For the purpose of the analysis, the investigation has considered all these needs for a small village community of 30 households in rural Bangladesh. Primary system inputs are cattle dung and contaminated water, with biogas, electricity, safe drinking water, and fertilizer are primary outputs. The study estimates the levelized cost of biogas and electricity generation and production cost of clean water, further augmented with a sensitivity analysis to observe the impact of uncertainty in key assumption and design parameters on cost. The payback period and IRR are determined in order to examine the financial feasibility of such polygeneration technologies. Primary end-user issues have been included by direct consultation with local stakeholders.

1.4 Methodology

The study was carried out as a case study in a rural community of Bangladesh. For the purpose of sizing a representative polygeneration system, a 30 household village community has been considered in this investigation. The average size of a rural and remote village community in Bangladesh usually lies between 25 to 50 households, depending on the local resources and other community facilities like job opportunities, communication, education, local markets etc. [Households, 2008]. Technical analysis is carried out on the basis of quantity and description of the substrates, gas yield, size of the components, electricity and heat energy production, electricity and heat energy consumption of biogas plant, and available energy. In the energy and mass analysis (section 5.1) the digester has been designed to fully accommodate all demands for cooking gas and/or electricity generation during the day. The generator supplies electricity according to estimated community demand, therefore no battery is considered for electricity storage. Demand patterns are assumed to be the same throughout the year and the generator operates for 8000 hours annually. The performance data is necessary for the design of integrated small-scale polygeneration systems featuring MD. The present investigation addresses this issue via an experimental investigation of a household AGMD water purifier prototype (2 L/hr nominal capacity) supplied by HVR Water Purification AB, Stockholm (subsidiary of Scarab Development AB). A parametric variation of coolant-side inlet temperature was conducted for plain and As-spiked tap water along with As-contaminated groundwater, and the resulting yield and thermal energy consumption were determined. The economic performance of the given integrated system has been carried out on the basis of levelized costs and internal rate of return concepts. The analysis did not accounted the investment costs for include land value, stall value, and dairy cow value. Levelized cost of electricity (LCOE) has been used as a tool for estimating production costs. The levelized cost for the production of biogas and electricity, life cycle production cost of water, and payback period of such a polygeneration system have been estimated based on the local market price and input received from stakeholder consultations in Bangladesh. Resource availability, efficiency, life span, T&D losses, system capital cost, operational and maintenance cost, fuel costs and replacement costs are some of the input parameters to calculate the LCOE. A sensitivity analysis has been performed considering the inherent uncertainty in assumptions and key parameters. Various input assumptions are discussed in section 5.2.

This study also analyses the key opportunities and challenges in introducing biogas-based polygeneration in the rural Bangladesh. One half-day workshop and a one-to-one local stakeholder consultation (research institute, biogas supply/installation companies, and various governmental and non-governmental organizations) were organized in Dhaka in 2012 to identify barriers and opportunities for the introduction of this new technology.

1.5 Outline of the thesis

The current thesis is divided into several chapters. The main research findings are presented in Chapters 3 through 5.

Chapter 1 begins with an introduction, motivation of the research performed during the course of the project, polygeneration background and methodology. This chapter also presents the objectives of the thesis.

Chapter 2 introduces a brief overview of Bangladesh energy status and background to the research topic as well as a review renewable energy resource, biogas potential and technology and current groundwater scenario and mitigation options. This chapter also presents a thorough review of previous works relevant to the topic.

Chapter 3 is devoted to the air-gap membrane distillation with experimental and parametric studies.

Chapter 4 contains a summary based on the results of technical specification of all kinds of related technologies in the integrated system.

Chapter 5 presents the techno-economic results of integrated system. Thermodynamic and details costs analysis of the entire system has been performed. A number of sensitivity analyses were performed to find improved cost analysis.

Chapter 6 contains discussion and conclusions of the entire thesis. The need for future works is also recognized.

2. Background

2.1 Energy situation in Bangladesh

Bangladesh is situated in north-eastern part of south Asia and shares its longest border (4000 km) with neighboring country India, Myanmar is the extreme southeast neighbor of Bangladesh and the Bay of Bengal is the southern boundary of it. With a land area of 147,570 km^2 and population of 164.20 million in 2012, Bangladesh is among the world's most densely populated nations (1099 people/km^2 in 2010) [BBS, 2010]. The country has been facing a severe power crisis for about two decades that is likely to deteriorate over the next few years. Bangladesh lacks a sufficient electricity generation capacity, fuel resources and grid networks to electrify the whole nation and has never enjoyed 100% electrification [Uddin and Taplin, 2006]. Per capita electricity generation in 2000–01, 2005–06 and 2011-2012 were 129 kWh, 170 kWh and 236 kWh, respectively [BPDB, 2012] which is lowest in south-Asian region. Only 42% of the total population is connected to grid electricity (about 80% of urban and 30% of rural households), with the vast majority being deprived of a power supply [BBS, 2012; Barnes et al., 2010; Kamal and Islam, 2010; Islam, 2010; Assaduzzaman et al., 2010].

Grid electricity is mostly derived from the cooperatives or PBSs (Palli Bidyut Samities), which serve rural areas through the national grid system. The Rural Electrification Board (REB), in its master plan of 2000, noted that it had supplied electricity services to about 31% of the total rural population. Its forecast for 2020 was a rural population of 97 million with electricity services, which would be about 70% of the total rural population. But unfortunately, there is no concrete action plan available till now. The Government, in face of the country's current power crisis envisions electricity for all by 2021 while ensuring a reliable supply at affordable prices. The target has been particularly set in line with the United Nations Millennium Development Goals (MDG) for economic development and poverty alleviation. Electricity generation in Bangladesh is overwhelmingly gas based. More than 67 percent of evening peak electricity is generated by using natural gas (Figure 2-1).

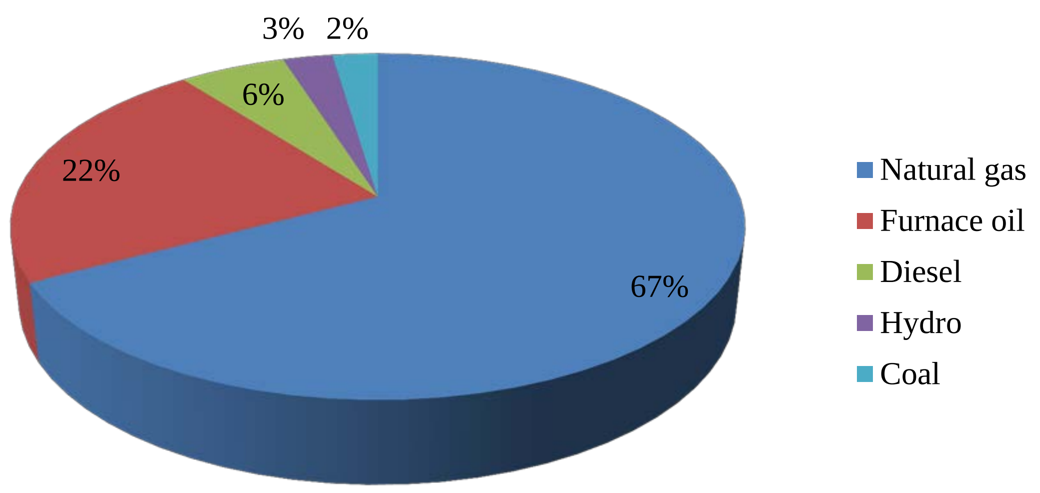

Figure 2-1: Electricity generation capacity (7500 MW) [BPDB, 2012]

Recently, rental power plants together have emerged as a serious challenge due to the Government has no option other than spending a substantial amount of money from its reserve to run the rental plants. The power produced by these plants is more than six times the cost of power from the standard gas-fired power stations. The government would have to provide subsidies worth about USD 2.8 billion on oil marketing and USD 1.1 billion on power purchase, mainly from rental power plants (1088 MW electricity), by the Power Development Board (PDB) in the 2012 fiscal year. Public and private sectors equally share the power generation sector of Bangladesh and 51 percent of Bangladesh's total power plants are owned by the state. Table 2-1 shows overall electricity generation and distribution scenario in year 2012;

Table 2-1: Energy scenario in Bangladesh 2012 [BPDB, 2012]

Sector	Status
Electricity growth	10% in FY 2012 (Average growth 7% since 1990)
Total consumer	13 million
Transmission line	8800 km
Distribution line	280000 km
Distribution loss	13.1%
Per capita power generation	236 kWh
Access to electricity	45%
Present generation capacity	7500 MW
Present demand	7600 MW
Present available generation	5600 MW
Recent maximum generation	6000 MW (3rd March 2012)
Maximum power supply to grid (excluding distribution loss)	5000 MW
Maximum load shedding in FY 2012	2500 MW

The Power System Master Plan 2010 forecasts the demand for electricity on the basis of GDP growth and the elasticity of electricity demand. According to the projections by PSMP, Grid system demand with Demand Side Management for 2015, 2020 and 2030 would be 10,283 MW, 17,304 MW and 33,708 MW respectively as opposed to the current (2012) demand of approximately 7,518 MW. The power demand forecast shows that the demand for electricity will be growing at around 10 percent over the next decade.

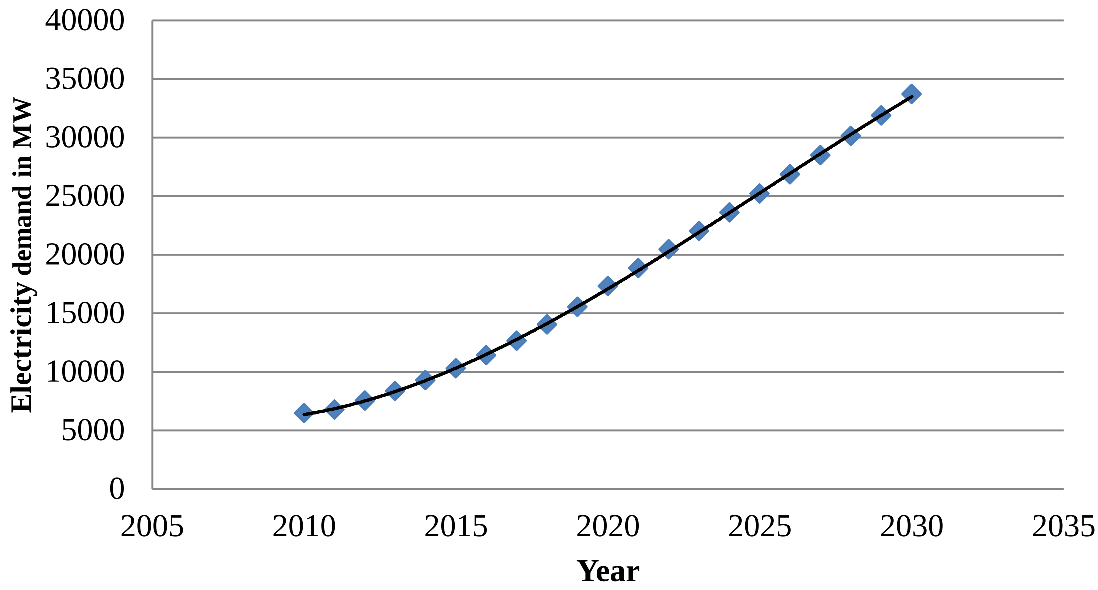

Figure 2-2: Peak electricity demand by 2030 (7% GDP) [PSMP, 2010]

Though, the target of generating electricity under the 20-year Power System Master Plan (PSMP) ending in 2030 is likely to remain elusive due to short supply of natural gas, fuel and other inputs, experts said [Anisul, 2012]. According to PDB to meet the demand, the installed capacity of electricity needs to be increased to 15,000MW and 39,000MW between 2015 and 2030 [PSMP, 2010]. Some 19,000 MW of electricity is projected to be generated from imported coal, 4,000 MW from nuclear power, 8,850 MW from gas, 3,500 MW from regional grid and 2,700 MW from hydro and renewable sources by 2030, according to PSMP 2010.

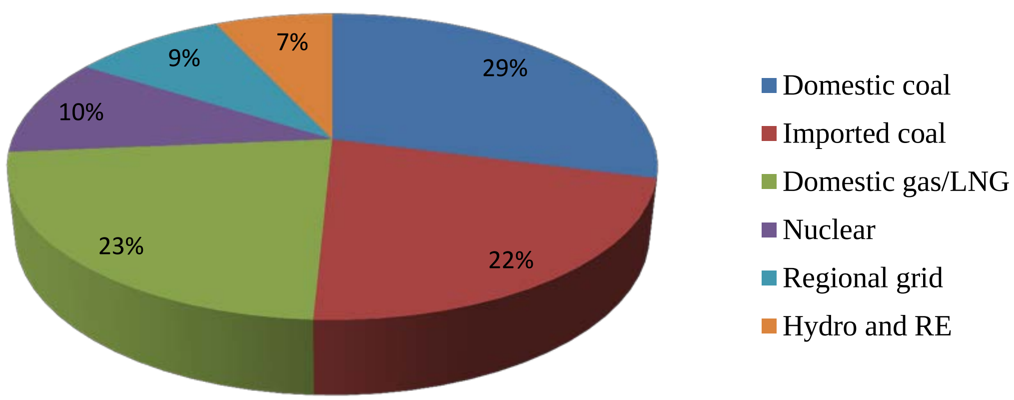

Figure 2-3: Primary fuels source for electricity by 2030 [PSMP, 2010]

Bangladesh government has estimated that 16.36 trillion cubic feet (Tcf) of recoverable gas reserve in its 25 discovered fields as of January 2013, would meet the country's projected energy demand up to 2020. After that, each year, there will be short supply of gas and this would increase to 4421 Mcfd by 2025. This means that to support the projected energy demand, 8.35 Tcf of additional gas would be required. This short supply of gas would have to be managed either by discovery of additional gas field or alternative sources of fuel. Dr. Hossain Monsur (Chairman of Petrobangla, Bangladesh), has also expressed doubt about the achievement of electricity generation target of different periods as mentioned in the PSPM 2010 [Anisul, 2012]. Till now nuclear energy is not given any serious thought. On the other hand, biomass still plays an important role in country's energy consumption. Biomass is the dominant energy source used as a source of thermal energy in domestic, commercial and industrial sectors in Bangladesh. Consequently, the shortage of power can be met by renewable energy resources which are abundant in nature.

2.1.1 Rural energy scenario

Significant variation in household energy use exists between rural and urban populations, between high and low income groups within a country [Pachauri and Spreng, 2004], and for rural household in Bangladesh it is even more substantial (see in Figure 2-4). Modern energy fuels such as kerosene, natural gas, and electricity combined meet less than 1 percent of rural household energy needs, and energy consumption in Bangladesh is less than one-tenth the global average. The major factors contributing to these differences are levels of urbanization, economic development, and living standards.

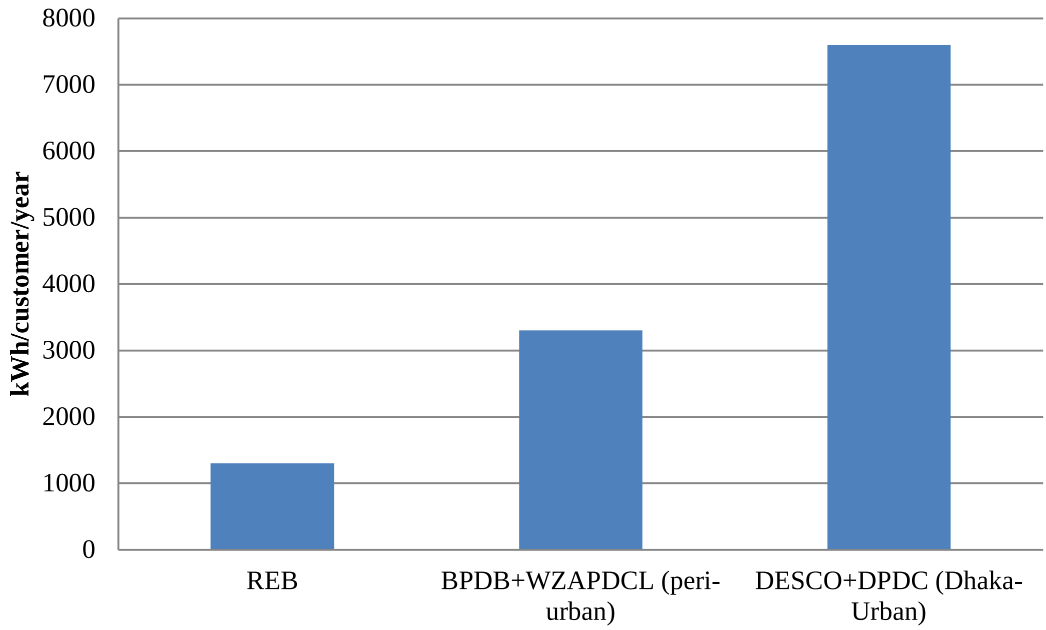

Figure 2-4: Access to electricity gap between rural and urban in 2010-2011 [Annual report, BPDB, 2011]

About 75% of the total population of Bangladesh lives in rural areas and total number off-grid household (HH) is about 17 million (total HH 29 million), a vast majority (89% or 15 million households) is concentrated in rural Bangladesh where the electrification rate dips to 23% (Figure 2-5).

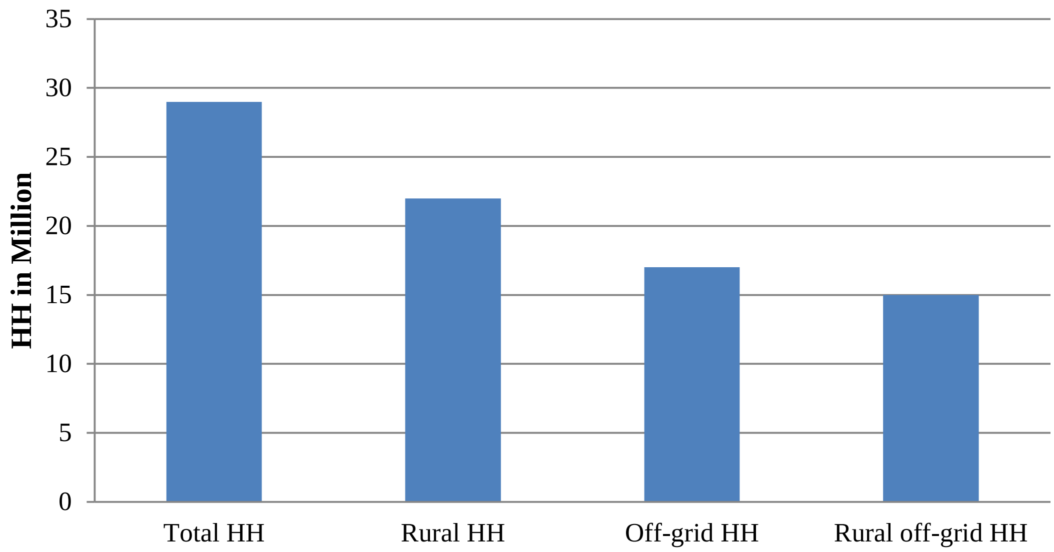

Figure 2-5: Number of off-grid households in Bangladesh [IFC, 2012]

The below Figure 2-6 shows that a large segment of the on-grid population is also under-electrified, facing significant daily power outages (about 50% load shedding in rural areas).

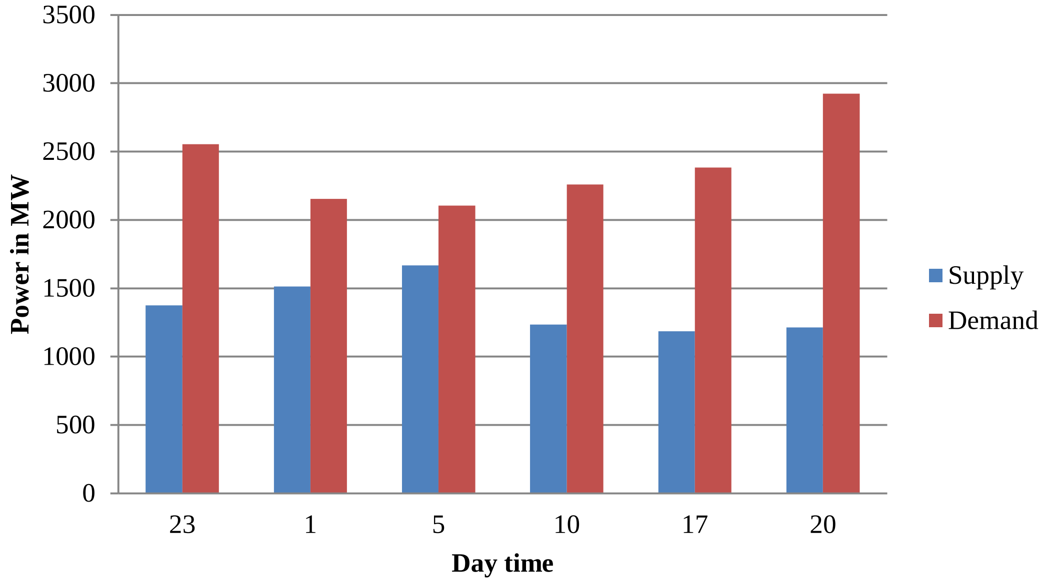

Figure 2-6*: *Gap between demand and supply in rural areas in March 2011 [MIS, REB, 2013]

It has been known that the household in the rural area is simple and does not require large quantities of electrical energy for lighting and entertaining and electrical appliances due to limited energy related activities and consequently low demand. While kerosene is the predominant non-biomass energy source for lighting, though, monthly average consumption of kerosene is 2.25 liters, which barely covers basic lighting services. Moreover, the gas being used has an impact on the national economy through fertilizer manufacture, electricity generation and direct energy use in some industries; it will not be economically feasible to supply the gas to the rural areas through pipelines in riverine Bangladesh [Khan, 2002]. In rural areas, most of this energy-use is for cooking and modern fuels (not generally used for cooking) account for only three percent of the energy balance. Biomass plays an important and complex role [FAO, 2009], and is used almost exclusively for cooking for nearly all households in rural areas. Fuelwood is also the single most important rural energy source in terms of energy unit (kgoe), accounting for some 44 percent of total consumption (see Figure 2-7). Including tree leaves and twigs, the share of tree-based biomass is nearly 60 percent of total household energy and crop and animal residue constitute other major sources. Because of the significant amount of energy required by cooking and the inefficiency of most rural stoves, the useful or delivered energy is lower than the percentages presented; however, they highlight the importance of biomass for cooking. At present, there is a crisis of biomass fuel, which constitutes 73% of total energy consumption. The crisis is leading the villagers to an increased use of crop residues and dung as fuel, which is reducing soil's valuable nutrients and organic matter [Danesh et al., 2010]. Unlike South Asian regions where liquefied petroleum gas (LPG) and other modern fuels have entered the marketplace, but rural Bangladesh still depends heavily on biomass for cooking fuel. About 90 % of all families in Bangladesh use traditional stoves for cooking and other heating purposes [Khan, 2002]. Many studies have shown that biomass burning cook stoves produce a number of harmful air pollutants including suspended particulate matters, carbon monoxide, and carcinogenic organic compounds. Due to poor ventilation in the most rural kitchens, women and children who spend an inordinate amount of time near the cooking activities are exposed to dangerous levels of air pollution [Hossain, 2003].

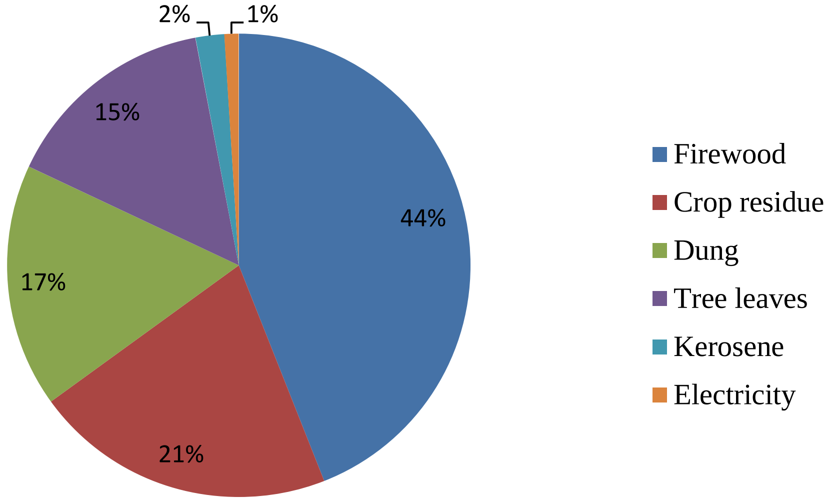

Figure 2-7: Rural household energy consumption by sources [BIDS Survey, 2004]

Though, rural electrification is characterized with many challenging factors such as low load density, poor load factor, rough terrain, and high capital and operating costs. Bangladesh, according to rural electrification policy, has aimed at grid expansion to all areas that are feasible based on presumed techno-economic criteria and has been considering two technical options for bringing electricity to rural areas: (i) extending and intensifying the central grid, and (ii) deploying off-grid technologies (in the form of a standalone option or a mini grid). The main economic activity in rural areas is agriculture, which limits productive uses of electricity, and consumers are often poor [Mohan, 1988]. The low load densities result in high cost for each unit of electricity, but it should be affordable for relatively poor customers. This dilemma makes rural electrification a complex task than an urban electrification project [World Bank, 2008]. In fact, rural electrification needs to involve rural community and societal dynamics instead of just implementing a technical matter of stringing lines [Barnes, 2007]. Therefore, the government's study finds that grid extension alone will not be sufficient to achieve the target of providing electricity to everyone. Thus, Bangladesh has taken serious efforts to disseminate renewable energy technologies, and consequently, it now hopes to bring 10 million rural people under renewable-based, off-grid electrification systems by 2012. If the trend continues, the country would achieve electrification for everyone by 2020. However, since 2006 there have been serious doubts that the off-grid based rural electrification program will achieve its targets due to some practical techno-economic challenges.

The rural communities are unaware of both the benefits of the RETs (Renewable energy technologies) and the adverse impact of existing practices on health, economy and the environment. Although, they often have access to renewable energy technologies, they lack the understanding of these technologies. Thus, they lack knowledge of successful replicable projects, government subsidies, potential financial partners, and the means for establishing renewable energy systems. The lack of adequate other end-uses of the RETs in the rural areas is the main obstacle in promoting the economic viability of RETs in the regions; this is because the major use of the renewable energy is confined to just lighting (solar, biogas, micro-hydro) and cooking (biogas). The lack of integration of renewable energy to other end uses is a major challenge of RETs for better market penetration. So, financial institutions are not readily motivated to invest in RETs because of the immature business models, market insecurity and implementation and usage risks [Surendra et al., 2011; Mondal et al., 2010].

2.1.2 Renewable energy scenario

One of the great promises of renewable energy technologies is the potential to provide electricity in areas not served by national power grids. Renewables are an almost unlimited source of energy if one considers the energy necessary by mankind, compared with the huge amount of energy we receive from the sun. Gradually renewable energy and its different energy conversion technologies have become economically viable, capable of competing with fossil-fuelled technologies in the energy market. Renewable energy plays an important role in the process of integrating the environment into energy policies through its potential to contribute to the objectives of sustainability. However, due to technological, political and economic restraints, at present, the contribution of renewable energy to overall power generation in the country is less than one percent [Ministry of Power, Energy and Mineral Resources of Bangladesh, 2008]. Having the huge prospects of solar, wind, biogas and biomass, micro and mini hydro and tidal energy to harness and transform Bangladesh government has already targeted to generate 5% of total electricity (about 514 MW from baseline scenario, PSMP 2010) from renewable energy by 2015 and 10% (about 1750 MW) by 2020 [Renewable energy policy, 2008]. Though, this seems to be quite an ambitious goal at the present energy scenario. Bangladesh government has already formulated a Renewable Energy Policy in 2008; it has not been enacted as a law yet. Therefore, concerned authorities are not bound to meet up all the facility or targets that are promised to boost up renewable energy sector. Different government and nongovernment organizations working separately or jointly to disseminate renewable energy technologies (RET) that reported in the recent literature [REIN, 2013; IDCOL, 2013; SRE program, LGED; SED, GIZ 2013; Grameen Shakti, 2013; BRAC, 2013] however, prospective planning and comprehensive understanding of this dynamic field requires as well as regressions, in this sector should be continually scrutinized [Khan et al., 2004]. From only biogas and biomass, there is a potential to generate 800 MW and 400 MW of electricity respectively [Sharif, 2009]. According to Rahman et al. [2011], 250 MW and 300 MW of electricity generation is possible from hydro and 376 MW and 1480 MW of electricity generation is possible to harness from solar energy by 2015 and 2020 respectively. In addition, from biomass and biogas, it is possible to get 60 MW and 120

MW by 2015 and 2020, respectively, where from wind; it is possible to get 6 MW and 100 MW, respectively. Tidal power prospect is about 4.57 MW in Bangladesh [Rahman et al., 2011]. However, new large-scale hydro power plant is not feasible due to its adverse effects on environment and biodiversity. In addition, extensive feasibility assessment is required before we go for geothermal-based electricity generation. In order to generate 687 MW of electricity (5% of total estimated electricity production by 2015) from renewable energy sources, investment of 196.5 million U.S. Dollar is required by 2015, and to generate 2000 MW (10% of total estimated electricity production by 2020) from renewable energy sources, investment of 371.5 million U.S. Dollar is required by 2020 [Rahman et al., 2012]. Although investment costs of renewables are generally higher compared to fossil fuel alternatives, this option becomes economically viable when all externalities (e.g. environmental cost, health hazards etc.) and lower operating cost are taken into consideration [Khan et al., 2004].

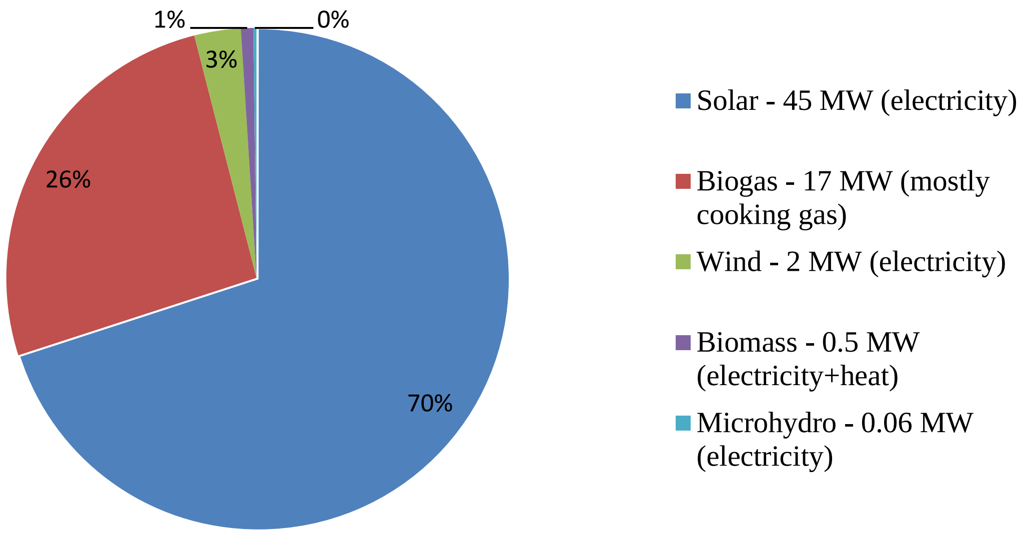

Figure 2-8: Renewable energy total installed capacity about 64.5 MW up to July 2009 [Renewable energy Bangladesh, Power Division, 2013; Baten et al., 2009]

Based on the information obtained, a comparative scenario of the five aforementioned renewable energy sectors of Bangladesh is illustrated in Figure 2-8 in terms of the installed capacity. Though capacity of solar, biomass, wind energy and hydropower based installations have been obtained in wattage, only the number of installed biogas domes are available as far as the biogas energy sector is concerned. So to obtain a comparative picture, equivalent wattage of the generated biogas in Bangladesh has been calculated [Baten et al., 2009].

2.2 Biogas potential and digesters technologies in Bangladesh

2.2.1 Biogas potential

Biogas is a renewable fuel produced by anaerobic digestion of organic material. It contains 50-70% methane (CH_4) and 30-50% carbon dioxide (CO_2), depending on the substrate [Sasse, 1988; Bond and Templeton, 2011] as well as small amounts of other gases including hydrogen sulphide (H_2S). The typical calorific value of biogas is about 21-24 MJ/m^3 [Dimpl, 2010] or around 6 kWh/m^3 which correspond 60% of methane contains in biogas. The anaerobic digestion (AD) process is used for the efficient conversion of livestock into clean renewable energy and organic fertilizer. The capture of biogas from digester will not only use for cooking, lighting and heating for clean water, but also substantially mitigate the potential local and global pollution. Cogeneration has proven energy efficient technology, when using biogas as a fuel. Methane rich biogas is a clean, efficient, and renewable source of energy, which provides a versatile carrier of energy and can be used as a substitute for other fuels (like firewood and cattle dung) in order to supply energy in rural areas [Yu et al., 2008]. Another important application of biogas is power generation through internal combustion engines to drive electric generators in rural areas [Monteiro et al., 2011; LBS, 2002]. However, biogas production with the agricultural base and cattle population in Bangladesh for use in only cooking purpose, but generation of electricity looks promising. The digestate or slurry from the digester is rich in ammonium and other nutrients used as an organic fertilizer or as fish feed [NAS, 1977; Singh, 1973].

Bangladesh is an agricultural based country where biomass plays a vital role as a major source of energy supply. Huge amount of biomass resources e.g. agriculture residues(crop/tree residue, rice husk, , jute stick etc.) , animal waste(cow dung, human excreta), fuel wood, tree leaves, municipal solid waste, vegetation, sugarcane bagasse, poultry droppings , garbage etc. meet the households and small industries energy demand. The considered livestock are cattle, buffalo, goat, sheep, horse, and chicken in Bangladesh. Total livestock production in Bangladesh has grown at 3.72 per cent annually from 2000-2010 [FAOSTAT, 2012]. The quantity of waste produced per animal per day varies depending on body size, type of feed and level of nutrition. The annual production rates of animal wastes and poultry droppings were estimated by employing the number of heads of the national herds (Table 2-2). It is estimated that about 30 billion m^3 of biogas could be obtained from the livestock residues of the country, equivalent to 1.5 million tons of kerosene (which is currently the principal fuel for lighting in rural areas) [NDBMP, 2010]. According to International Finance Corporation (IFC), the number of poultry farms in Bangladesh is 215000. About 82 million CFT of biogas can be produced per day which is equivalent to 30 billion CFT of biogas per year. These amounts of biogas can produce 3.65 GWh of electricity per day which is equivalent to 1.33 TWh per year [BPDB, 2007]. For 14 hours of operation this biogas can run a 260 MW generation unit. About 95% of poultry farmers lack awareness of farm management and struggle to survive and stay profitable. In addition, about 4,500 million tons of waste is generated daily by poultry farms, resulting in 2 million tons of GHG emissions and negatively affecting the environment. However, the waste could be a source of additional revenue for farmers, if converted into energy [IFC, 2013].

Table 2-2: Major livestock in Bangladesh in 2010 (head count in Million) [Faostat, 2012]

Cattle	Buffalo	Goat	Sheep	Poultry
23,05	1,35	50	1,82	270,7

Table 2-2 summaries the potential for AD in Bangladesh on the basis of livestock and households. Van Nes et al. [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 to construct biogas plants. These data were based upon the households who have five or more cattle heads. The dung produced by 5 cattle is sufficient to feed a biogas plant with a gas output of 3 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].

Table 2-3: Number of household with cattle and poultry birds [BBS, 2005; BCAS, 2005]

Livestock	Size of cattle/poultry farm	Number of household
Cattle	With 1-2 heads	5106994
Cows and buffaloes	With 3-4 heads	2111498
	With 5 heads and above	952872
Poultry	Less than 249	15000
	With 250-999	80,000
	With 1000 or more	21250

2.2.2 Background: Digester in Bangladesh

Biogas technology is not only well spread and established in China and India but also considered a reasonable success using animal dung as a main feedstock (over 4 million in India and 26,7 million in China up to 2007) [MNES, 1998; Chen et al., 2010]. India and Nepal have installed family size biogas plants corresponding to 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]. Despite of this huge potential, only few number of biogas plants have been deployed till date. Besides, most of these plants are unable to produce the expected amount of biogas as most of the digesters of these plants are made locally and they don't have any scheme for monitoring and controlling temperature, pH, and bacterial population in digester. According to the Infrastructure Development Company Ltd. (IDCOL), a government owned company in Bangladesh, the total technical potential of domestic biogas plants in the country is 3 million units. Though, the level of household and commercial biogas technology is not encouraging in Bangladesh due to some practical constraints, however the climate and potential of available feedstock can motivate to further development of biogas technology. At present different implementing authorities in Bangladesh is mainly active in promoting the technology without proper attention to research and development to renovate and optimize the design by suiting them to the local condition. However, several studies have figured out that some existing biogas plants have been facing severe difficulties due to lack of technical knowledge coupled with cold climates, are hindrances in increasing service coverage in poor rural areas. The main problem with a family-sized plant is low biogas yield during the winter and rainy seasons whereas the problems for community-sized plants relate to ineffective management, and sharing of benefits. Household biogas plant using cattle dung can be feasible when 5-8 cows are available per family.

Among the other potential alternative sources of rural energy, biogas generated from animal dung is undoubtedly one of the most appropriate sources of energy in the rural communities. Keeping this fact in mind Infrastructure Development Company Limited (IDCOL) is implementing National Domestic Biogas and Manure Programme (NDBMP) through several national and local partner organisations with the technical and financial assistance of Netherlands Development Organisation (SNV) and Kreditanstalt für Wiederaufbau (KfW). The overall objective of the NDBMP is to further develop and disseminate domestic biogas plants in rural areas with the ultimate goal to establish a sustainable and commercial biogas sector in Bangladesh. This programme will help to attain objectives of Poverty Reduction

Strategic Plan and also MDG (Millennium Development Goal) set by Government of Bangladesh. IDCOL has planned to introduce 0.1 million household biogas technology by 2016 [Mahmood Malik, 2013]. Traditionally, censuses on livestock in Bangladesh usually show the total number of cattle instead of household-wise number of cattle. It makes difficult to find out number of biogas plants that could be built. At least four cows are required in a household for the smallest size of plant with production capacity of 1.2 m^3 which will be feasible. As per the 1996 census by Bangladesh Bureau of Statistics (BBS), holdings with 3- 4 heads cow per household was 2,111,498 and with holdings with 5 heads and above was 952,872 [SNV, 2005], So, the total number of plant that could be built only cattle dung as feedstock as per SNV report was 3,064,370 [Hamid et al., 2013].

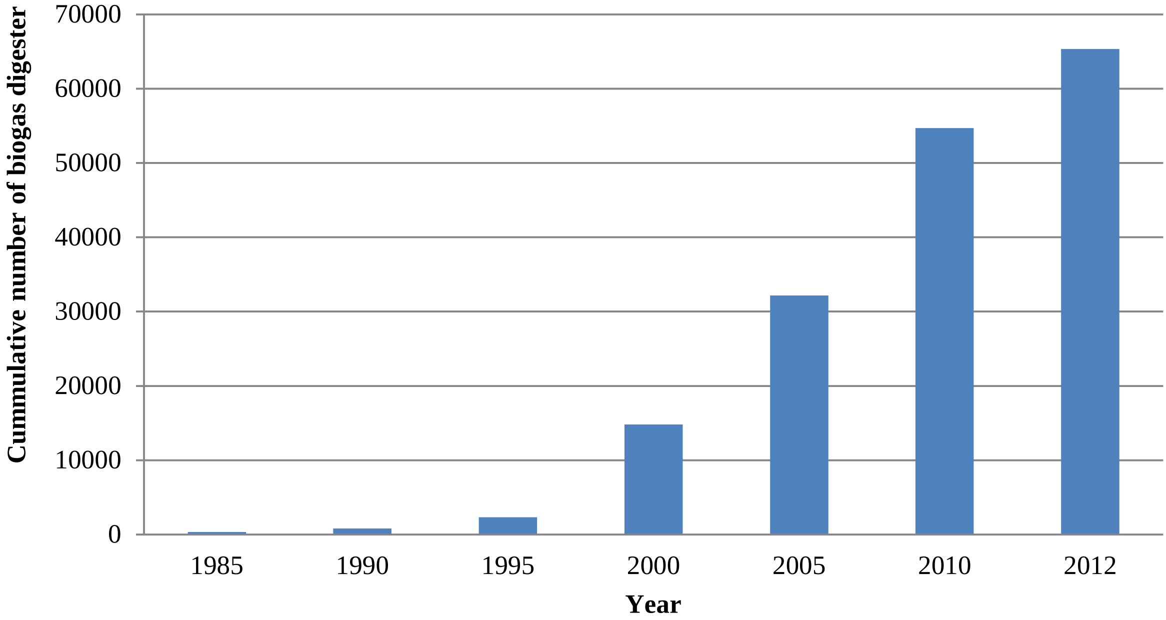

Figure 2-9: Total number of installed digesters up to 2012 [IDCOL, 2012]

Major organizations like Infrastructure Development Company Limited (IDCOL), Grameen Shakti (GS), and BCSIR are currently engaged in dissemination of domestic biogas plants (1.2 - 4.8 m^3 digester size) in Bangladesh. As up to 31st of December 2012, a total of around 65,317 biogas plants have already been installed in Bangladesh. Table 2-9 shows the number of domestic biogas plants installed by major organizations in Bangladesh as of December 2012. Among the several digesters developed in Asian countries, the fixed dome model (developed by China) and floating drum model (developed by India), but the fixed-dome biogas plant has been used and popular in this country mainly for simplicity in operation. About 92% of biogas plants are cow dung based, 6% based on poultry waste and 1-2% based on other substrates.

Table 2-4: Organization wise digester installation

Organizations	Number
IDCOL	26,311
BCSIR	22,334
Grameen Shakti (outside of IDCOL)	7,000
NGOs and others	9,672
Total	65,317

2.3 Technical performance analysis of existing biogas digesters

Biogas plants can supply required cooking gas and electricity to the dairy and poultry farm itself and to the neighboring localities where national grid power is not available. This will also reduce CO_2 emission, alleviate environmental pollution, bad odor produced in farms, create job scopes for people of the adjacent area, mitigate the stress on the national grid and can generate revenue selling organic fertilizer. Besides, efficient management of produced biogas, electricity and heat wastage will provide the maximum benefit out of the available resources. Despite all these prospects only a limited number of biogas plants are deployed in the poultry and dairy farms of Bangladesh. Besides all, the plants already deployed are not managed properly [Bhattacharya and Timilsina, 2009] which further reduces the production of biogas yield hence decrease the production efficiency.

A technical survey reports [Ghimire, 2005] (66 biogas plants under analysis in three different districts in Bangladesh) showed that 31 (47%) plants were functioning satisfactorily but the digester efficiency was less than 50%, 21 (32%) plants were functioning partly and the remaining 14 (21%) plants were not functioning at all during the time of field investigation. The most popular size AD plant is 3.2 m^3 plant (50% of plant installed). The reasons for non-functioning were non-availability of feeding materials especially due to selling of cattle after the installation of biogas plant, poor workmanship during construction, sub-standard quality of construction materials and appliances, non-availability of repair and maintenance services, defects in pipelines and poor operational activities. The digesters lower input to output ratio suggested either (i) the feeding material fed into the digesters was not fully digested and escaped out of the plant prior to its full digestion either because of short-circuiting (as a results of dead volumes in digester or displacement chamber) or higher water-dung ratio in the feeding, or (ii) the produced gas did not store in the gasholder, rather escaped in the atmosphere either because of undersized volume of gasholder or cracks in the dome, or (iii) the volume of displacement chamber was small as a result the produced gas could not be pushed to the point of application or (iv) biogas produced in the digester was not conveyed to the point of application efficiently because of the technical and operational defects in various components of biogas plant.

2.3.1 Biogas plants survey data and analysis

The field survey in different areas of Bangladesh, it was quite clear that the locally made digester is mostly fixed dome type and the local owner wants the home size digester for their own cooking purposes only. They do not care about maximize and/or optimize the performance and efficiency of the digesters. In order to realize the existing biogas digesters conditions, survey information was analyzed on present status of biogas plants. The existing condition of different components of biogas plant was observed in detail during the field investigation to assess the quality of construction, effectiveness of maintenance activities carried out and the operational status prior to categorizing them. Several trips to Bangladesh were undertaken to acquire the data for this study. This researcher visited several Grameen Shakti (GS) locally made AD plants for household and farm users. Both primary and secondary data were collected from domestic AD systems. The secondary data was acquired before the primary data and will be presented in this order. A total of 11 biogas plants were visited and introductions to several engineers of the company were made. Throughout the length of this work, communication with engineers and data supplied by them represent some of the data mentioned here. Eight of the 11 plants visited used poultry waste as feedstock.

Table 2-5: Survey biogas plants in Bangladesh

Name of biogas plants	Size m^3	Feedstocks	Genset	Gas burner	Comment
BD Green Agro Complex	4.8 and 21	Poultry waste (15000)	15 kWe (10 hrs per day)	5 families double burner	Electricity supply to firm only
Mrs. Khan's Poultry Firm	2x6	Poultry waste (2000)	7.5 kWe (10 hrs per day)	10 families	Electricity supply to firm only
Dewan poultry firm	40	Poultry waste (6000)	7.5 kWe (10 hrs per day)	20 families	Electricity supply to firm only
Rajib poultry firm	40	Poultry waste (6000)	7.5 kWe	10 families	Electricity supply to firm only
Al-Shisir poultry firm	40	Poultry waste (6000)	10 kWe	4 families	Electricity supply to firm only
Fuad poultry firm	No digester	Poultry waste (4500)	Diesel gen	None	Not relevant
Rakib poultry firm	4.8	Poultry waste (1500)	Diesel gen	2 families	Not relevant
Jahangir nagar University campus	2x50	Kitchen waste (2000 kg)	No engine	70 families	Not relevant
Farid pur muslim mission	3x50	Poultry (30000) and 14 (cow) wastes	2x4.5 kWe	About 700 students and staff (equva120 families)	Electricity supply to residents of mission
Practical action	6.8	MSW	No engine	4 families	Not relevant
Rohan dairy firm	80	Cow waste (250 cows)	15 kWe	40 families	Own dairy farm

From the farm visits conducted by this author, it was observed that the farmer didn't follow the amount of feedstock prescribed in the manual; instead the farmer used less amount of feedstock daily compared to the optimum required. Furthermore, the farmers in most of the farms visited did not apply the feed daily. Their feedstock application rate was once per two day of 4-5 times a day. According to GS, biogas yield should be 0.037 m^3/kg of dung and 0.071 m^3/kg of poultry litter. But field investigation data has shown that the actual yield and compositions of biogas was different (see Table 2-6).

Table 2-6: Biogas compositions in psychrophilic condition in Bangladesh

Biogas composition	Cow dung (volume %), GS	Poultry (volume %), GS	Cow dung	Poultry
CH_4	62.5	65.00	59.90	61.59
CO_2	37.4	34.97	42.10	38.39
CO	0.00	0.00	0	0
H_2S	0.10	0.30	0	0.02

Rahman et al. [2011], in their local digesters survey found that the most of local users used a lower daily feedstock compared to the required dose – 33% less as recommended in the operations manual provided by Grameen Shakti (GS). Inadequate number of cattle was the main reason given. It was also found during AD plant visit that the farmer didn't charge the plant properly; they charged it 3 - 4 times per week whereas it is essential to feed the digesters every day, therefore the microbial growth is affected. Lack of knowledge appeared to be the reason for such type of poor management. Additionally, the survey [Rahman et al., 2011] compared to the Grameen Shakti manual (biogas yield and composition rate) results show the cattle small holding AD plant and poultry farm AD were 57% and 29% efficient (biogas yield efficiency). This might be due to the improper management of biogas plants by the rural stakeholders and/or some operational factors and other general factors affecting biogas production. In another recent survey [ISD, 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. Periodic loading and unloading are very important for maximizing the biogas production.

Moreover, operating parameters are important to get out the maximum biogas yield from the digesters. The pH value maintaining is one of them and biogas production reduces many folds for the pH value of less than 5 as the bacteria population decrease significantly under the circumstances. The value of pH between 6.8 and 7.2 gives the best production of biogas. Anything outside of this range reduces biogas production. Hence it is very important to maintain the pH. Usually pH of a digester is self-regulating, hence any aberration of it tend to be converged to the reference value on its own. But there could be cases where pH needed to be controlled if too much deviation is observed. Usually lime water is introduced to the digester to maintain pH. For locally made digesters there are no arrangements for periodic measurement of pH which could reduce the biogas production.

Temperature of digester is the most important parameter for optimal biogas production. The average outside temperature over the year varies between 15°C to 35°C. But the inside temperature of a biogas digester in Bangladesh remains at 22°C – 27°C, which is very near to the optimum requirement [Islam, 2014]. The maximum and minimum temperature can vary over a larger range. So if temperature is not controlled the production of biogas will vary with the variation of temperature. The variation of temperature will reduce biogas yield and methane content of the gas. Bangladesh has a suitable climate for biogas production. The biogas yield and methane content vary over the year, consequently electricity generation also varies. Neither biogas yield or methane content nor electricity generation is monitored for local digesters. But methane content of biogas is monitored for Nazim Poultry Farm (local digester, fixed dome type) at Rangpur, but not tabulated. The methane content during the hotter part of the year varies among 60% to 70%. But during the cooler part it can fall as low as 40% [Islam et al., 2013]. The performance of local (without digester heating or temperature control) and imported digesters (digester heating under constant temperature) is shown in Figure 2-10 and Table 2-7. It was observed that the biogas production rate all around the year was constant for the temperature control imported digester. The imported digester inside temperature is maintained about 35-38°C all around the year with help of engine exhaust gas (temperature about 500-650°C) via heat exchanger.

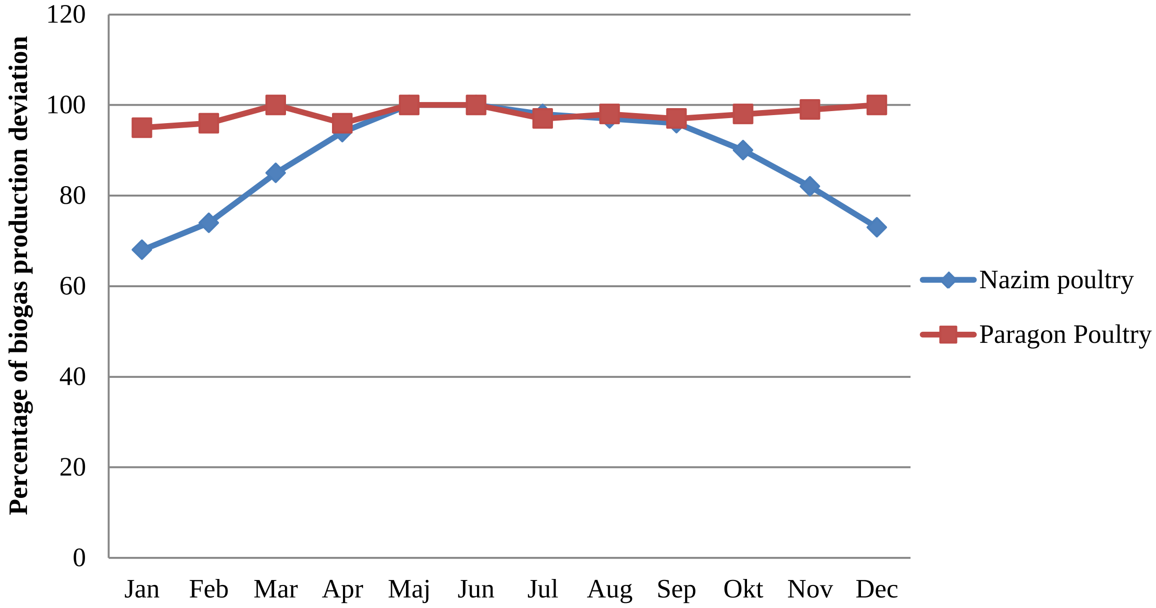

Figure 2-10: Variation of biogas yield throughout the year

Table 2-7: Comparisons between two types of digesters in Bangladesh

Biogas plants	Animal waste (t/day)	Total solid (kg)/HRT(days)	Biogas (m^3/kg TS)	Electricity (kWh/day)	Digester efficiency (%)	Digester inside temperature
Paragon Poultry	20	6000/20	0.7	6300	86-90	35-38
Nazim poultry	0.08	16/40	0.4	10	50-60	22-27

2.4 Arsenic in groundwater and mitigation options

The shallow tubewells in rural Bangladesh, which are safe from microbial contaminants, are the major source of water as these are much less expensive and easier to install. But this success was challenged by the discovery of widespread (like several developing Southeast Asian countries), arsenic contamination in groundwater exceeding the Bangladesh drinking water standard of 50 microgram per liter and the country faces immeasurable health consequences as a result [Manna et al., 2010]. According to the United Nation’s World Health Organisation (WHO), the arsenic contamination of water wells in Bangladesh has caused the worst mass poisoning in history. The groundwater of 50 districts out of a total of 64 districts contained arsenic higher than the country standard for shallow tubewell drinking water (50 µg/L), and in around 60 districts surface water was contaminated with arsenic levels higher than WHO recommendations (10 µg/L) [Chakraborty et al., 2010; Khan et al., 2006; Khan et al., 2003]. According to Tan et al. [2010], 20% of deaths in Bangladesh can be attributed to arsenic poisoning due to various diseases including lung, skin, and bladder and kidney cancers. An arsenic-related mortality rate of 1 in every 16 adult deaths could represent an economic burden of 13 billion United States dollars (US$) in lost productivity alone over the next 20 years [Sara et al., 2012]. Moreover, researchers estimate that around half of the nation’s 164 million people have been seriously exposed to arsenic contaminated drinking water [Tan et al., 2010]. Uddin et al. [2007], reports that the range of arsenic concentration in ground water of Bangladesh is between 0.25 µg/L to 1600 µg/L.

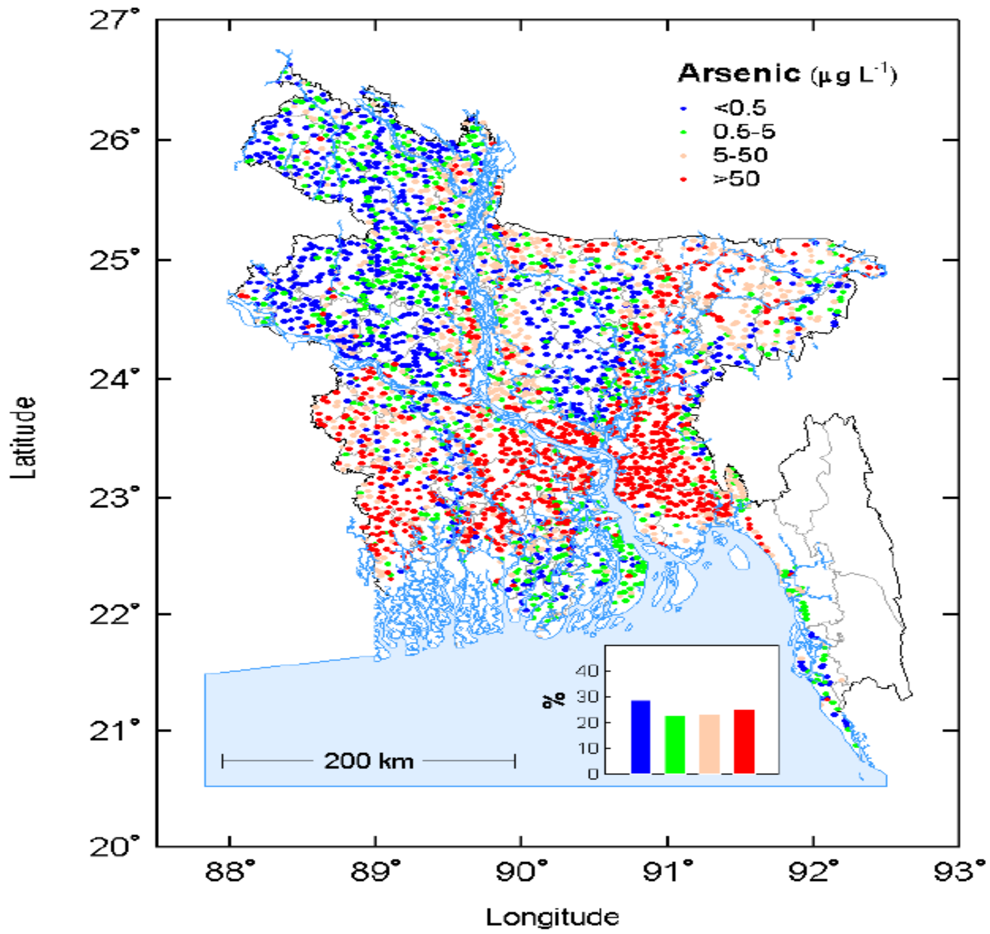

Figure 2-11: Distribution of arsenic in Bangladesh [DPHE/BGS/DFID, 2000]

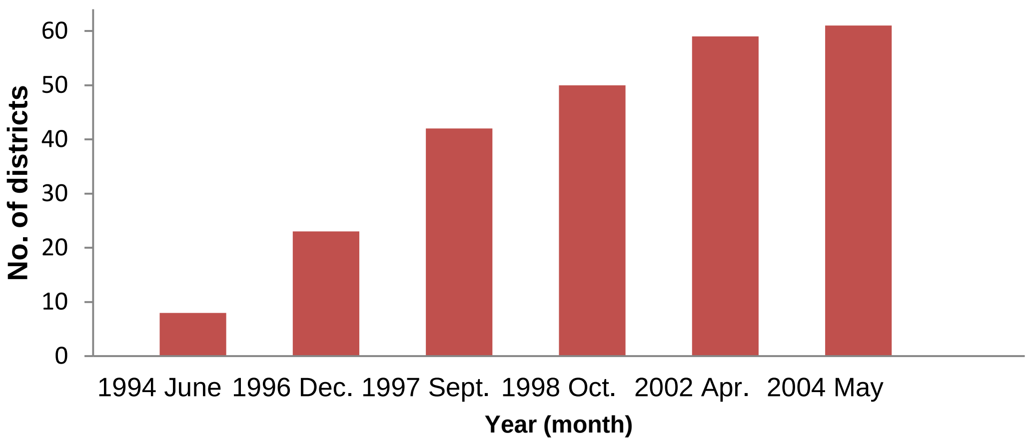

Figure 2-12: Arsenic contaminated districts over time in Bangladesh [Khan et al., 2008]

Treatment cost of arsenic-related disease is far beyond the monthly income of the rural people. The survey carried out by Barkat et al., [2002] in three Bangladesh villages shows that about 73% of the rural population does not have sufficient money to bear the expenditure of the arsenic-related diseases. They are the ultimate victims of arsenic poisoning effects and saline ground water consumption. In many affected areas the villagers do not have access to any secondary source of arsenic-free safe water. Surface water treatment and subsequent distribution of treated water in the remote areas is complex and costly. Safe water supply is the first and foremost necessity in countering arsenic contamination, for many people in the country knowingly drinks contaminated water simply because they do not have source of safe water.

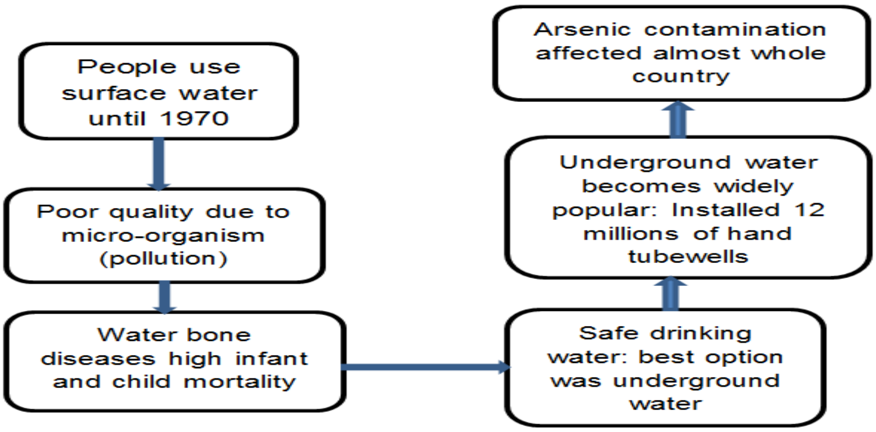

Figure 2-13: Water consumption scenario in rural Bangladesh

2.4.1 Mitigation options and existing water treatment technologies

The arsenic problem began, with a well-meaning attempt to provide clean drinking water for Bangladeshis, who suffered from cholera and other diseases caused by bacteria in water taken from surface reservoirs. To remedy that problem, the Bangladesh government, with the help of international aid organizations, drilled between 12 million wells at depths ranging from 50 to 300 feet to provide safe water for individual households. One of the key challenges towards overcoming this problem is the development and implementation of technologies that meet several tough demands: technically sound, robust in operation, cost effective, and environmentally compatible.

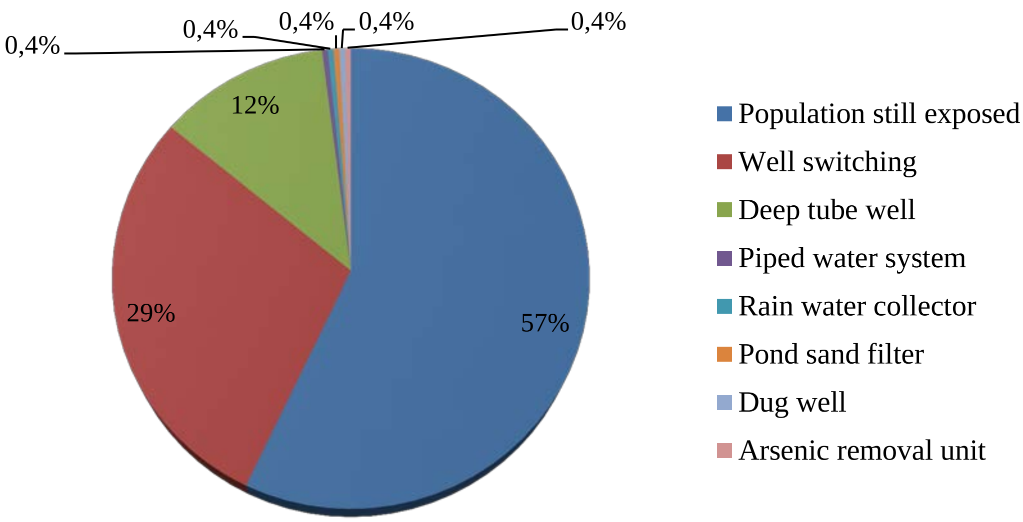

Figure 2-14: Impact of arsenic affected drinking water [Smedley and Kinniburgh, 2002]

The impact of arsenic in drinking water in Bangladesh is huge and complex. The principal arsenic mitigation strategy in rural Bangladesh is the provision of water supplies with acceptable levels of arsenic among exposed populations [Howard et al., 2006]. Considering these variety and magnitude of the problem, a number of alternative arsenic-free water supply technologies are identified and tested in several affected areas of Bangladesh [Howard et al., 2006; Hoque et al., 2000] by government agencies aided by international organizations. Mitigation options only focused on activities to provide arsenic-free safe water and it can be grouped as: (a) using arsenic-contaminated ground water after removal of arsenic and (b) using arsenic-safe water that may or may not require other treatments [Hoque et al., 2004]. Some of the principal options tested in Bangladesh to date are (i) pond sand filters (PSF), (ii) rain water harvesting, (iii) improved dug wells, (iv) deep tubewells, and (v) taped water. For instance, dug wells and pond sand filters were associated with intense microbial contamination and the estimated burden of disease was high [Howard et al., 2006; MacDonald, 2003]. Rain water was of good quality in the monsoon but not in the dry season. Deep tube-well is considered as the best option with an overall rating of good quality [Howard et al., 2006], recently this option is also reported to be arsenic contaminated and hence exists some uncertainty about this option [Khan et al., 2007]. On the other hand, arsenic removal may be more appropriate in these situations. Historically, the most common conventional technologies for arsenic removal have been coagulation with metal salts, lime softening, and iron/manganese removal, precipitation, adsorption and ion exchange. They have been tried for removal of high arsenic concentration arsenic from tubewell drinking water. Unfortunately all these options are limited by one or more problems like seasonally varies bacterial contamination, high health risks, less acceptance, difficulties in maintenance due to cost, time, labor and uncertainty [Howard et al., 2006; Hoque et al., 2004; Hoque et al., 2000]. The commonly used conventional methods employ adsorption processes – coagulation and ion exchange [Uddin et al., 2007]. Incorporating such processes is viable economically only at a large scale in centralized water treatment plants, requiring heavy capital outlays and skilled staff in addition to the necessary distribution systems and their maintenance. Also conventional methods are most effective on As(V), whereas As(III) is more prevalent in groundwater [Uddin et al., 2007]. Therefore alternatives are needed for distributed deployment and operation in small communities. The below Table 2-8 has shown present performance analysis of some distributed safe water options and surveyed has done after three years.

Table 2-8: Results - performance analysis (current condition) in Bangladesh [SASMIT, 2012]

Options type	Option provided	Option surveyed	Option functional
Arsenic removal filter	841	All	None
Filter to remove bacteria from arsenic safe surface water (Bishudhya filter)	190	All	None
Pond sand filter	23	All	3
Rain water harvested	147	All	50

2.4.2 Concentration brine disposal from contaminated feed solution

Disposal of the arsenic-contaminated concentrated sludge from water purification unit may be a concern. The waste stream produced by purifier is highly concentrated brine. This brine streams may require some pretreatment prior to discharge. In rural Bangladesh, a family of five drinking highly contaminated water (say, 500 µg/L arsenic) will need approximately 15 liters per day for drinking. If a household arsenic removal system is used, some 7.5 milligrams of arsenic will need to be removed from water daily. This translates to about 2.5 grams, or 1/12 of an ounce, of arsenic per year, assuming that the family has no other sources of water for drinking. With this perspective, the household annual production of 2.5 grams of arsenic is insignificant. Waste should still be handled responsibly - it is not recommended to simply discard arsenic-rich sludge's on the ground, since children are known to consume significant amounts of dust and dirt. As we have known that all the arsenic treatment technologies ultimately concentrate arsenic in feedwater, sorption media, sludge or liquid media and indiscriminate disposal of these may lead to environmental pollution. Hence, environmentally safe disposal of sludge, saturated media and liquid wastes rich in arsenic is of high concern. Arsenic levels in wastes stream will depend on influent concentrations, but may reach several thousand µg/kg concentrated waste solution. Depending on costs, it may be economical to dispose of concentrated stream. The stability of these solutions needs to be evaluated when considering disposal options. If arsenic is likely to leach out after disposal, the wastes may require a specially constructed hazardous waste disposal facility, or additional treatment to immobilize arsenic. If the arsenic is so tightly bound to the solid wastes that it will not leach out, the wastes can be disposed of along with other municipal solid wastes [Johnston et al., 2001]. However, the sludge could be deposited along with other solid wastes, mixed with animal manure. Experiments were conducted to assess transformation of arsenic from aqueous solutions in the presence of cow dung. Some studies suggested that bio-chemical (e.g., bio-methylation) process in the presence of fresh cow-dung may led to significant reduction of arsenic from arsenic rich treatment wastes [Johnston et al., 2001] and transforming it into less toxic and volatile compounds. Some researchers in West Bengal and Bangladesh, at Jadavpur University in India, have observed that over 90% of arsenic bound in sludge was found to be removed in this way [Chakraborti, 1999]. Some arsenic concentrated sludge samples were analyzed at the BUET Environmental Laboratory (Bangladesh) and a toxicity characteristic leaching test was conducted to determine the quantity of mobile arsenic in the sludge samples. This study has concluded that the arsenic treatment units rendered the majority of the arsenic into a stable and non-mobile phase. No hazardous leachate was identified from the sludge produced from these units.

These initial results give the impression that leaching of arsenic from sludge/soil generated from arsenic removal processes is not a major problem. However, the leachate concentrations are all well below the drinking water criteria of 0.05 mg/L. It should also be noted that further dilution may occur after leaching of arsenic from sludge/soil, further reducing the arsenic concentration in the leachate. With these arguments in mind, it is safe to assume that no dangerous level of arsenic leaching is occurring from the sludge from various treatment processes in use. The arsenic being removed from the drinking water remains in a stable and non-mobile form in the sludge. Therefore, present arsenic-sludge disposal methods appear to be safe and not to contribute to recontamination of the environment [Hamel and Zinia, 2001].

3. Experimental Study on Air-Gap Membrane Distillation

3.1 Introduction

A key challenge towards overcoming arsenic poisoning is the development and implementation of water treatment technologies that meet several tough demands: technically sound, robust in operation, cost effective, and environmentally compatible. Several technologies have been tried for removal of high arsenic concentration arsenic from tubewell drinking water; see Table 3-1 for a summary. The commonly used conventional methods employ adsorption processes – coagulation and ion exchange [Uddin et al., 2007]. Incorporating such processes is viable economically only at a large scale in centralized water treatment plants, requiring heavy capital outlays and skilled staff in addition to the necessary distribution systems and their maintenance. Therefore alternatives are needed for distributed deployment and operation in small communities.

Reverse osmosis (RO), a widespread membrane technology for a broad range of capacities, exhibits very good to excellent separation efficiencies and has potential as a water treatment technology in this context. However drawbacks like formation of polarization film, fouling, and high electricity consumption are limiting factors [Pangarkar et al., 2011]. Several experimental results showed that reverse osmosis (RO) is an effective method for separation of arsenic up to 90%; however RO failed to remove arsenic concentration to safe levels when groundwater arsenic concentrations are very high [Figoli et al., 2010]. Membrane distillation (MD) has also been considered as an alternative technology for arsenic removal. In short MD is a thermal water purification process involving a hydrophobic, microporous membrane. Hot feed is kept on one side of the membrane, and a vapor pressure difference is established across the membrane via cooling on the opposite side. Water evaporates from the feed, passes through the membrane, and condenses; all non-volatile components are retained in the liquid phase, thus ensuring extremely high separation efficiency and high product water purity. Khayet and Matsuura [2011] provide a comprehensive overview of MD technology and applications. Pangarkar and Sane [2011] mention MD’s advantages over other technologies like low-grade energy utilization, low pressure and cost, and possibility to integrate MD with combined electricity, heat, cooling, and other energy services (i.e. polygeneration). A few MD studies have specifically considered arsenic removal. Qu et al. [2009] experimentally investigated direct contact membrane distillation (DCMD) for arsenic removal; DCMD was found to have a higher removal efficiency rate (above 99.95%) than RO and also exhibited the ability to treat high-concentration arsenic solutions. Manna et al. [2010] and Pal and Manna [2010] achieved almost 100% As separation efficiency in a laboratory-scale DCMD unit supplied with heat from an evacuated tube solar collector. Small scale vacuum membrane distillation (VMD) was tested for arsenic contaminated water at low feed temperatures [Criscuoli et al., 2012], and excellent separation efficiency was demonstrated.

Air gap membrane distillation (AGMD) has also been proposed as a promising approach that combines the excellent separation characteristics of DCMD and VMD with lower specific thermal energy consumption [Sääsk, 2009]. Islam [2005] studied arsenic removal by AGMD using a small-scale commercial prototype module and reported successful treatment of arsenic-contaminated groundwater in Bangladesh. Moreover, highly arsenic concentrated (240 µg/L) surface water in Högsby municipality in Sweden was treated in the lab, and arsenic concentration in the product water was below detection limits, 0.5 µg/L [Islam, 2005]. Kullab and Martin [2011] investigated AGMD for flue gas condensate treatment in biomassfired boilers; here product water in pilot-scale trials exhibited As levels below detection limits (1μg/L), despite high levels of heavy metals and other hazardous components in the feedstock.

Table 3-1: Comparison of water purification methods for arsenic removal

Method	As separation efficiency	Cost	Comments
Filtration	low	low	Uncertain/ incomplete As removal
Carbon absorption	medium	low	Uncertain/ incomplete As removal
RO	high	high	high electricity demand
DCMD	high	high	High thermal energy consumption
VMD	high	high	High thermal energy consumption and complex vacuum system
AGMD	high	high	High thermal energy consumption
MSF	high	high	Suitable only for large scale systems
Flocculation	Medium to high	medium	Suitable only for large scale and complex water distribution systems

The integration of membrane distillation with industrial or power plant waste heat or with solar thermal systems offers several advantages including lower thermal energy consumption, reduction of overall energy consumption, reduction of greenhouse gas emissions, reduced pure water production costs due to waste heat recovery, and effective process integration for multiple products. Temperature levels on the hot side (up to 90^{o}C) are amenable to thermal integration with a variety of appropriate sources. Moreover, the cold side temperatures can be increased to fairly high amounts (up to 70^{o}C) while exhibiting reasonable yields, opening up further possibilities for thermal integration. Considering the socio-economic situation of rural areas in Bangladesh, AGMD seems difficult to be applied alone due to high capital cost and energy consumption; therefore an integrated approach could be a viable alternative. Recently, Kumar et al. [2013], have presented a solar hot water system with integrated AGMD for water purification.

The above studies indicate that AGMD is a promising technology for producing arsenic-free drinking water, however further research is required to firmly quantify actual performance in terms of separation efficiency and thermal energy consumption for near-commercial modules. Such data is necessary for the design of integrated small-scale polygeneration systems featuring MD. The present investigation addresses this issue via an experimental investigation of a household AGMD water purifier prototype (2 L/hr nominal capacity) supplied by HVR Water Purification AB, Stockholm (subsidiary of Scarab Development AB). A parametric variation of coolant-side inlet temperature was conducted for plain and As-spiked tap water along with As-contaminated groundwater, and the resulting yield and thermal energy consumption were determined.

3.2 Methodology

3.2.1 AGMD experimental setup

A schematic representation of the air gap membrane distillation (AGMD) system is shown in Figure 3-1. The membrane distillation system consists of three sub-sections: the feed compartment, where each of the hot feed solutions (arsenic contaminated groundwater and arsenic spiked tap water) was usually passed; the cooling compartment, in which water was passed on one side of the condensing plate; and the permeate compartment, which was placed between the feed and coolant compartments. The permeate vapor diffused through the membrane and condensed due to contact with the cooling plate.

Two immersion heaters (combined rate of 4.5 kW) provide temperature control to feedwater contained in a 24 liter tank. A small circulation pump and bypass valve allow the hot-side flow rate to be controlled, and a rotameter is employed to measure flowrate. Once-through tap water is used as a heat sink, which can be heat exchanged with an external source to raise the inlet coolant temperature to the desired level. Here a second rotameter with built in control valve measures cold water flowrate in the cooling channel. Product water is measured with a graduated cylinder and stopwatch, typically during a 30-minute period of steady operation. To measure the feed and cold temperatures, thermocouples were installed at the inlets and outlets of the module and were connected to a data logger (Keithley 2701 DMM with a 7706 card). The inlet and outlet temperatures of the feed solution and the cooling water are continually measured by the thermocouples. Experimental errors are as follows: temperature, +/- 2.0^{o}C; flow rate, +/- 0.1 L/min; yield, +/- 0.02 L/hr; and conductivity ±1µS/cm. The AGMD module consists of a 2.4 cm separation between two vertical condensations plates, behind which are located serpentine cooling channels. A polypropylene cassette with membranes attached to either side is placed between the condensation surfaces (cassette dimensions 42 cm wide by 24 cm high, total membrane area 0.19 m^2). This arrangement provides for an initial gap of 9 mm on each side, although the actual gap size is reduced by bulging of the membranes during operation. The feedstock is introduced at the bottom of the cassette and flows out from the top, as seen in Figure 3-1(b). The membrane material is PTFE (polytetrafluoroethylene, supplied by Gore) with a porosity of 80% and thickness of 0.2 mm.

3.2.2 Experimental procedure

Experiments were carried out using mainly groundwater and arsenic-spiked contaminated water and the characteristics of this water are given in Table 3-2. A finely perforated stainless steel plate supported the membrane in the module. The feed temperature in the feed tank was about 80^{o}C and the circulation pump at the ground level. Feed side and distillate side temperatures were controlled by controlling the ground level circulation pump and using thermostatic baths attached to the module. During experiments, the feed was at atmospheric pressure. Leakages were checked prior to each run. Inlet feed pressure was controlled to avoid membrane wetting. Data were collected after the system had reached steady state.

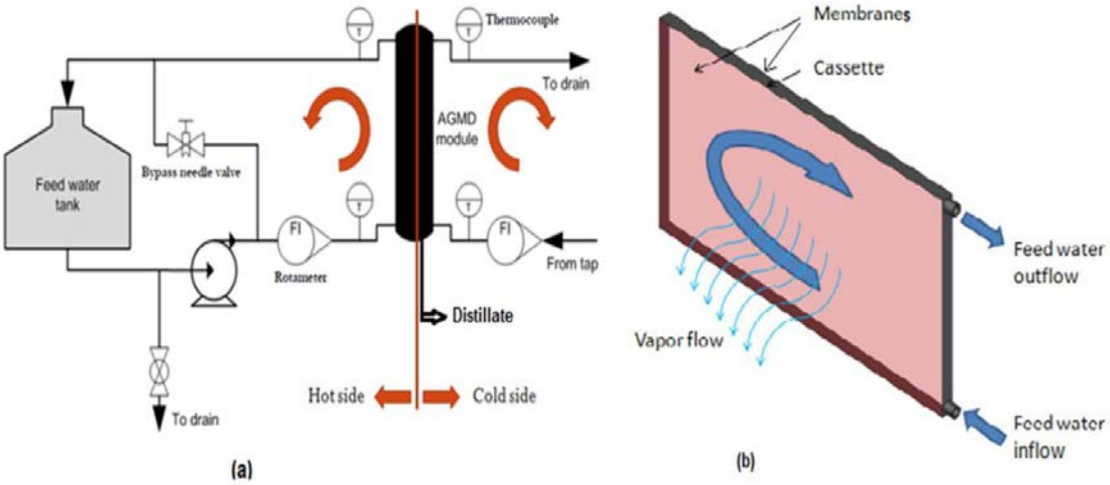

Figure 3-1: (a) MD bench scale unit setup at KTH, (b) Membrane cassette (MD)

The AGMD experiments consist of analyzing the performance of the system under different operating conditions, namely various cold-side temperature levels. The operating conditions on the cold side included a flow rate of 1.9 L/min and a range of coolant inlet temperatures: 15°C, 30°C, 45°C, 55°C, and 70°C. On the hot side, the temperature was kept constant at about 80°C, with a constant feed flow of 3.8 L/min. Flowrates are selected to lie in the upper range in terms of ensuring low ΔT across the particular side while keeping pressure drop (linked to pumping power requirements) and absolute pressure (linked to membrane liquid entry pressure limitations) at reasonable levels.

The initial conductivity of plain, contaminated groundwater and arsenic-spiked tap water is about 250 µS/cm at 25°C. The arsenic contaminated groundwater was collected from Högsby municipality in Sweden and the sample water was analyzed by ICP-OES (measurement standard deviation is <±1%). The arsenic spiked water was synthesized from $CaSO_4{\cdot}2H_2O$, $MgSO_4$, Na_2CO_3 and KNO_3. Feedwater characteristics are shown in Table 3-2.

Table 3-2: Primarily chemical constituents of tested feedwaters

Parameter	Unit	As-contaminated groundwater (Högsby municipality, Sweden)	As-spiked tap water, high concentration	As-spiked tap water, medium concentration
As	µg/L	366	1800	300
Ca^{2+}	mg/L	64	40	50
Mg^{2+}	mg/L	21	10	12.5
Na^{+}	mg/L	17.4	15	100
K^{+}	mg/L	6.44	5	5
Conductivity	µS/cm	270	250	250
pH		8.48	8.2	8.2

3.3 Results

3.3.1 Parametric study

In the AGMD process, the applied driving force is the temperature difference between the hot and the cold water flow. The direct driving force that makes the water molecules diffuse across membrane and air gap is the water vapor pressure difference between the hot water surface at the inner membrane radius and the condenser layer surface. It can be seen in Figure 3-2, the saturated water vapor pressure increases exponentially with temperature. This means that a given temperature difference results in a larger flux with increasing hot water temperature. The experimental campaign has been focused on the analysis of the effects of feed and coolant temperature difference on the process performance. MD is an energy intensive technology and so energy economy is an important issue. Unlike the pressure-driven separation processes, energy consumption in MD systems includes both thermal energy necessary to heat the feed aqueous solution and to cool the permeate aqueous solution or condensation and the electrical energy required to run the circulation pumps, vacuum pumps or compressors. However, the heat energy requirement in MD can be by far more than 90% of the total energy requirement and increases drastically with the feed temperature. It is to note that electrical energy is more expensive than low-grade thermal energy.

The performance of the AGMD prototype is evaluated by analyzing pure water flow rates and specific thermal energy requirements (kWh/m^3) as a function of feed and coolant temperature difference. As mentioned previously, experiments were performed for high and low temperature differences across the membrane for arsenic contaminated groundwater and arsenic-spiked water. A feedstock-to-coolant temperature difference ΔT is defined for reference purposes:

$$\Delta T = T_{fi} - T_{ci} \quad (1)$$

where T_{fi} and T_{ci} are the inlet temperatures of the feed and coolant, respectively. Figure 3-2 shows the effect of this temperature difference on permeate flux at constant feed flow and coolant flow rate (the temperature difference is based on inlet conditions). The influence of coolant temperature was examined by varying the coolant fluid temperature between 15 to 70°C at constant hot feed temperature, flow rate and feed concentration. The permeate flux declined when the coolant temperature increased.

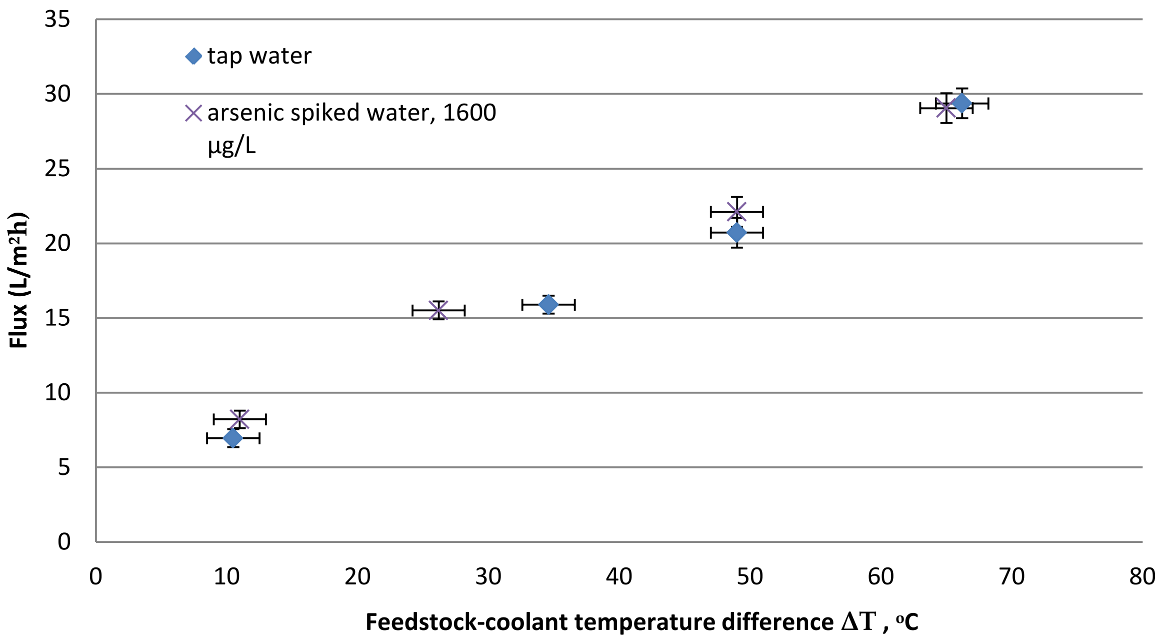

Figure 3-2: Product water flux as a function of temperature difference across the membrane (feed water flow 3.8 L/min, coolant flow 1.9 L/min, feedwater inlet temperature ca 80 °C, coolant inlet temperature varying)

It was observed that the thermal energy consumption in MD is very much sensitive to the feed temperature. This is mainly due to the exponentially increased mass flux and to the decrease of the amount of heat lost by conduction through the membrane with the increase of the feed temperature. At high feed temperatures the heat transferred through the membrane by conduction will be negligible compared with the heat transferred due to the transmembrane mass flux. Therefore, the energy consumption per unit of distillate may be reduced appreciably at high operating feed temperatures. The results show the increase of permeate flux with increase in temperature difference, an expected observation owing to the higher driving forces in this scenario. A small but significant flux is measured at a very low temperature difference, corresponding to a coolant temperature of around 70°C, which has implications for heat recovery on the cold side (see next section). This result can be attributed to the fact that decreasing the coolant temperature leads to an increase in the vapour pressure difference across the membrane, thus an enhancement of the flux. Overall the performance of the AGMD commercial prototype is within expectations, although the permeate flux has been reported to be much higher in DCMD and VMD (2-6 times increase, respectively) [Khayet and Matsuura, 2011; Alklaibi and Lior, 2007].

The MD unit's thermal energy requirement essentially consists in the heat required to increase the feed flow rate temperature from chilling water out from cold side. One of the most important parameters of the AGMD process is how much heat it contributes to produce a specific quantity of vapors (that passing through the membrane) from the total incident radiation. The general definition of the thermal recovery ratio (TRR) is the theoretical energy needed for distillate produced divided by the total thermal energy input. To improve energy efficiency in MD, a portion of the heat from the retentate should be recovered to preheat the feed aqueous solution. The maximum heat recovery should be as high as possible. Installment of heat recovery system increases the capital investment costs but at the same time brings benefit in the operating costs. The temperature and concentration polarization effects, thermal conduction through the membrane and heat loss to the surroundings should be minimized in

order to increase energy efficiency. Internal heat recovery can be achieved by AGMD since the modules allow the latent heat of vaporization to be transferred to the coolant channel via the distillate. The specific thermal energy consumption has been estimated in two ways:
Enthalpy drop across the hot side,

$$Q_1 = \dot{m}_h c_{ph}(T_{hi} - T_{ho})/\dot{m}_p \quad (2)$$

Net enthalpy change,

$$Q_2 = [\dot{m}_h c_{ph}(T_{hi} - T_{ho}) - \dot{m}_c c_{pc}(T_{co} - T_{ci})]/\dot{m}_p \quad (3)$$

where $\dot{m}$ is the mass flow rate and c_p is the specific heat for cold (subscript c), hot (subscript h), and product water streams (subscript p); subscripts i and o denote inlet and outlet, respectively. It was assumed that c_p values (4.2 kJ/kg K) are same for the contaminated feeds and cooling water. Feedwater flow rates ($\dot{m}_h$), cooling water flow rates ($\dot{m}_c$), feed inlet and outlet temperature and cooling inlet and outlet temperatures are shown in Table A1 (in Appendix). Figure 3-3 shows this data as a function of feedstock-to-coolant temperature difference. Specific thermal energy consumption as defined by Q_1 shows a weak correlation to temperature, especially when considering the high level of uncertainty in propagated errors. The slight increase at higher ΔT is attributed mainly to the fact that the enthalpy drop across the hot feedstock side rises at a faster rate than the concomitant augmentation in product water yield (Figure 3-2). The opposite trend can be seen in the specific thermal energy consumption as defined by Q_2, i.e. as the feedstock-coolant temperature difference is raised, the rate of increase in product water yield dominates over the difference in net feedstock and coolant enthalpy change. Moreover heat recovery is enhanced with higher driving forces, which is reflected in a reduction of Q_2 at higher feedstock-coolant temperature differences.

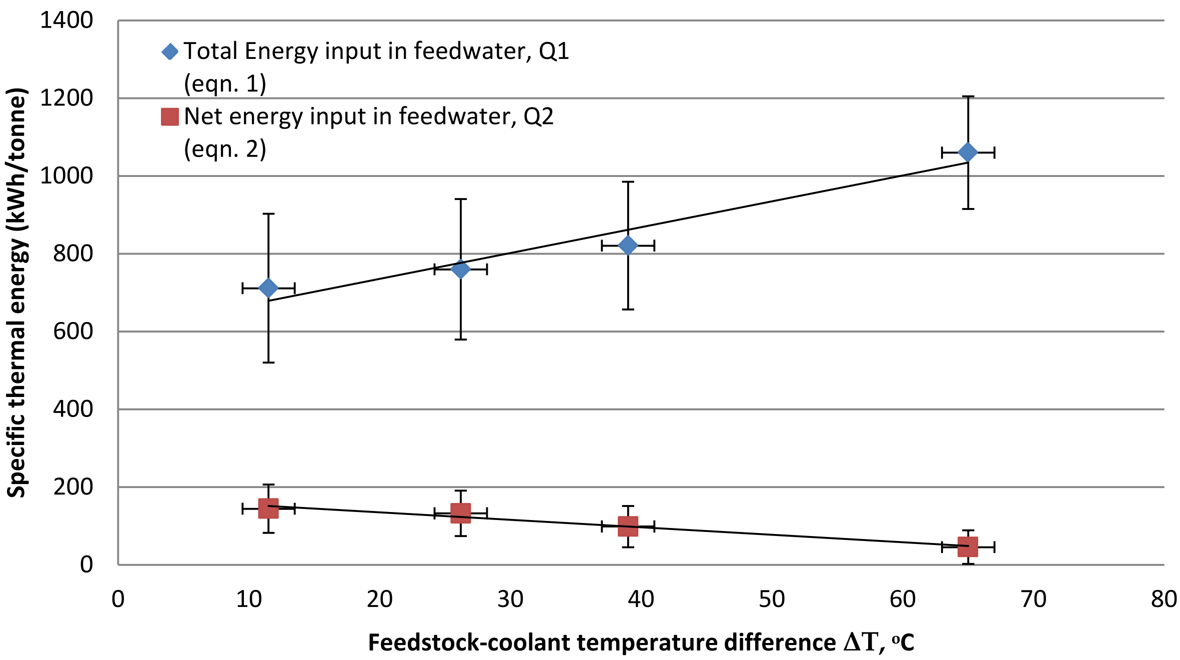

Figure 3-3: Specific thermal energy consumption for AGMD module (feed water flow 3.8 L/min, coolant flow 1.9 L/min, feedwater temperature ca 80 °C, coolant temperature varying)

Concerning thermal energy consumption, Kullab and Martin [2011] performed a full-scale simulation using Aspen utilities, assuming the MD facility connected to the district heating network. Assuming a 10 m^3/h production capacity and no energy recovery of the system, simulations predicted a specific thermal energy consumption (defined considering as useful energy output, i.e. not consumed by the process, also the heat gained from exiting brine for heating purposes) ranging from 5 to 12 kWh/m^3 and a specific electricity consumption ranging from 0.6 to 1.5 kWh/m^3 for two different scenarios [Blanco Galvez et al., 2009]. In the past years other SCARAB modules have been tested in a solar-powered unit at the Plataforma Solar de Almeria (PSA) within the framework of the MEDESOL project (PSA). Each module was characterised by 2.8 m^2 of membrane surface and nominal distillate flux ranging from 5 to 10 L/m^2/h [Blanco Galvez et al., 2009]. Preliminary results from the first testing of the system (PSA) indicated a specific flux of 3.2 L/m^2/h, with an energy consumption of 1300 kWh/m^3, thus much higher than the values previously shown.

3.3.2 Product water quality analysis of contaminated groundwater and arsenic-spiked tap water feeds

Values of product water conductivity were around 0.6 to 1.5 µS/cm at 25°C, indicating a very high purity level. The major advantage of AGMD process when compared with reverse osmosis or other purification technology is the relatively minimal effect of feed concentration on the flux and it was well observed in the present investigation. (With an increase of feed concentration in RO, the performance of the system may significantly suffer as increased feed concentrations may reduce the driving force for mass transfer across the membrane, thus increasing mineral passage through the membrane). Table 3-3 contains the product water analyses of the three different feeds (analyses conducted by Activation Laboratories Ltd, Ontario, Canada, and measurement standard deviation ±0.5%). The results are very promising in terms of arsenic concentration in the distillate, which was at extremely low levels. The analysis showed that the permeate arsenic concentration is not affected by operating parameters (like temperature and flow rate variations), and the concentration of arsenic in distilled remain below 0.4µg/L for all the samples tested.

Table 3-3: Water quality analysis for distillate water (groundwater and arsenic-spiked tap waters)

Parameter	Unit	As-contaminated groundwater feed (Högsby municipality, Sweden)	As-spiked tap water feed (1800 µg/L)	As-spiked tap water feed (300 µg/L)
As	µg/L	<0.4	<0.03	<0.03
Ca^{2+}	mg/L	<0.7	<0.7	<0.7
Mg^{2+}	mg/L	0.014	0.002	<0.02
Na^{+}	mg/L	0.02	0.012	<0.17
K^{+}	mg/L	<0.03	<0.03	<0.03
Conductivity	µS/cm	0.6-0.7	0.6-1.5	0.6-1.5
pH		6	6	6

3.4 Concluding remarks

Air gap membrane distillation has been demonstrated as a viable technology for arsenic removal with realistic arsenic contaminated feedstocks. Yields are maximized by increasing the temperature difference between feedstock and coolant, yet there is scope to utilize high coolant temperatures to achieve low specific thermal energy consumption and thus enhance heat recovery. Temperature levels on the hot side (at about $80^{o}C$) are amenable to thermal integration with a variety of appropriate sources - biomass-derived waste heat, solar thermal, etc. Moreover cold side temperatures can be increased to fairly high amounts (up to $70^{o}C$) while exhibiting reasonable yields, opening up further possibilities for thermal integration. The additional advantage of MD is that they make use of the millions of shallow tube wells already built that tap arsenic-rich waters. Considering the socio-economic situation of rural areas in Bangladesh, AGMD seems difficult to be applied alone due to high capital cost and energy consumption. Therefore, an integrated system could be one of feasible and viable alternative to solve the safe and arsenic free drinking water. The future aim is to develop and commercialize a simple low-cost polygeneration system with an integrated biogas digester, gas engine, and AGMD unit, and activities are already underway.

4. Technical Specification of Integrated System

4.1 System and components descriptions

The proposed polygeneration system, including the inputs and various levels of outputs is shown in Figure 4-1 and presents the general layout of an integrated multigeneration system, which shows that from a primary energy input several useful outputs are obtained.

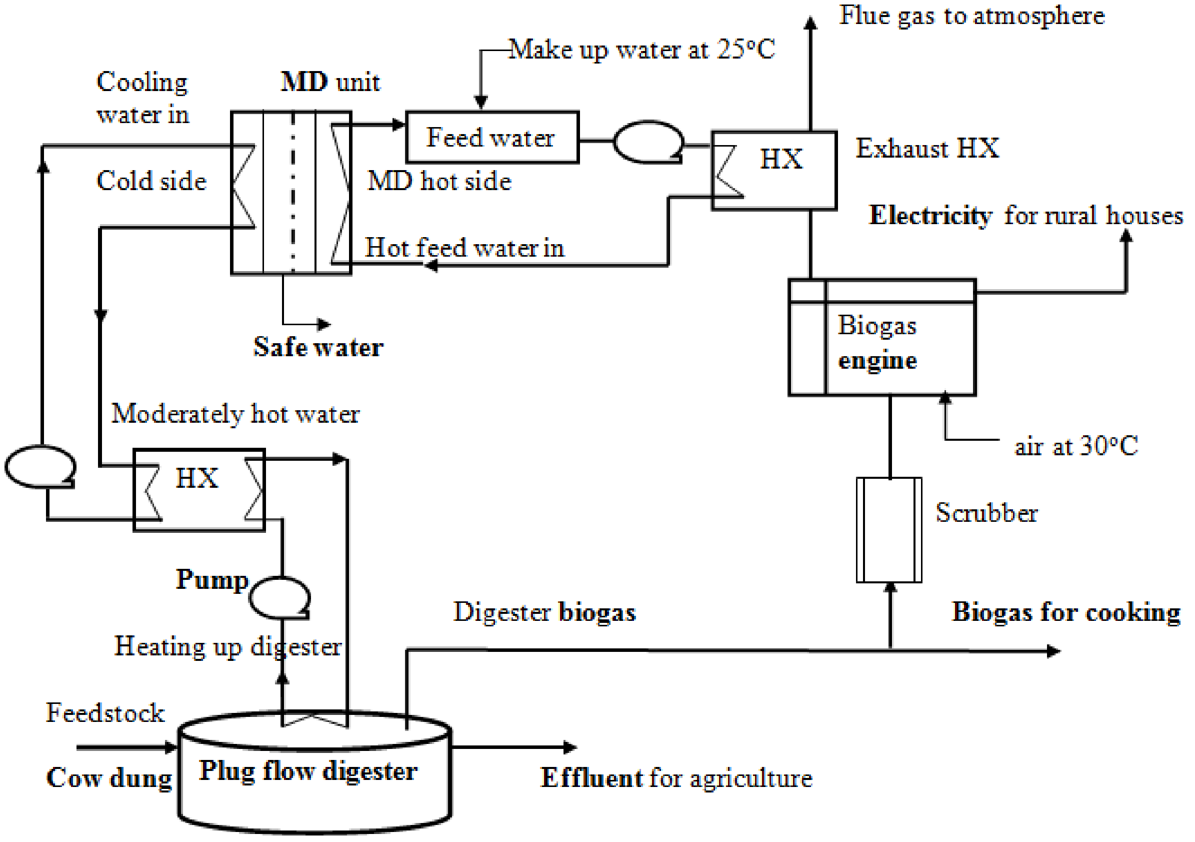

Figure 4-1: Integrated systems for electricity, cooking gas and safe water production

In short, a plug flow digester feed with cow dung mixing and pre-heated hot water supply is considered for delivering the required amount of biogas. The digester operates at constant operating temperatures under mesophilic conditions, with gravity feed and discharge. Generated biogas from the digester is either routed to a cooking stove or is burnt in a biogas engine; here exhaust flue gas passes through a heat exchanger for heating up arsenic contaminated feed water, which is supplied to the feed side of a membrane distillation (MD) unit. The cooling circuit of the MD unit is heat exchanged with the digester and enhances the anaerobic processes. Scalability of the system depends primarily on the size of the digester and engine; a rough range of 10 kW to 100 kW electricity capacities is anticipated to be most feasible. The set of technologies to supply each demand composed a complex tree-form scheme, in which cow manure feed biogas is main energy supply to the system along with contaminated ground water. The four supported demands (electricity, cooking gas, pure water, and organic fertilizer) were also included. The available technologies are briefly described in the following sections.

4.2 Technical specification-biogas digester

Despite of this huge potential, only few number of biogas plants have been deployed till date. Besides, most of these plants are unable to produce the expected amount of biogas as most of the digesters of these plants are made locally and they don't have any scheme for monitoring and controlling temperature, pH, bacterial population in digester, mixture of different substrate, hydraulic retention time, total solid (TS), periodic agitation, periodic loading and unloading of substrate etc. Types and design of digesters is varied based on availability of local feedstock, geographical and environmental conditions. It is always preferable to have digesters underground due to its potential benefits in tropical countries especially in Bangladesh [Bin, 1989]. Anaerobic digester output depends on several different factors for optimum performance. Biogas contains 50-70% methane (CH_4) and 30-50% carbon dioxide (CO_2), depending on the substrate [Sasse, 1988; Bond and Templeton, 2011] as well as small amounts of other gases including hydrogen sulphide (H_2S). The typical calorific value of biogas is about 21-24 MJ/m^3 [Dimpl, 2010] or around 6 kWh/m^3 which correspond 60% of methane contains in biogas. The efficiency of the digester depends on many factors such as technological conditions (pH, temperature, etc.), micro-organisms, type of substrate and its quality and degradability, etc. [Omar et al., 2003; Schwart, 2005; Chynoweth, 2001; Rajendran et al., 2012; Baldwin et al., 2009; Sobotka, 1983]. In general, the amount and quality of biogas depends not only on the type of feedstocks, but also on the digester design, temperature inside the digester, C/N ratio, mixing and retention time. Recently, one study has been analyzed on focusing the impacts of above mentioned factors on biogas production by comparing biogas production between locally made digesters and imported digesters. The result reveals that up to 75% more biogas is generated in imported digesters than the locally made digesters [Islam et al., 2013]. Cow dung is easily biodegradable. The daily production of manure depends on the feed type, level of nutrition and body weight of cow [Hossain, 2003; Rongdu, 2006]. Table 4-1 shows sources of feedstocks, body weight, manure yield, total solids (TS) and percentage of methane (CH_4) in product biogas.

Table 4-1: the TS%, C/N ratio, daily gas yield per kg TS and CH_4

Manure source	Body weight (kg)	Manure yield (kg/day)	TS%	C/N ratio	Gas yield (m3/kg TS, at 25-35 ^oC)	CH_4%
Chicken	1	0.1	25	9.6:1	0.33	60-65
Cow[a]	500	35	17	25:1	0.25	50-77
Cow[b]	200	10-15	8-14%	24:1	0.25	50-70
Cow[c]	150	10-12	10-16	25:1	0.30	55-65

Note: TS (total solid), C/N (carbon and nitrogen ratio), a=American and European cows, b= South Asian cows, c=Bangladeshi cows.

Table 4-1 illustrates that the biogas production per cow is relatively low in South Asia compared to Europe and the US; this discrepancy is linked to the animal's weight, manure quality and quantity, and the design and operation conditions of digesters. The average weight of Bangladeshi cow (150 kg) is lower than Asian cow (200 kg) and the manure yield, gas production rate and total solid content will vary according to body weight and feed type [DBCC, SNV 2011; FAO, 1996].

Recently, plug flow digesters are gaining interest in south Asia due to its potential benefit and multi applicable features. The dome type of digester is generally good for small volume animal waste slurries as feedstock and biogas use for household cooking purpose only (small scale biogas production). The plug flow (or channel) digester has ability to handle larger volume efficiently compare to dome type digester; perhaps the simplest and least expensive digester, it is able to produce gas with wide variety of feedstocks with high percentage of solids content, and it does not need any internal mixing [Jewell and Kabrick, 1981; Jewell and Dell-Orto, 1981]. Plug flow digesters requires less feedstock input than fixed dome and floating drum digesters, and additionally these digesters ensure uniform flow rate, offering a sufficient flow of slurry and resulting in more biogas production than fixed dome and covered lagoon digesters [Nzila et al., 2012; Denis and Burke, 2001]. A digesters ability to efficiently operate is relative the retention time (plus other factors such as temp, feedstocks, pH etc.). Retention time is generally determined by dividing the total digestate volume of the digester by the inflow. As dome digesters get larger, what happens is short circuiting inside the digester caused by incomplete mixing – i.e. the inflow material moves in a preferential laminar flow towards the outflow and there are dead zones or slow flow zones towards the sides of the digester. To say this another way, there is an uneven flow regime inside the reactor which results in the effective retention time being reduced for some materials and increased for others. In a plug flow digester the material flows along the digester in a more uniform speed as a "plug". In this way the calculated retention time is closer to the real retention time for all material entering the digester, which results in greater efficiency. However, for slurry and non-slurry feedstocks such as direct feeding of animal waste and biomass, agro-residues, weeds, USW or co-digestion etc. where solid and unprocessed biomass is the feed, then the plug flow approach overcomes various problems related to floating, scum formation and segregation of feed that happens typically to dome type plants fed with solid biomass. Accounting for over 50% of all installed AD designs, plug-flow digesters generally have a highest success rate [Cantrell et al., 2008].

Temperature is the most important factor that has a significant impact on biogas production throughout the digestion process. Most importantly, rural people suffer from very low digestion rates or in stagnation during the winter season, when the temperature drops below 12°C. In the higher range of temperature (35-50^{o}C), decomposition and biogas production rate occurs more rapidly than at low temperature range (below 30^{o}C), but the process is sensitive due to changes in feed materials and temperature. Gas production efficiency generally increases with temperature, roughly doubling for every 10^{o}C rise between 15^{o}C and 35^{o}C (cow manure as a feedstock) [Alvarez et al., 2006]. The digesters which are mostly operates either with mesophilic or thermophilic conditions and the optimum temperature are 35^{o}C and 55^{o}C respectively [Ward et al., 2008]. The mesophilic digester is more popular than thermophilic due to the fact that thermophilic bacteria are more sensitive to temperature fluctuations [Biey et al., 2003], and the optimum temperature range for mesophilic digester is reported to 33-37^{o}C [Fernandez et al., 2008; AD, USA, 2012; Chae et al., 2008; REIN Bangladesh, 2012; Pain et al., 1988]. Digester retention time has a significant effect on biogas production at higher operating temperature [Pain et al., 1988]. The optimal retention time for plug flow digester at mesophilic conditions (35^{o}C) is about 20 days. In order to optimize the digestion process the digester must be operated at constant temperature. For the integrated polygeneration process presented herein, an advantage is that temperature inside the plug flow digester can be maintained at about 35±2^{o}C (mesophilic condition) by utilizing waste heat from cooling side of membrane distillation process. For mesophilic manure digestion, sludge has to be heated from about 27±2 to 35^{o}C, or a difference of 8^{o}C. Table 4-2 contains a summary of the digester parameters considered in this study.

Table 4-2: Digester input parameters

Digester	Parameters
Digester type	Plug flow
Feedstock	Cow dung
Total solid	10-16%
Temperature and pressure inside the digester	35±2^{o}C& 1 bar
Hydraulic retention time	20±2 days
Biogas quality	60-62% CH_4, 38-40% CO_2
Biogas calorific value	22 MJ/m^3

The value of pH between 6.8 and 7.2 gives the best production of biogas [Islam et al., 2013]. Anything outside of this range reduces biogas production. Hence it is very important to maintain the pH. Usually pH of a digester is self-regulating, hence any aberration of it tend to be converged to the reference value on its own. But there could be cases where pH needed to be controlled if too much deviation is observed. Usually lime water is introduced to the digester to maintain pH.

4.3 Technical specification-biogas engine

Biogas can be used to produce both power and heat in the same plant. About 30-40 percent of the energy can be extracted as electricity and the remainder as heat. There are several different technical solutions available to produce CHP from farm-based biogas. The use of internal combustion (IC) engines with biogas is long established and reliable [Wellinger and Lindberg, 2001]. As we know that small and medium sized biogas plants are available in many developing countries, however, only very few plants are used for electricity generation in comparison to Europe and the US. IC engines are sub-divided into two categories: compression engines, and spark ignition engines. Both types of engine may be converted to run on the biogas produced by anaerobic digesters. Different types of engines have different characteristics and in Germany, CI engines are used primarily in small biogas plants. Usually large biogas plants are generally more economically viable than smaller ones. On the other hand, electricity generation from biogas is technically suitable even for relatively small scale (10-100kW) applications [Dimpl, 2010]. In theory biogas can be used as fuel in nearly all types of combustion engines, such as gas engines (Otto engine), diesel engines, gas turbines and Stirling engines. Small scale gas turbines are expensive, design and manufacturing is challenging and operation and maintenance requires specific skills; therefore they are hardly used for small scale application in developing countries. Stirling engines have the advantage of being fuel flexible, but they are relatively expensive and characterized by low electric efficiency. Therefore, internal combustion engines are considered to be the most viable alternative for small biogas power plants [Dimpl, 2010]. In terms of fuel quality for IC engines, the presence of CO_2 in biogas reduces the air fuel ratio of the engine [Nadira, 2006], while H_2S removal is necessary for eliminating unwanted corrosion. It is for this reason that levels of H_2S less than 1000 ppm are recommended [Wellinger and Lindberg, 2001].

The concentration of H_2S in biogas generated from cattle manure typically ranges between 1,000 and 2,400 ppm, depending on large part on the sulfate content of the local water; for poultry waste the figure is much higher, between 3000 ppm to 8000 ppm [Gofran, 2013]. The H2S and moisture was reduced effectively through iron sponge process for example in Raj poultry farm; this approach is considered here [Raj poultry farm, 2011]. The electric efficiency of the engine can vary from 25-40% depending upon engine design and load factor [IC engine, 2013; Lantz, 2012]. The remainder of this energy, about 45-55% of low grade thermal heat, can be partially recovered using suitable heat exchangers. Biogas has the advantage of high transformation efficiency and low emission rate. Especially, the technology of controlling carbon dioxide emissions from flue gas are applicable to small to medium scale CHP, CCHP and the HP/CHP technology. Considering the high exhaust temperature of small scale units, the afterheat utilization of exhaust is advantageous in increasing the heat output and the overall set efficiency. Based on methane content and biogas engine efficiency, power generation from biogas can be calculated for the proposed integrated biogas plant. Table 4-3 provides a summary of the engine specifications.

Table 4-3: Biogas engine characteristics [Biogas Engine, COGEN 2013]

Biogas engine	Parameters
Capacity of Biogas engine	10 kWe
Engine electric efficiency	32%
Thermal efficiency	43%
NOx emission	250 mg/Nm^3
CO emission	1000 mg/Nm^3

4.4 Technical specification-heat exchanger

An effective way to increase the energy efficiency of the system is to recover waste heat in a combined heat and power (CHP) generation mode [Biogas engine, 2013]. Waste heat is generated in a process by the way of fuel combustion or chemical reaction, and then dumped into the environment even though it could still be reused for some useful and economic purpose. Large quantity of hot flue gases is generated from boilers, furnaces and IC engines etc. If some of this waste heat could be recovered, a considerable amount of primary fuel could be saved. The energy lost in waste gases cannot be fully recovered. However, much of the heat could be recovered and losses be minimized by adopting heat exchangers. A key component in waste heat recovery is the heat exchanger which captures unused heat from flue gases. In this case, efficient heat exchange plays an important role in increasing the overall energy utilization performance. The hot exhaust combustion gases flows on the exterior of the heat exchanger and transfer heat to relatively cold water assumed to be entering the heat exchanger between 25^{o}C-65^{o}C. Pressure drop is minimized on both the combustion gases and water side of the heat exchanger. Corrosion and fouling are common issues when extracting heat at higher temperature from combustion gases exhaust stream, so it is important to select appropriate heat exchanger materials.

Plate heat exchangers are often used on low-viscous applications with moderate demands on pressures and operating temperatures. Gasket material is chosen to tolerate the operating temperature and properties of the processing fluid. Counter flow heat exchanger is simple in design and provides the most thermally effective arrangement for recovery of heat from exhaust flue gases. The technology for heat recovery from flue gas through a boiler or heat exchanger is commercially available [IC engine, 2013; Lantz, 2012; Zupancic and Ros, 2003], for example from Eskilstuna Biogas CHP Plant in Sweden (Jenbacher biogas engine). In the present analysis, we considered B5/Dx36 SWEP plate heat exchanger [SWEP, Sweden, 2013]. The available recovery heat can be used for feed water heating in the MD modules. The waste heat temperature is a key factor determining waste heat recovery feasibility. Waste heat temperatures can vary significantly, with cooling water returns having low temperature about 25^{o}C and exhaust gas temperature having about 550°C. The temperature of waste heat influences the rate of heat transfer between a heat source and heat sink, which significantly influences recovery feasibility. The simplified expression (losses are neglected) for heat transfer rate in heat exchanger can be generalized by the following equation:

$$Q = \dot{m} c_p (T_i - T_o) \tag{4}$$

where Q the heat transfer rate, $\dot{m}$ is mass flow rate of fluid, c_p is specific heat and T_i , T_o are inlet and outlet temperatures (Q is positive on the hot side and negative on the cold side).

Moreover, the heat exchanger design equation (5),

$$Q = UA\Delta T_{lm} \tag{5}$$

can be used to determine the required heat transfer area, A, for a heat exchanger. The heat transfer area can be calculated after values have been determined or estimated for the required heat transfer rate, Q; the overall heat transfer coefficient, U, and the log mean temperature difference for the heat exchanger, ΔT_{lm}, based on the values of several input parameters.

The pinch temperature for heat exchanger is set to 5 K. Thus the MD feed water temperature out of heat exchanger in hot side is around 90°C. In the digester side, the cold water input temperature is set to 25°C. We used SSP G7-calculation software [SWEP, Sweden, 2013] with our designed input parameters for the analysis of plate heat exchanger performance. These values are summarized in Table 4-4.

Table 4-4: Heat exchanger inlet and outlet temperatures

Heat exchanger	Inlet temperature (^{o}C)	Outlet temperature(^{o}C)
Flue gases	550	110
MD hot feed water	65	90
MD cold water	30	50
Digester water	25	45

There are many commercially available water-water heat exchangers that can successfully fulfill such lower temperature heat recovery from cold side of MD and can be utilized digester heating. Additionally, feedwater pumps are required for the digester and MD for hot and cold water supply. The main objective of the feedwater pump is to be able to determine the power required to raise the pressure of a given flow rate of water. The following hypotheses have been used for the calculation of the pump:

- No heat exchange between the pump and the environment.
- Variations of kinetic and potential energy are negligible.
- Internal dissipation is characterised by the hydraulic efficiency.

The power requirement of the pump can be calculated based on the current mass flow rate and the variation of pressure required.

4.5 Technical specification-air-gap membrane distillation (AGMD)

Comprehensive investigations [Pal et al., 2007a; Pal et al., 2007b; Wickramasinghe et al., 2004; Pagana et al., 2008; Hsieh et al., 2008; Xia et al., 2007; Hering and Elimelech, 1996; Greenleof et al., 2006; Brandhuber and Amy, 2001; Fagarassy et al., 2009; Nguyen et al., 2009] have been carried out over the last 40-50 years on removal of arsenic from ground water. Conventional technologies like adsorption, chemical coagulation–precipitation, and ion-exchange have been established as the broad technology options of water purification. Major drawbacks of these conventional processes over membrane processes are the requirements of multiple chemical treatments, pre- or post-treatment of drinking water, skilled operation, different arsenic ions (As(III) and As(V)) removal rate efficiency, high running and capital cost and more importantly, regeneration of medium and handling of arsenic contaminated sludge.

Membrane distillation (MD) could be a promising and novel process that can be adapted for water purification effectively in rural areas of developing countries. It is a thermally driven separation process in which only vapor molecules (water) from hot feed are passed through porous hydrophobic membrane and condensate in cold side, giving contaminated free safe water. Compared to other water purification technologies, MD has relative advantages regarding energy consumption, utilization for waste heat recovery, simple operation and its ability to integrate with low-temperature heat sources inherent in many polygeneration concepts [Al-Obaidani et al., 2008]. It operates at feed temperatures up to 90^oC. Pal and Manna [2010] showed in a small pilot scale experiment that MD could be an ideal technology option as almost 100% arsenic can be removed from contaminated ground water. This study focused on direct contact membrane distillation (DCMD), which in general features high yields but low thermal efficiencies owing to thermal bridging between the two liquid streams (feed and coolant/distillate) located on either side of the membrane. Air Gap Membrane Distillation (AGMD) may be the favored MD technology for small-scale polygeneration owing to higher thermal efficiencies (here the distillate is isolated from the membrane and feed via a thin layer of moist air; coolant flows on the back side of a condensation surface). Kullab and Martin [2011] investigated semi-commercial AGMD demineralization integrated with combined heat and power (CHP). Results showed that all non-volatile components in flue gas condensate, including arsenic, could be completely separated. The present study considers the two-stage cascaded MD module arrangement presented in Kullab and Martin [2011], with the number of cassettes per module scaled down from ten to five. Other parameters are listed in Table 4-5.

Table 4-5: Membrane distillation

Membrane distillation unit	Parameters
Type of MD	AGMD semi-commercial unit
Feed water source	Contaminated shallow tube-well water
Membrane material	PTFE
Number of modules	2
One module comprises	5 cassettes
Membrane area	0.19 m^2/module

Heat transfer in AGMD configurations is very important and assumed as the rate controlling mechanism [El-Bourawi et al., 2006]. To analyze the heat transfer mechanism, a cross section of AGMD cassette (see Figure 4-2) is considered. Heat transfer is carried out in four steps: (1) heat flux from the feed solution to the liquid-vapor interface across the thermally boundary layer in the feed channel (2) heat flux by conduction and latent heat of vaporization across the membrane; (3) heat transfer from the permeate side of the membrane to the condensation layer/film on condensation plate; (4) heat transfer from the condensation film to the cooling liquid across the condensation plate and thermal boundary layer of the cooling liquid [Kullab and Martin, 2011].

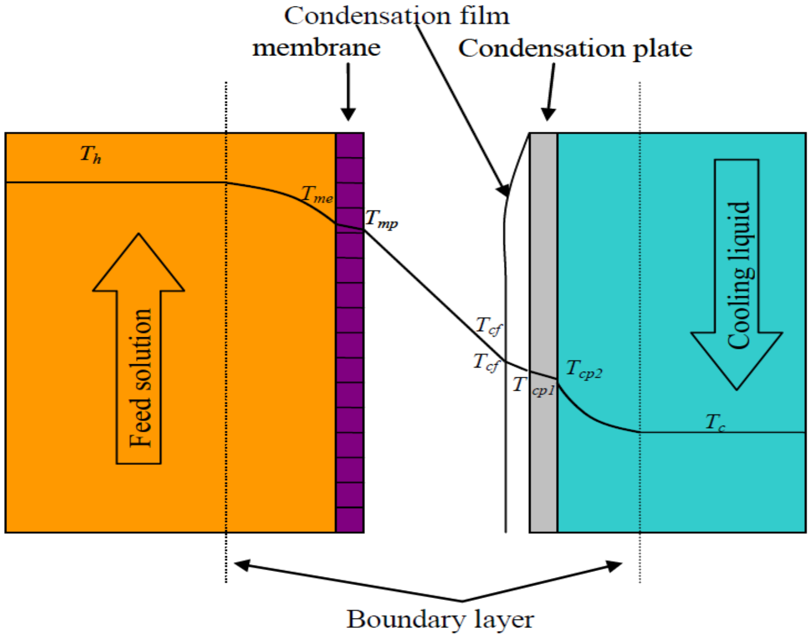

Figure 4-2: Cross-section AGMD [Kullab and Martin, 2011]

Mass transport of a volatile species occurs in two steps [El-Bourawi, et al., 2006], (1) mass transport from the bulk feed solution to the feed membrane surface, (2) mass transport through the membrane pores and (3) mass transport from the membrane surface to permeate bulk liquid. In the case of AGMD configuration, the mass transported through the membrane is affected by diffusion through the pores and free convection in the air gap [Dhahbi et al., 2002].

5. Integrated System Analysis and Results

A techno-economic evaluation was performed to illustrate the viability of the biogas engine, integrated with a MD unit. System integration in engineering entails combining several modules of subsystems into a larger system in which the subsystems work together to achieve better performance (effectiveness or efficiency). Energy process integration encompass techniques based on the thermodynamic and economic analysis of individual components as well as the system as a whole, oriented to design and improve production systems, maximizing the efficiency of consumed resources. According to the definition, the efficiency of a multigeneration system can be expressed as the ratio of useful output(s) to the consumed primary energy at input. The design and analysis of integrated systems requires the consideration of a wide range of factors, all of which must be held in focus during the synthesis process. Nowadays, designing integrated systems based purely on technical criteria is no longer a possibility; economic, environmental and societal concerns must also be addressed. This process is complicated in the case of a biogas integrated plant (or indeed any renewable energy system) by the fact that operation of the plant is strongly dependent on the local meteorological conditions, which can vary significantly throughout the year. In order to quantify the performance of the integrated polygeneration plants it is necessary to define a number of appropriate performance indicators. A mixture of thermodynamic and economic indicators is considered, in order to allow the technical, financial and societal value of the power plants to be evaluated, and thus ensure that the selected designs fit well within a framework of sustainable development. The performance indicators below include thermodynamic and economic performance indicators. The techno-economic feasibility assessment of a particular technology begins with evaluating the technological appropriateness, economic viability and other financial incentives of a technology for it to get successfully disseminated at a given location.

5.1 Mass and energy balance

The mass balance around the plant was calculated wet weight basis. In the wet weight balance water additions from both the process and facilities supplies were included as inputs. The digester operation is unsteady. Waste disposal occurs once a day. The anaerobic bacteria digest the organic wastes during several days (about two weeks). Biogas is produced during this period. The digester operation also involves a water flow supplied to the plant and the digestate being continuously extracted. Methane and carbon dioxide volumes were corrected to STP and it was assumed that the spot values for methane concentration are representative of a 24-h period. CHP (combined heat and power) is a highly efficient approach to produce electricity and heat in a single thermodynamic process [Streckiene et al., 2009] from different sources of fuels such as biogas. The assumed efficiencies for the CHP in our model are 26-32% electric energy conversion and 50% thermal energy conversion [Pöschl et al., 2010; Streckiene et al., 2009]. Therefore, the energy losses are assumed to be around 15-20%. No other losses are included in this analysis. There was no way of to measure directly the heat output associated with the integrated plant or the amount of this heat that used to maintain the temperature of the digestion plant. At the time when the CHP unit is not generating electricity, due to scheduled maintenance, breakdown, or gas quality below the threshold limit, the biogas is burnt in a separate boiler unit to produce hot water. In order to increase the efficiency at which fuel is burnt in the biogas plant, a combined-cycle layout has been considered, in which the exhaust gases from the gas engine is used to raise feedwater temperature in a heat recovery heat exchanger, which is then used to drive a membrane distillation.

The detailed thermodynamic analysis has been done to characterize the performance of the plant, taking into account the effects of part-load operation of all of the equipment. The analyses continuously verify the measurements and calculate performance data. The system is designed to identify equipment degradation as it occurs over time. The simplified performance equations used and describe the impact of the controllable parameters on the overall plant performance. Calculations were based on data from existing plug flow digesters, biogas engines, and available experimental data from a semi-commercial MD unit. Considering mass flows, there are two main inputs (cow manure as a feedstock for digester and contaminated feed water for MD) and four major outputs (biogas, electricity, safe water and fertilizer). Biogas is taken to be continuously supplied from the 150 m^3 plug flow digester operating at constant temperature. Daily biogas production is calculated from the appropriate biogas yield, the daily volume of slurry fed to the digester and the percent of total solids in slurry. The amount of energy produced from biogas is calculated from the volume. To evaluate the energy balance and energy efficiency in biogas systems based on various raw materials, an energy input/output ratio was defined. The energy input/output ratio was calculated as the sum of primary energy input into a biogas system divided by the energy content in the biogas produced. It was assumed that the daily product biogas can be fully utilized for cooking gas and/or electricity generation during the day. It was also assumed that the digesters would operate at their designed maximum capacity for the entire period of operation. Deciding on the load is one of the most important steps in the design of the proposed integrated systems. Performance of this integrated biogas system has been considered for quasi-steady state conditions (constant performance during each hour of operation) under constant ambient temperatures (about 26-28^{o}C). The generator supplies electricity according to community demand, therefore no battery is considered for electricity storage. The number of operating hours presented in the literature varies between 6300 h and 8300 as an up to 8380 h for one engine. Main assumptions of the analysis were constant demands throughout the year and high operation periods (8000 h/year). Deciding on the load is one of the most important steps in the design of proposed integrated system.

5.1.1 Household energy load profile

In rural households, energy is needed to meet basic subsistence needs essential for a minimum level of human comfort. These needs consist of cooking, lighting, space-heating, and the operation of household appliances and devices. Of these, cooking energy needs constitute about 60-80% of the household energy needs in rural areas. The promotion of efficient biogas digesters and improved cookstoves with an efficiency rating of up to four times that of traditional stoves is a common feature in the rural energy programs of several countries in Asia. The Households in the rural area is simple and does not require large quantities of electricity for lighting and electrical appliances due to not being connected with the national grid network. A rural household generally uses electrical energy for lighting, ceiling fan, mobile charging and entertaining [Bala and Siddique, 2009]. This load is based on three energy efficient lamps (compact fluorescent bulb, 15W each), one ceiling fan (40 watt), one television (40 W), radio, mobile chargers and others (25 W) for each family of the rural settings [Bala and Siddique, 2009; World Bank report; Miah et al., 2010]. Timing of electricity used is the same with throughout the year (in practice there is only a little variation during winter and summer due to timing of sunset and sunrise). Average TV operating time is 6 h per day and ceiling fans running 7 to 8 h per day. We assumed that the total electricity demand of households in the village is 27 kWh/day (0.9 kWh/household/day, with an average of 6 to 8 hours lighting, listening to radio and watching TV), cooking gas demand of 0.2 m^3/meal/person (two meals per day) [Bond and Templeton, 2011], and drinking water demand of 3 liters per person per day [Rahman et al., 2013].

5.1.2 Integrated system performance evaluation

The Gas production quantity and total production of biogas are a function of the feedstock's organic content and biodegradability. Table 5-2 presents technical results of the case study, showing biogas and energy yield and characteristics of biogas and biogas production rates throughout the day. Figure 5-1 shows the production and consumption of electricity and heat energy results for the feedstock received by the AD plant. The generation of electricity from biogas takes place via the CHP generator. The generator will supply electric power (38 kWh/day) to local dairy and poultry farms all around the day for lighting, ceiling fan and pumping water. Additional electricity (95 kWh/day) will be supplied to local business stores, and productive activities like motors are used to grind grain, operate power tools, and irrigate farmland. Table 5-1 summarizes the main technical parameters of the system.

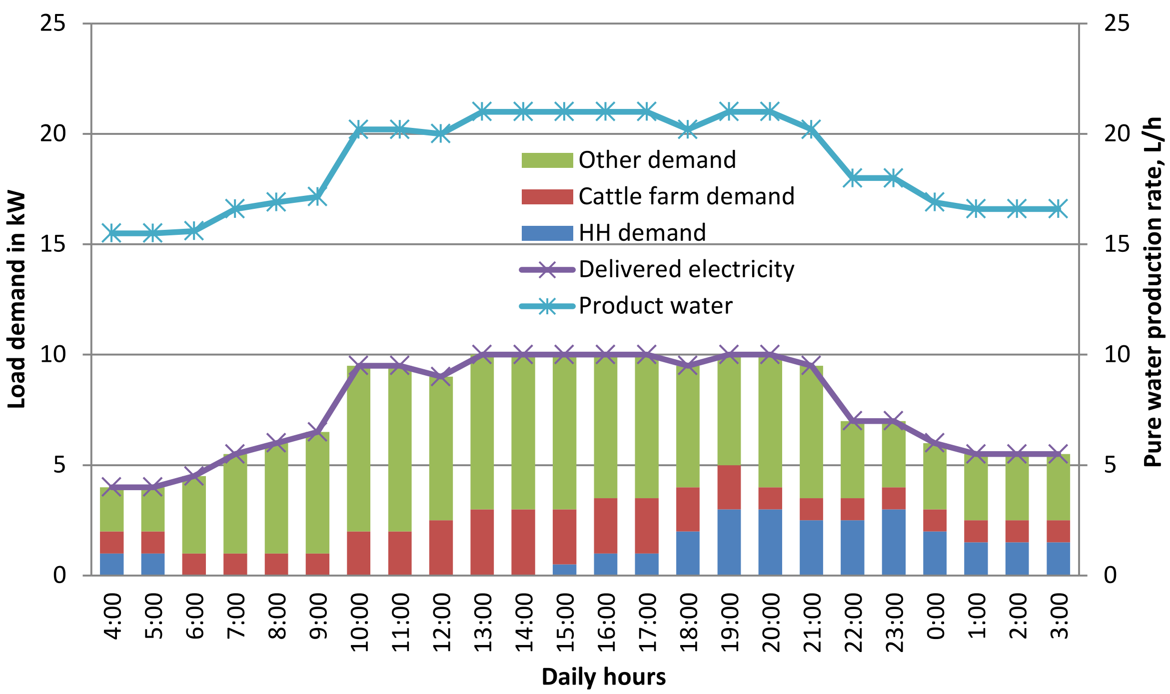

Figure 5-1: Hourly average electricity demand proposed community and electricity supplied by biogas and pure water production of integrated system

The daily load profile graph (Figure 5-1) shows the hourly demand of electricity during the day for different purposes in the village. It also shows that the electricity consumption is high at 13:00 PM till 21:00 PM and interestingly it is possible to supply cooking gas between 6:00 AM to 12:00 PM (for two meals) before peak electricity demand. However, the proposed system would supply biogas for both cooking and electricity generation at the same time through parallel connection and additionally it was assumed that the digester has enough space to store unused product gas for a while during the day.

Table 5-1: Technical parameter considered for the integrated system

Parameters	Unit
Number of households (HH)	30
Number of inhabitants per HH	5
Total household electricity demand in village	27 kWh//day
Cattle and poultry farm (including pump and MD unit) electricity demand	38 kWh/day
Other village productive activities electricity demand	95 kWh/day
Gas for cooking	0.36 Nm^3/person/day
Water for drinking	3 liters/person/day

The gas generator runs in part load operation during the day and the maximum and minimum engine loads are 100% and 40% (10% distribution loss also included in the load demand Figure 5-1) and the engine electric efficiency varies linearly from 32% to 26% respectively. Pure water production rates are directly related to engine load, as shown in Figure 5-1 (right hand axis): hourly production is higher when the engine runs its maximum load (100%, about 10 kW), and lower at 1:00 AM to 9:00 AM when the engine runs at minimum load (40-60%, about 4-6 kW). The estimated and calculated electricity, cooking gas and pure water demand for the total energy load and contribution of biogas to cover this demand are shown in Table 5-2.

Table 5-2: Key performance data of integrated system

Items	Unit
No. of cows	235
Cow dung	10 kg/day/cow
Total amount of cow dung	2350 kg/day
Daily biogas production	133 Nm^3/day
Gas for cooking	53.2 Nm^3/day
Total biogas flow rate to the engine	79.8 Nm^3/day
Safe water production	448 L/day

The results show that the energy output from the biogas systems can be significantly affected by the input data chosen. The variations found in input data are partly explained by differences in assumptions made about the system design. For instance, the digester feedstock is assumed to be collected in the efficient system in rural areas. Input data on the digestion process are based on experiences of operating different biogas plants as well as on theoretical calculations. The pure water production from MD is dependent on biogas engine load, engine electric efficiency and exhaust gases flowrates.

5.1.3 Concluding remarks

This above example demonstrates the important benefit of multiple energy and water purification system integration (viz. biogas engine and membrane distillation) and polygeneration. The polygeneration can potentially generate even better efficiencies than cogeneration. Energy losses due to fluid friction are ignored; the water pump work is ignored because it is significantly small with respect to produced power. An improved system design and more energy efficient processes can reduce the energy input. The input data used for the operation of the biogas plant, for instance, are based on existing biogas plants and technologies used today, and do not necessarily reflect the future developments. Biogas digester is a relatively new technology in terms of electricity generation and it is likely that there is a considerable potential for improvement in the energy performance.

The polygeneration systems in which appropriate process integration has been achieved can increase very significantly the energy and material efficiency of production processes without a further technological breakthrough. For this reason, this system usually represents a lower consumption of energy resources, decreased environmental (fossil fuel) burden and economic savings. In this study, attention has been focused on energy and economic aspects. There is very distinct case study of polygeneration systems have been presented and has achieved a very significant increase of energy efficiency in addition to other resources efficiencies, e.g., pure water. The potential economic benefits of polygeneration systems have also been illustrated in the next section. It can be concluded that appropriate process integration allows a dramatic reduction in local energy resources consumption. It is an under-utilized technique, very likely due to its high complexity in terms of design and operation, particularly when dealing with polygeneration systems. Furthermore, in many cases it requires multidisciplinary approaches as well as multi- disciplinary teams for its development. Nevertheless, process integration presents very promising future applications that will be required to facilitate the switch from our current highly inefficient use of energy resources to a more efficient use and thereby sustainable development.

5.2 Economic analysis

No device is useful unless it is cost-effective. The economic feasibility, however, depends upon the optimization of the trade-off between high useful energy collected under specified design conditions and low material and manufacture cost. Economic feasibility of the dual-purpose plant is highly influenced by the price of fuel and electricity (purchase and selling price). Economic efficiency is crucial for the application of polygeneration systems. Many factors, such as investment and operating costs and the fuel price were obviously taken into account in the assessment. Main assumptions of the analysis were constant demands, high operation periods (8000 h/year) and a distribution of heat between the system components. The economic parameters calculated and discussed in this paper was the levelized cost. Special attention was paid to the two different options for possible coupling between a biogas energy system and a water purification unit (MD), in order to:

- Address other basic aspects of a biogas system such as the initial investment.
- Single out the possible factors to fill the gap between the production cost by biogas energy, electricity and conventional technologies.
- Accurately estimate the production cost of distilled water.

REN21 [2007] has estimated the cost of electricity supply by most common renewable energy technologies in the rural areas. REN21 suggests that several of the renewable energy technologies might be the most economical generation choices for mini-grids or standalone systems if sufficient renewable resources are available. ESMAP's [2007] technical report presents a costs review of arrange of off-grid/mini-grid technologies covering a wider spectrum of capacities from 50W to 100kW. Several studies have also presented site-specific levelized electricity supply costs for off-grid options in developing countries context and cost analyses showed that biogas based electricity is more competitive than other renewable based technology [Mondal and Denich, 2010; Nandi and Ghosh, 2010; Subhes, 2012].

The digester cost remains fairly constant for all scale of generation. Generator cost for locally converted biogas generators remain small, but for imported generator the cost is fairly high. Other costs remain fairly constant all over. Many factors enter into the economics of distillation. Among these are the following: intake water quality, plant capital cost, energy cost, labor and maintenance cost, concentrate disposal cost, and financing interest rate. Energy is the largest segment of water production cost of all desalination systems. Main distillation processes use low-temperature heat for vaporization and electrical energy for water pumping. The levelized cost of producing biogas, electricity and pure water production with the integrated system is discussed here in this section and it is one of the common tools used to evaluate the viability of an energy system. Levelized cost of electricity (LCOE) can be adopted in making such comparison and for determining the least cost pathways [Nguyen, 2007; Thiam, 2010; Rahman et al., 2013]. The levelized cost is the net present value of total lifetime costs of the energy system (considering capital cost, operation maintenance cost, component replacement cost and the fuel cost) divided by the quantity of energy produced over the system lifetime. The levelized cost of energy is also used for comparing the energy generation costs of different options and thus for choosing the appropriate technology. When considering the energy systems in question, the levelized cost of energy (LCOE) depends on feedstock handling cost, capital cost of digester and gas engine, operation and maintenance cost of the digester and gas engine system, and fuel cost. Levelized cost is the discounted average cost per kWh of useful electrical energy produced by the system over the life period of the technology which can be expressed as Equation (5).

LCOE = Total life time cost of the project /Total life time useful energy produced (6)

The parameters associated with the system reliability such as life spans of the components and system, and plant availability are another important input in estimating the LCOE. Similarly, the performance indicators such as system losses, efficiency and load factors, and financial parameters such as system capital cost, installation cost, operation and maintenance cost, discount rate, price escalation rates are also important factors in determining the LCOE of technologies. The residual value of the plant after its life time, and the system degradation factor has not been taken into account for simplification. The life time costs of the project are basically the discounted costs incurred each year and summed over the life time. These costs include capital costs (C_c), operation and maintenance cost (C_{om}); replacement cost (C_r), and fuel cost (C_f). If the amount of useful energy produced over the total life period of the system is (El) then LCOE is represented by Equation (6) as follows:

$$LCOE = \frac{C_c + C_{om} + C_r + C_f}{E_l} \quad (7)$$

The methodology of estimating the levelized cost of various energy technologies discussed in Mainali and Silveira [2013] has been used in the present study. All the cost figures are collected from the local market and are expressed in terms of USD (2013). The amortization of the capital investment has been done with the discount rate of 10% over the technology life span and the general price escalation factor of 5% has been assumed in this study [Jalil, 2013]. The payback period and IRR is also discussed in this section.

5.2.1 Levelized costs of biogas

In the capital cost of constructing a biogas digester, operational cost, replaceable items cost and their life spans and other basic assumptions are listed in Table 5-3. The operation and maintenance (O&M) costs of biogas production represents the cost of various inputs to the biogas system, i.e. cost of water for mixing materials, labor cost and maintenance, supervision, storage and disposal of the slurry, gas distribution and utilization, and the administration required to operate the system [Purohit, 2007; CAEEDAC, 1999]. Maintenance cost of biogas plant is considered as the replacement cost for valves, socket, gas pipes etc. The annual operation cost of the biogas plant is estimated to be 5% of the capital investment cost. The fuel cost includes the cost of electricity for running the water pump and the cost of acquisition of raw materials for the substrate (feedstock handling). Moreover, sensitivity analysis of biogas and electricity production cost is followed in this section and section 5.2.2 respectively.

Table 5-3: Techno-economic parameters of the biogas production unit

Description/Specification	Values
Construction of biogas digester with production capacity of 150 m^3 gas in USD[a]	6875
Pipes and valves for the plant in USD[b]	375
Water pump 1 set in USD[b]	188
Life span of water pump (yr)	5
Heat exchanger 1 set in USD[c]	750
Life span of heat exchanger (yr)	10
Pipe and accessories for gas distribution @ 25 m per HH	1050
Transportation and installation costs	463
Feedstock handling cost in USD/ton[d]	2.5
Life Span of the Unit in years	20
Levelized cost of biogas production USD/kWh	0.015

[a][Talukder, 2010; Gofran, 2009; Zaman, 2007], [b][Talukder, 2010; Mainali, 2012], [c][Kullab and Martin, 2007], [d][Mainali, 2012]

The estimated cost for the construction of a 150 m^3 biogas plant of is around 8650 USD (the cost includes the civil construction cost of the biogas digester, pipes and valves, accessories, heat exchanger and water pump) [Talukder, 2010; Zaman, 2007; Gofran, 2009; Mainali, 2012]. The construction cost of biogas plant has been estimated considering the local market labour and material cost. For the comparison, the cost of similar size digester in Vietnam was found to be 9000 USD (SNV, 2013) [Mathew, 2013]. The total cost of the biogas sub unit system including distribution pipeline cost is USD 9700. The levelized cost of biogas production can vary from 0.015 USD/kWh. The capital costs of digester and gas engine have a significant effect on the overall energy production cost. Effects on levelized costs of biogas production and electricity generation for the variation of feedstock handling cost, capital costs of digester and generator are discussed in this section. The cost for feedstock management/handing differs depending upon how the livestock is raised. If the cattle can be herded to a centralized pasture or barn, then cow dung collection/handling will be comparatively easy; conversely sparse grazing practices will greatly increase handling costs. So depending upon the situation handling cost can vary from 0.1 Taka/kg (i.e.1.25 USD/ton) to 0.5 Taka/kg (i.e.6.25 USD/ton).

A sensitivity analysis has been performed for levelized costs of biogas production with feedstock handling costs from 1.25 USD/ton to 6.25 USD/ton and capital costs of digester (-20% to +50% change of digester capital costs) to demonstrate in what extent the levelized costs of biogas varies with these changes (see Figure 5-2). The levelized cost of biogas production will be 0.011 USD/kWh and 0.028 USD/kWh depending upon variation in the feedstock handling costs. If the capital cost is increased by 50%, levelized costs also increase although only moderately (see Figure 5-2). A fivefold increase in FHC (feedstock handling cost) results in about half as much an increase in levelized costs, demonstrating the importance of proper feedstock management and handling.

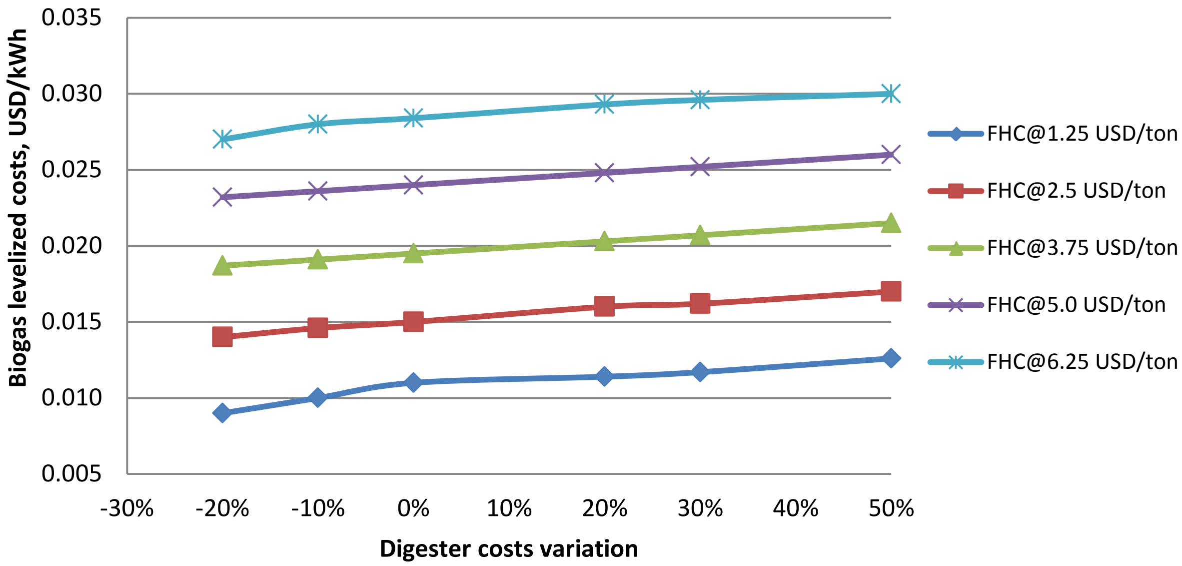

Figure 5-2: Variation in levelized costs of biogas production with the variation in digester costs, and feedstock handling charge (FHC)

5.2.2 Levelized costs of electricity

Another sub-unit within the integrated system is the electricity generation unit. The cost details of additional equipment for such sub unit, i.e. generator, H_2S scrubber for upgrading the gas quality, pipes and valves, control and protection system cost, distribution line cost and other assumptions are included in Table 5-4. The annual operation cost of electricity generation is estimated to be 3% of the capital cost of the generation sub unit. The cost for supplying electricity is estimated to be around USD 9800. The electricity supply cost is very depended on the type of generator chosen. There are various types of generator available in the market, from low cost engine manufactured in China to high cost engine manufactured in Europe. A European-manufactured engine has been selected for this study. The cost of electricity sub system can be reduced by half if the locally available Chinese generators are chosen but the quality of such system cannot be guaranteed.

Table 5-4: Techno-economic parameters of the electricity generation unit

Description/Specification	Values
Construction of biogas generator 3 phase, 10 kWe in USD[a]	6750
Life span of Generator (yr)	10
Pipes and valves for the plant in USD	625
H_2S scrubber and moisture absorber for gas quality upgrade 1 set in USD[b]	150
Life span of H_2S scrubber (yr)	10
Control and Protection systems in USD	700
Load density in HH/km^2[c]	200
Distribution line in km per km^2	4
Distribution lines cost in USD	1300
Transportation and installation of equipment	300
Fuel Cost (Biogas fuel) in USD/kWh (see in Table 5-3)	0.015
Levelized cost of electricity USD/kWh	0.042

[a]Engine cost [Biogas, 2013] [b]scrubber cost [Zaman, 2007; Gofran, 2009] [c]resembles the rural village of Bangladesh

With these techno-economic parameters (Table 5-4), the levelized cost of the electricity production is 0.042 USD/kWh. The electricity generation from the biogas is one of the least cost decentralized options provided if there is sufficient feedstock available [Timilsina et al., 2011]. For comparison, in Bangladesh, the levelized cost of electricity from solar PV is 0.525 USD/kWh and from wind turbine is 0.646 USD/kWh [Nandi, 2009].

The sensitivity analysis was further performed for the levelized costs of electricity (LCOE) with the variation in (i) the biogas production cost (i.e. 0.009 USD/kWh to 0.03 USD/kWh) and (ii) generator capital costs (from -50% to 50%). The analysis shows that the LCOE varies linearly with the variation in the generator capital cost and biogas production cost (see Figure 5-3). With a 50% increase in the generator cost the levelized cost of electricity varies from 0.051 USD/kWh to 0.058 USD/kWh depending upon the biogas production cost of 0.009 USD/kWh to 0.03 USD/kWh respectively. On the other hand, with the decrease in the generator cost by 50%, the levelized cost of electricity varies from 0.0276 USD/kWh to 0.034 USD/kWh depending upon the biogas production cost.

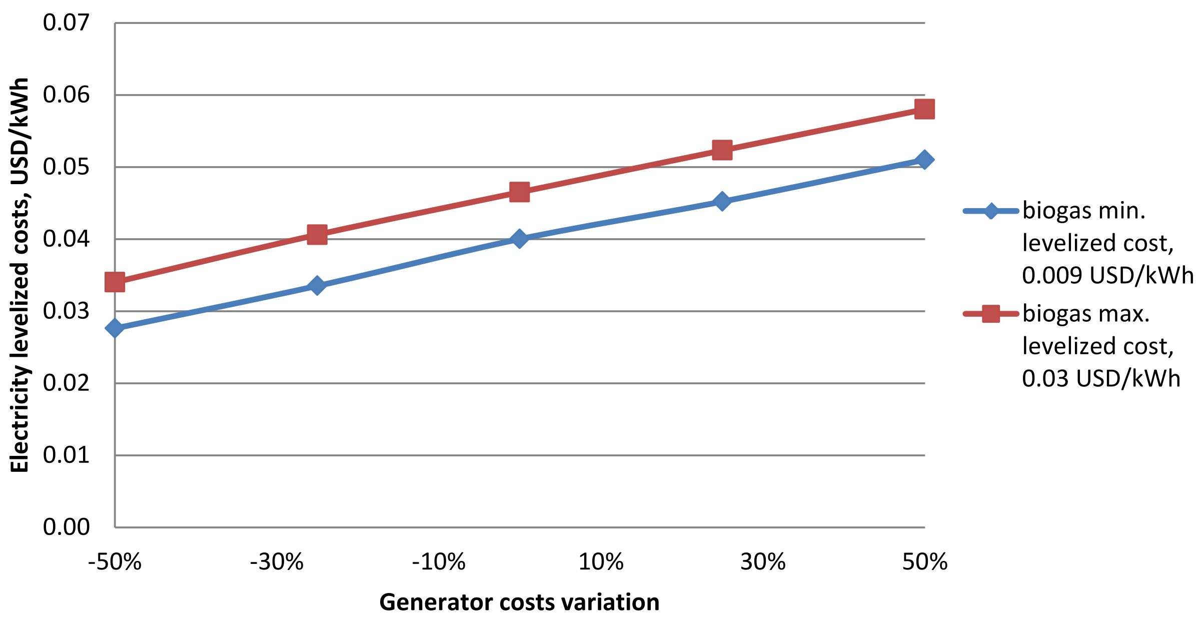

Figure 5-3: Variation in levelized costs of electricity with change in generator costs, and feedstock handling costs

5.2.3 Pure water production costs

The following economic analysis considers the capital and operating costs directly related to the MD unit, including all necessary connections. Capital cost of MD includes process equipment, membrane modules, installation and building, control instrumentation, auxiliary equipment. The cost of MD module, heat exchangers, water pump, piping and valves, pressure gauge and temperature indicators, bottling cost for water distributions and other assumptions have been listed in Table 5-5. The yearly operational cost has been assumed to be 1% of the total capital cost. The cost for water purification unit is estimated to be USD 6500. The cost of energy is zero because of waste heat recovery from flue gas of engine. The water purification cost is much higher (3 to 5 times) when using conventional or renewable energy as sources of heating energy [Shatat et al., 2013]. The module used in the calculations was based on the design by Scarab Development AB.

Table 5-5: Techno-economic parameters of a membrane distillation unit

Description/Specification	Values
MD unit in USD [Nobel, 2013]	3900
Hydrophobic membrane 2 sets in USD (replacement cost)	625
Life span of the hydrophobic membrane (yr)	5
Heat exchanger, 2 sets in USD [Kullab and Martin, 2007]	1125
Life span of heat exchanger (yr)	10
Water Pump, 2 sets [Kullab and Martin, 2007]	375
Life span of the pump (yr)	5
Piping and valve cost [Kullab and Martin, 2007]	565
Pressure and temp indicators [Kullab and Martin, 2007]	315
Bottling cost in USD[a]	265
Water production cost (considering life cycle cost) in USD/liter	0.003

[a]Regarding bottling charge, water is distributed in 20 L jars with a unit cost of USD 4.4. Two jars for each HH have been considered.

5.2.4 Integrated system cost, payback time and internal rate of returns

The integrated system total cost USD 26,050 has been split up into three distinct sub systems corresponding to their outputs. The share of the polygeneration sub unit's costs is represented in Figure 5-4. It has been seen that share of cost of the MD unit is about 50% lower compare to biogas production and electricity generation unit's costs (both units share costs are quite similar).

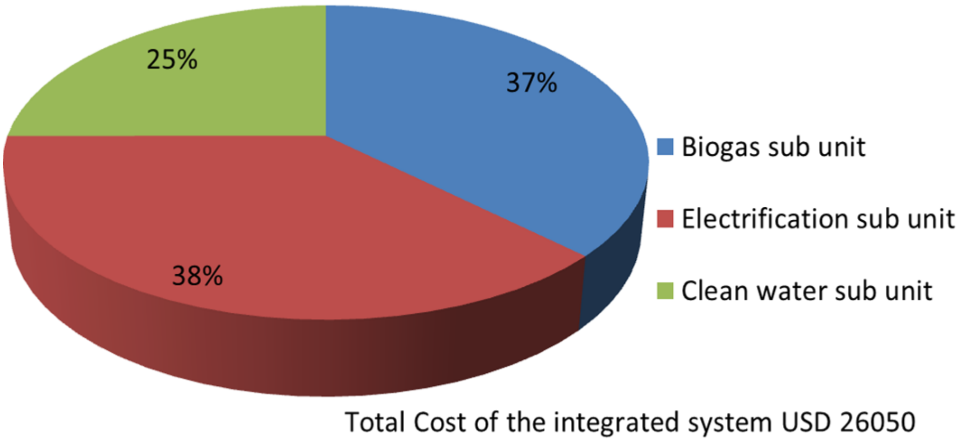

Figure 5-4: Share of cost in the integrated polygeneration system

This assessment was aimed to investigate the feasibilities of integrated system from biogas and supply within the community and farm to sale the energy and water. The payback period was taken as an indicator. Activities that create the revenue from the polygeneration system are presented in Table 5-6. The values used here for revenues are based on the average values that have been collected during the stakeholder consultation and these values are used to estimate the net economic benefit and projected payback period of such polygeneration system.

Table 5-6: Revenue from the biogas based polygeneration system

Description/Specification	Revenue in USD/Year
Sales of electricity to the households (@ 0.073 USD/ kWh)[a]	711
Sales of electricity for different end uses (@ 0.073 USD/ kWh)	2500
Sales of biogas to the households (@ USD 10/HH/month)	3600
Sales of safe drinking water (@ 0.005 USD/liter)	810
Net revenue from slurry as fertilizer (@ 24.4 USD/ ton)[b]	3345

[a]Estimation was based on discussion with local Palli Bidyut Samiti (PBS), Rural Electrification Board (REB) [BREB, 2010] and local stakeholders workshop [Mainali, 2012], [b]Assuming the 40% of the feedstock materials turns into slurry and 40% of total wet sludge will be available on market as fertilizer.

The payback period has been estimated in two different cases to understand the influential parameter in determining the financial attractiveness of the project. Case I where the payback is calculated only considering the revenue from selling electricity, biogas and water, Case II (Revenues from case I and sales from slurry is also taken into account). The analysis shows that payback period in case I is 4 years, and if the slurry could be sold as fertilizer, the payback period is very attractive (2.6 years) (Figure 5-4).

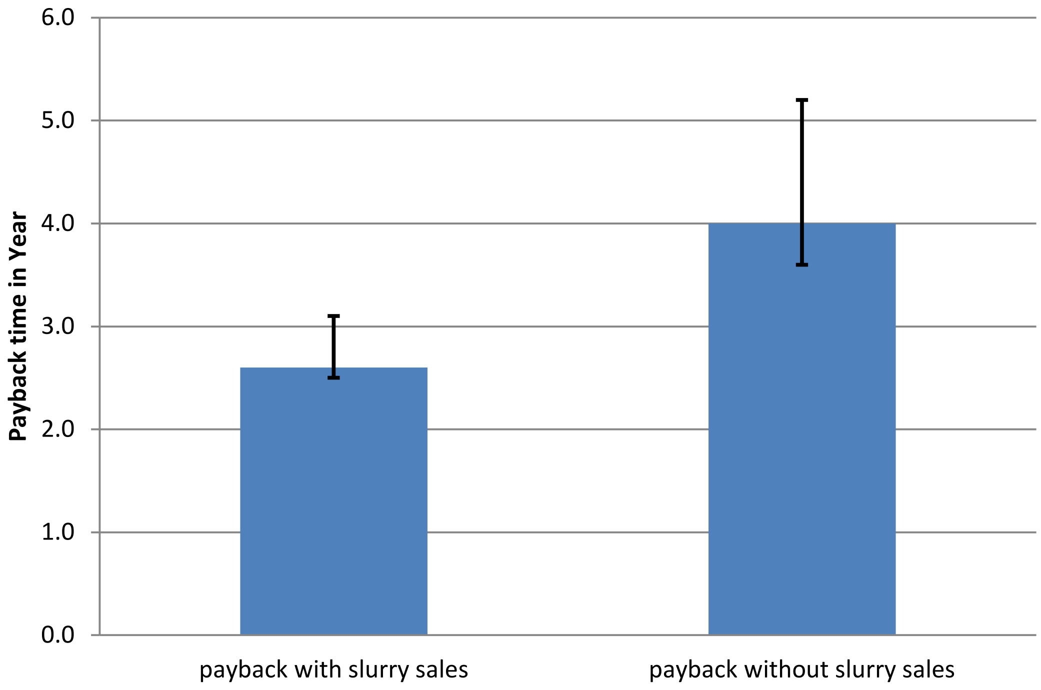

Figure 5-5: Payback periods of polygeneration system

Error bars show the minimum and maximum payback period with lower and higher feedstock handling costs (see previous section). Analysis also revealed that payback time without slurry sales is highly sensitive with the feedstock handling charge. Slurry is a by-product from the biogas digester. However, as seen from the calculation, it is very influential in determining the economic feasibility of the project. Thus, in the integrated polygeneration system, slurry management and development of a market for the slurry is equally important [Talukder, 2010; Zaman, 2007; Mainali, 2012]. The Internal rate of return (IRR) has been calculated for the given situation both with slurry sales and without slurry sales. The analysis shows that IRR for the polygeneration schemes is 13.8% without the slurry sales and with the slurry sales this could reach up to 31.6%. It is clearly seen that the proposed integrated system are economically viable with short payback period (less than 3 years), high NPV and IRR. In addition, the importance of sensitivity analysis with respect to the biogas price and generator price has also been recognized in order to identify the impact of electricity and biogas price variations that may happen in the future.

5.3 Opportunities and barriers

For understanding the existing sectorial realities, strengths and limitations are essential elements in designing any new energy system. Stakeholder consultation was vital in terms of understanding the expert's perception about the sector. This has also been important to identify key opportunities and barriers in defining the polygeneration concept as a sustainable solution. Many partner organizations working in the biogas sector have strong network across the countries and micro credit market has been well established – all favorable towards the dissemination of polygeneration technology. Policy interventions are other tools to push technology in the market. The existing Bangladesh renewable energy policy- (2008) has perceived biogas based electrification as an alternative during the case of load shedding. So, there is need to explore the conditions under which biogas based polygeneration could be the mainstream supply source meeting a rural village's cooking energy needs, electricity and drinking water demands. The existing biogas sector has been mainly promoted the household scale biogas digester and subsidy and credit mechanism are designed accordingly. IDCOL is executing National Domestic Biogas and Manure Programme (NDBMP) with support from government of Bangladesh, Netherlands Development Organization-SNV and German organization Kfw. This is the largest biogas programme in Bangladesh. It provides 9000 BDT (1 USD= 80 BDT) as a subsidy for the plant through partner organizations, which covers about 30% to 40% of the total cost of biogas plant. Besides, IDCOL also gives loans for the commercial biogas plants at the interest rate of 7-9% [NDBMP, 2010]. This credit is funded by a World Bank soft loan. Another organization, German Technical Cooperation (GIZ) adopted a different financial modality for the social biogas plants and commercial biogas plant. For the social biogas plant, subsidy was 20,000 BDT with mandatory owner's equity contribution of minimum 15% of the plant cost and the remaining was a micro-credit at the interest rate of 10% to 14% for maximum two years period, but in case of commercial biogas plants, there was no subsidy [Chakrabarty et al., 2013]. There are some initiatives towards promoting community-based biogas, although there is little experience and no financial support programmes exist. Thus the financing of polygeneration system remains a major challenge. Interestingly, global attention to climate change has favored the use of renewable energy sources and CO_2 emission reductions via e.g. polygeneration and the creation of carbon markets. The displacement of kerosene for lighting, diesel for electricity (running small business, farms and water purification unit) along with decreasing deforestation due to substitution of firewood by biogas for cooking and reduction in the uses of natural gas due to substitution of urea fertilizer by slurry is some of the potential areas in the reduction of greenhouse gases. This has not been further explored within the scope of this paper; however the possibility of carbon credit considering the whole supply chain is an important area that needs further investigation. Although the carbon credit scheme provides additional financing for such project, it faces challenges like a low quantity of certified emission reduction credits (CERs), associated high transactional costs for clean development mechanism (CDM) activities, and the dilemma of additionality [Uddin and Taplin, 2009].

Another important issue is the availability of feedstock. To provide all above mentioned three services, (cooking gas, electricity and safe drinking water); the analysis has shown that there is a need of about eight cattle per household. Discussions with local stakeholders identified this area as a major challenge to meet this requirement unless villages are selected with significant animal husbandry or if the biogas plant is linked to a large dairy farm or poultry farm. If the government enforces a policy for the construction of biogas plant in poultry and dairy farm for their waste management, this could be effective in promoting commercial biogas plants and polygeneration while also effectively solving the waste management problem of the poultry and dairy farms.

From above economic analysis, it can be said that the financial benefit of biogas technology is greatly increased if the slurry byproduct is used effectively on farms. Bioslurry may be considered as a good quality organic fertilizer for agriculture and has a potential market in Bangladesh. Grameen Shakti (GS) has made an agreement with two companies to market bioslurry organic fertilizers from its constructed biogas plants under the brand name Grameen Shakti Jaibo Sar. SNV-IDCOL has also started implementing a national program where use of both biogas for household cooking and bioslurry as organic fertilizer are being promoted [Islam, 2006]. However, the management of feedstock and slurry has been challenging to the users and many of them are reluctant and are not willing to do the dung mixing job every day as they consider this as dirty job but such problem can be avoided by hiring full time operators for the plant.

Use of biogas has contributed to significant benefits in terms of health, socio-economic status, women’s workload, agriculture and environment. The remarkable benefits come from saved time and money. According to IDCOL [NDBMP survey report, 2010] annual survey reports, the 300 households in one year have saved 23,816 workdays through reduced time required for cooking and management of fuel. Though, social and non-pay attitude problems have been identified as barriers in rural areas, which in turn have made private investors reluctant to be active in biogas projects. The major challenge of rural energy business in a poor country is (i) high upfront cost associated with the technology (ii) low incomes and (iii) lack of access to credit [Mainali and Silveira, 2012]. However, as per experts, main concern for the scale up is the business model and financing mechanism which need further exploration.

6. Discussion and Conclusion

The energy and arsenic free pure water crisis and possible alternatives are really big issues in rural Bangladesh. Modern energy and pure water needs should be considered within the overall context of community life and the needs of different rural communities vary widely, and finding appropriate technologies and effective implementation strategies can be very site-specific. An integrated biogas-based polygeneration system has been designed to meet the needs of 30 households in a rural village in Bangladesh. For remote villages which are not connected to a grid, decentralized application of renewable energy sources provide a suitable alternative for electricity access. The use of biogas in households also saves women and children from exposure to indoor pollution, and the time as well as the effort they spend in collecting firewood and cooking with inefficient fuel sources. Thus this technology provides various environment-related advantages and social related advantages, while providing energy solutions to energy deprived rural areas. The most important aspect to highlight here is that with this integration, the amount of waste heat generated in the gas engine are effectively used for water purification, savings the significant primary energy for cleaning the contaminated water in comparison to conventional systems. One important and unique advantage of this process lies in the use of waste heat from flue gases; and can be used to treat contaminated water via membrane distillation. Additional energy for digester heating which would otherwise have to be supplied through additional heating could be supplied from MD cooling side heat recovery. A plug flow system is suitable for tropical countries and operation and maintenance is simple; the system is also economically viable. Another important feature is to use waste heat from the coolant side of the MD unit in order to maintain mesophilic conditions inside the digester and to increase biogas production by about 20%. One of the key challenges towards overcoming the arsenic problem (contaminated water) is the development and implementation of technologies that meet several tough demands: technically sound, robust in operation, cost effective, and environmentally compatible. Air gap membrane distillation (AGMD) has been demonstrated as a viable technology for arsenic removal with realistic feedstocks. Yields are maximized by increasing the temperature difference between feedstock and coolant, yet there is scope to utilize high coolant temperatures to achieve low specific thermal energy consumption and thus enhance heat recovery.

From a technological point of view it could be feasible to co-produce heat and power simultaneously using biogas gas as a feed. However, whether the proposed polygeneration (biogas digester, gas engine and membrane distillation unit) system is very distinctive (new and innovative) and can be adopted and applied in local rural community mostly depends on whether the system is techno-economically profitable. The thermodynamic performance indicators measure the technical performance of the integrated plant. The hybrid thermo-mechanical systems require the simultaneous supply of electricity and heat, with rated water flows depending on the demand of energy and water and capacity of biogas plant and the membrane distillation unit; optimizing a dual-purpose CHP-hybrid distillation plant is a quite complex issue. The main difficulty encountered when sizing and operating CHP plants with MD unit is to cover by a combined process two distinct energy demands for heat and electricity. Coupling CHP with the production of pure water (easily storable) by distillation could simplify the optimization, but requires an in-depth understanding of the productive process. The purpose of supplying electricity and water by a CHP-hybrid distillation plant at the minimum techno-economically feasible capacity induced to adopt a biogas reciprocate engine; in order to feed the MD section at the mild temperature required, heat recovery in series from the exhaust gases were considered, producing hot water at 85-90^{o}C. The operation

of the integrated system was simulated for different values of permeate flow rate (at fixed distillate flow rate); the results are shown in Table 5-2. Two types of energy – low-temperature heat and electricity – are required for most distillation processes. The low-temperature heat represents the main portion of the energy input and the electricity is used to drive the system's pumps. Energy consumption of the MD unit depends mainly on the feed temperature, water flow rate and the recovery rate. The operating pressure is related to the total dissolved solids (TDS) concentration of the feed water; therefore, high-salinity water requires a higher amount of energy due to higher osmotic pressure. Low pressure is needed to membrane distillation for water purification; therefore, different membranes are used and much higher recovery ratios are possible, which makes energy consumption low. The electrical energy consumption ranges from 1.5 to 2.5 kWh/m^3. The number of operating hours and availability of biogas-based polygeneration are two additional parameters of importance regarding the economic performance of the systems. However, when comparing reported operating hours for different biogas plants, it is important to consider that the number of operating hours is affected not only by the performance of the engine or the biogas plant but also by decisions made when the engine was installed. Thus, an engine may deliberately be over dimensioned in order to allow for future expansion or reduce the risk of flaring of excess biogas, which would result in fewer operating, full-load hours compared to a smaller engine. In this study, the annual numbers of full-load hours are set to 8000. However, due to limited data, in this study it is assumed that the gas engine has the same number of operating hours at full load as conventional engines. Finally it can be said that polygeneration systems in which appropriate process integration has been achieved can increase very significantly the energy and material efficiency of production processes without a further technological breakthrough.
Designing an integrated polygeneration plant based purely on technical considerations will lead to designs that, whilst achieving high performance, are likely to be too expensive to be economically viable. At the same time, focusing solely on costs will likely lead to designs that are excessively harmful to the environment and which, despite producing low-cost electricity, may not truly be the best solution for meeting the needs of society. It is therefore necessary to evaluate not only the technical, i.e. thermodynamic, performance of the power system, but also to assign costs to the construction and operation of the plant. The economic analysis was based on the digesters capital cost, which accounts for the major cost of community based biogas plants. The cost for producing biogas from animal waste feedstock has been analyzed in various studies, resulting in different costs depending on scale, substrate, cost of capital, transportation needs, process energy input, etc. The investment cost refers to a basic biogas plant, not including special buildings to handle substrate or personal areas since the biogas plants are located at a farm. When calculating the production cost for a process operated under mesophilic conditions, it is assumed that the hydraulic retention time can be decreased without decreasing methane yields, leading to a higher throughput of manure compared to a process operated under mesophilic conditions. Thus, the production of biogas is increased without increasing the investment. From this study, it can be said that one of the main encouraging issues of the integrated system are the levelized costs of the three major services: cooking gas (0.015 USD/kWh), electricity (0.042 USD/kWh) and safe water (0.003 USD/liter[1]). Additionally, the payback period is between 2.6 to 04 years depending upon how

[1] One USD equivalent to 80 Taka (BDT)

we formulate the conditions. Moreover, the levelized cost per kWh of electricity from the integrated system is about 12 times lower than solar PV and wind turbines. At present, the main barrier for MD is the capital cost because the units are not yet commercially available; however commercialization is on the way. The revenue that can be generated by selling electricity, cooking gas and pure water is strongly dependent on the price at which the energy and water is sold. In a liberalized electricity market electricity and water prices can vary significantly, both over the course of the day and throughout the year due to shifting patterns of supply and demand. Of interest to the designer is the minimum electricity and water sale price which, over the lifetime of the integrated plant, generates enough revenue to pay back the initial loan, cover the operating costs and accumulate reserves to pay for decommissioning once operation has ceased; in other words, it is the commodity sale price which gives a net present value of zero. This minimum energy and water sale price is known as the levelized cost of the product (or LCOE), and is possibly the most important indicator of the economic performance of an integrated plant. Generally speaking, a lower levelized cost of electricity and water means that the plant will be a more profitable investment. The LCOE analysis as per carried out in this study is based on resource availability, existing market costs, prevailing policies and near-term developments. One of the basic limitations of this methodology in evaluating pathways is its static nature. We carried out some sensitivity analysis to reflect the uncertainty associated with the various parameters. However, the long term and much more complex risks and uncertainties associated with market and technological development, policy and regulatory changes need other types of analysis linked to the specific country development strategy. The possibility of using waste energy powered water purifiers could broaden the scope of the application of renewable energy polygeneration system.

Though these kinds of integrated systems are attractive in terms of their socio- economic benefits, there may be constraints on the resource side. The logistics of biogas production, including feedstock and digestate transportation, must be determined at the local level to produce the most environmentally advantageous, economical, and energy efficient system. An average of 8 cows per household is needed to feed the digester which might be challenging for a single family to achieve. However, this challenge can be addressed either by looking for multiple feedstock (i.e. mixing cow dung with other feed stocks such as different livestock, vegetables and agricultural waste, and solar PV etc.) or by considering the big dairy farms in rural areas as potential locations for centralized production. Manure is a relatively cheap feedstock which, however, requires higher investments compared to crops and crop residues where the situation is the reverse, a higher feedstock cost but lower investment cost. The dissemination rate of this capital intensive integrated system would be faster if it could be implemented as an energy and water business run by the rural community. In this study, we have only considered steady state operation of the integrated polygeneration system but we did not evaluate any dynamic performance and ways of optimization of such a system. Model has been used to perform a simplified technical performance and economic analysis of the integrated system. If the integrated system work properly, it will be necessary to find out best control strategy also.

6.1 Future work

Though these kinds of integrated systems are attractive in terms of their socio- economic benefits, there may be constraints on the resource side, i.e. availability of digester feedstock (linked to livestock limitations or waste collection and handling difficulties). An appropriate business model for this kind of project with inclusion of CDM's has not been explored in this work but would warrant further investigation. Consideration of dynamic performance aspects would be a logical continuation of this investigation, allowing for a deeper understanding of the system operation as well as how this approach can be optimized. It is an under-utilized technique, very likely due to its high complexity in terms of design and operation, particularly when dealing with polygeneration systems. Furthermore, in many cases it requires multidisciplinary approaches as well as multi- disciplinary teams for its development. Possible social, institutional and financial barriers in the implementation and dissemination of polygeneration plants are other areas for future study. Finally, the concept needs to be demonstrated via in-field trials.

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Appendixes

Table A1- Inlet and outlet parameters

Feedwater flow rate (L/min)	Cooling water flow (L/min)	Feed inlet temp. ^oC	Feed outlet temp. ^oC	Cooling inlet temp. ^oC	Cooling outlet temp. ^oC
3.8	1.9	80±2	70±2	15±2	36±2
3.8	1.9	80±2	72±2	30±2	47±2
3.8	1.9	80±2	73.5±2	45±2	55±2
3.8	1.9	80±2	76±2	55±2	65±2
3.8	1.9	80±2	78±2	70±2	72.5±2