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# Sustainable development of biogas resources in East Africa using transdisciplinary design models

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SUSTAINABLE DEVELOPMENT OF BIOGAS RESOURCES IN EAST AFRICA USING TRANSDISCIPLINARY DESIGN MODELS

A Thesis

Submitted to the Faculty

of

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by

Christopher M. Limiac

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To my family, for their love, faith, and support.

To my wonderfully delightful friends who have been with me through my academic journey, for their support, understanding, and ability to provide opportune distractions and respite; without which, I'd have been a much less happy student. You know who you are…

To God, for being my guide.

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# ABSTRACT

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Installation of anaerobic digestion systems in urban developing communities has the potential to address multiple problems related to energy and sanitation in a combined systems approach. Anaerobic digesters are used to generate a relatively clean and rich source of energy in the form of biogas to address energy poverty issues. The design resources available for anaerobic digestion projects must be improved to provide greater technical support and project transparency. In order to develop holistic solutions to grand challenges like energy poverty, engineers must be prepared to operate with the complexities of diverse environments. Globalization and the improvement of transdisciplinary project design models have had a profound influence on the international development community. Development engineers must address problems from various frames of reference so as to generate solutions which will be effective and long lasting. The methods of fully integrating systems into a community, while maintaining high quality engineered solutions, are paramount. Implementation of appropriate technologies will be a key enabling technique for effective problem solving and the application of solutions. The purpose of this research is to examine the biogas mechanisms, infrastructure, design tools, and design models that can be developed and implemented to ensure quality, systems based solutions delivered in an effectively holistic and transdisciplinary manner. In order to understand this, the literature exploring the various processes and technologies powering biogas programs as well as those pertaining to transdisciplinary sustainable development models are analyzed. Additionally, this research expands on the development of a design tool and construction manual for biogas digester programs and comments on the current design and implementation models in biogas programs in the context of working with the United Nations on urban biogas resources.

# CHAPTER 1. INTRODUCTION

## 1.1 Problem Statement

The installation of biogas producing systems through methods of anaerobic digestion is a viable mechanism for both generating energy and providing improved sanitation systems. An inclusive systems approach such as processing household and municipal wastes through anaerobic digesters can address multiple problems at once in a holistic manner, benefiting those who lack adequate access to urban service facilities. Furthermore, evidence supports that international development projects have the potential to benefit a large number of people with very real problems. Engineers involved in these kinds of projects would profit from an understanding of transdisciplinary methods of developing design and implementation models. This thesis will explore anaerobic digestion as a means to produce a sustainable energy source and analyze various trends in international development and academia regarding how transdisciplinary research can transition into effective project development and implementation. In practice, international sustainable development endeavors are seen at many levels worldwide; from student project teams at universities, to multination agreements and undertakings. To combat lack of access to adequate sanitation and energy resources, work is done in conjunction with the United Nations Human

Settlement Program (UN-Habitat) to develop urban energy solutions.

The Urban Energy Unit is working on developing a manual which details construction, installation, and maintenance of biogas digesters for small scale community centers. The contents of this manual are meant to be easily replicated and implemented into appropriate systems and locations for the procurement of biogas through processing biological waste materials. United Nations projects are meant to serve as possible demonstrations of solutions to problems that are seen by a multitude of people. The work with UN-Habitat addresses the existing needs regarding:

1. The need for a design model which sizes and designates the appropriate reactor type for a given scale and input source while providing the user with an estimate of the amount of energy that the plant can generate.
2. A manual for designing, construction, operating, and maintaining fixed-dome biogas digesters for the provision of urban energy and the treatment of biological waste.
3. Methods for reducing retention times of the anaerobic digestion process.
4. Recommendations on methods to promote biogas technologies in developing regions beyond basic levels to next stage generations.

## 1.2 Research Topics

Projects such as this one, which address multifaceted problems in developing regions, must be assessed in an appropriately diverse manner so as to help ensure long term success. To help accomplish this, it is necessary to understand the methods through which transdisciplinarity is achieved in the context of international development. Likewise, a cognitive understanding of biogas production through anaerobic digestion must be gained and expressed. A holistic understanding of this process must be conveyed so as to understand the impacts that installation of anaerobic digesters can have in a community. It should be understood that project designs cannot simply be cut and paste jobs from one community to another. To be effective; projects of this scale need to be specifically tailored to the community and situation at hand.

### 1.2.1 Anaerobic Digestion

Anaerobic digestion (AD) is the process through which biological materials are broken down by microorganisms in the absence of oxygen. This phenomenon was first noted by physicists Robert Boyle, known for the Boyle's Law regarding the relationships between gas pressure and volume, and Stephen Hale in observations of flammable gasses which escaped when sediments of some water bodies were disturbed (Fergusen & Mah, 2006). AD, also referred to as the fermentation process, is widely employed at the industrial and domestic level to treat biological waste materials. This process was employed in limited applications following its discovery, ranging from underground digesters in India to street lamp fuel systems in Britain. Academically fueled research into the AD process began in the 1930's, where exploration into its potential application in large scale industrial production as a waste treatment and energy production method began in earnest (Humanik et al., 2007).

The byproduct of AD that is of interest is biogas; a gaseous mixture of approximately 70% methane ($CH_4$), 29% carbon dioxide ($CO_2$), and small amounts of hydrogen sulfide ($H_2S$). Biogas is a readily usable source of energy which can be burned in its current state for use as a cooking fuel, or used as a fuel source for electricity producing gas engines. Furthermore, AD serves as a process to break down or neutralize pathogens and harmful bacteria in waste materials. Nitrogen and phosphorus, valuable minerals which can be used as crop fertilizers, are concentrated in the liquid effluent by product of AD which stems from the digester. At the domestic scale and within the setting of developing regions, a variety of simple anaerobic digesters, or biogas reactors, are used to treat biological waste materials and produce an energy rich fuel source (Gunaseelan, 1997). Small scale digesters are often used to produce biogas which is burned as a cooking fuel or to produce heat or light. Large scale anaerobic digesters are often used for the treatment of municipal waste in industrialized countries like Germany, the United Kingdom, and the United States of America. Biogas resulting from the large plants is often used to fuel electricity producing gas engine generators. Reactors which utilize the AD process are an example of an appropriate technology which addresses multiple problems which are prolific in developing regions.

### 1.2.2 International Sustainable Development Projects

International development projects are often described as being "sustainable development" projects in developing regions; a term which became a buzz phrase within international aid agencies in decades past (Lélé, 1991). Often times, the term

Sustainable Development (SD) is used to describe development projects focused around ecologic sustainability or environmentally sound project solutions. SD has also been interpreted as symbolizing development indicative of sustained growth or change. Development projects are often thought of as truly being successful when there is a notable level of sustainability within the scope. In the international community, development can be defined as a particular process directed by change. Furthermore, definitions of development exemplify both the objectives of a project and the means of achieving these objectives. Sustainability implies a level of long term establishment and endurance of a solution integrated into a project. Figure 1.1 is a semantic map which helps to visualize the connections made between the phrase "Sustainable Development" and the interpretations that people make regarding it (Lélé, 1991). From this, sustainable development is shown to encompass the methods through which objectives are achieved; taking into account the effects the methods have during their development. It can be seen that the goals of sustainable development projects are stable and maintainable growth and progress for a community. Nolan summarizes this as "Successful development, as we shall see, requires people who plan and carry out development to learn a great deal about cultural worlds other than their own, and use what they know intelligently" (Nolan, 2002).

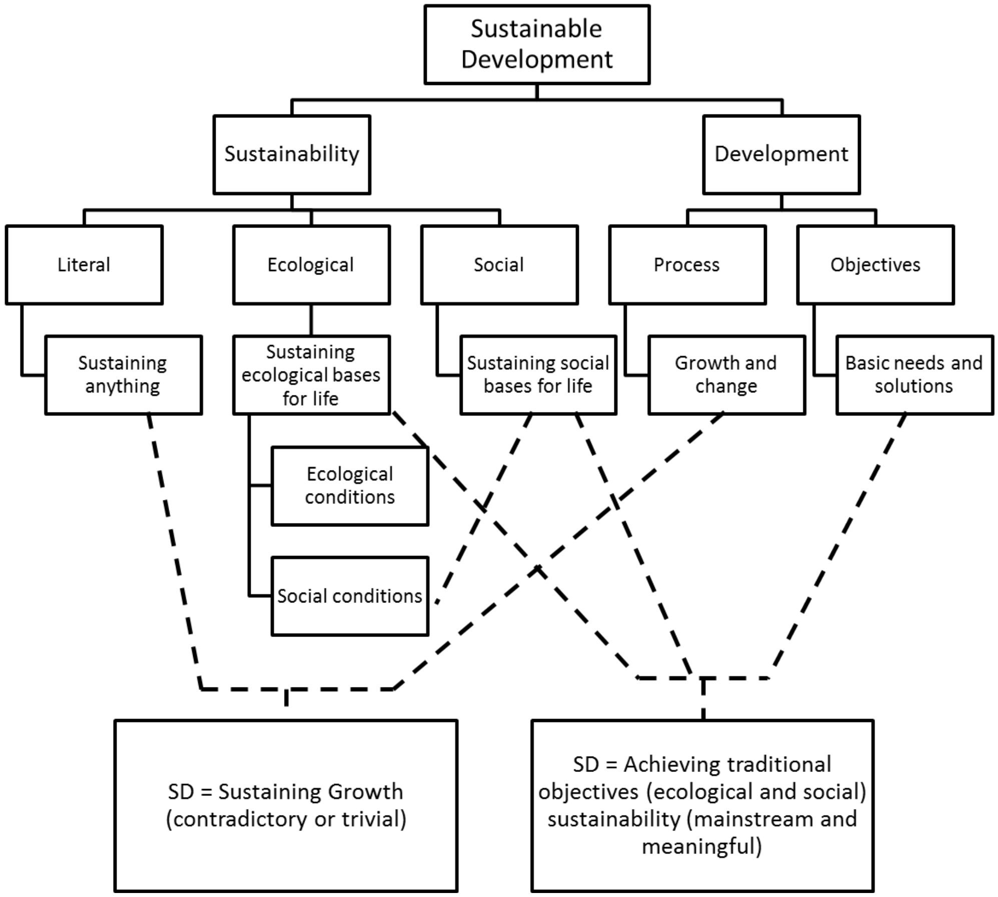



Figure 1.1: The semantics of sustainable development (Adapted from Lélé, 1991).

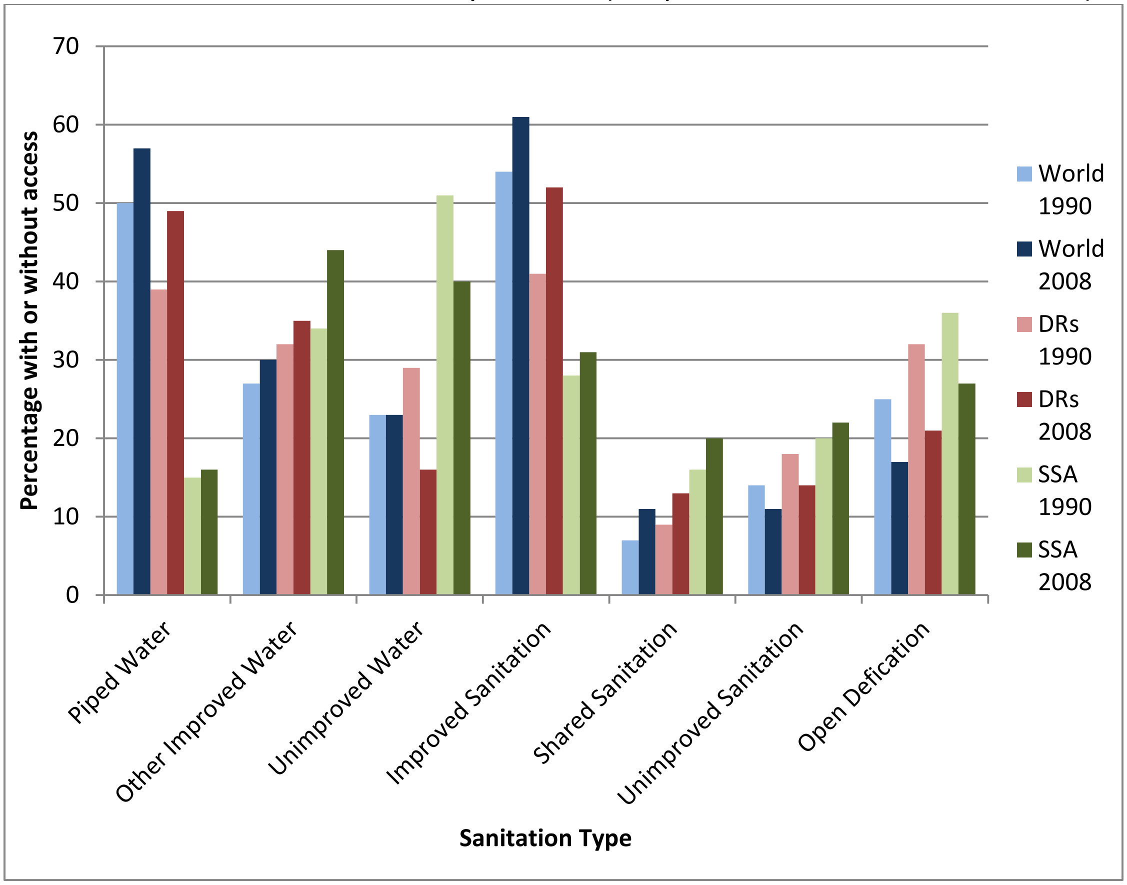
### 1.2.3 Transdisciplinary Research and Design Models

International sustainable development addresses the global challenges surrounding poverty and inequality. Yet, these problems feature complexities that are often overlooked and discounted when tackled by one specific field of specialization (Sillitoe, 2004; Limiac et al., 2013). By examining successful development projects, it is be observed that cooperation across different academic fields is necessary to address problems in a more effective and holistic manner (Sillitoe, 2004; Limiac et al., 2013). A discussion of a transdisciplinary design model must provide a definition of transdisciplinary research within a problem-driven context. Transdisciplinary research (TR) stemmed from the realization that many real world problems cannot be compartmentalized into specific academic disciplines. The recognition that a holistic nexus approach to problem solving is necessary for effective solutions was a large contributor towards the transdisciplinary push. The nexus moves beyond disciplinary-specific problems and solutions: increasing opportunities for cooperation by promoting a model of transdisciplinarity. Transdisciplinary research is often defined as a process of mutual learning and understanding, where combining the perspectives of multiple disciplines allows new ideas and theories to be produced (Pohl, 2005). According to John Robinson, of the University of British Columbia, the highest level and most effective method of fusing ideas is through a model which displays transdisciplinarity; combining new ideas and integrating multiple disciplines (Robinson, 2008). As the “trans” prefix would suggest, the traditional boundaries separating academic and philosophic disciplines with regard to problem analysis and problem solving techniques are transcended. A balance is found between disciplines which advance towards a singular goal. With respect to international development, a transdisciplinary model allows technical solutions to be properly and effectively integrated into existing cultural systems. Transdisciplinary development methods go beyond the limitations of a single disciplinary group to produce a holistic design which can be better integrated into a community or system (Limiac et al., 2013).

## 1.3 Problems in Developing Regions

Many people around the world lack access to clean and adequate water supplies, specifically those residing in developing regions (WHO & UNICEF, 2006). The World Health Organization (WHO) and the United Nations International Children's Emergency Fund (UNICEF) produced a report in 2010 outlining the change in percentage of people in the world with access to sanitation and clean water, an excerpt of this is seen in table 1.1. This table does show global improvements over an 18 year period; about 87% of the world has access to some form of an improved drinking water source (WHO & UNICEF, 2010). In general, the amount of access to piped water and water from other improved sources has increased and unimproved water has decreased, while improved and shared sanitation use has increased and the amount of unimproved sanitation and open defecation have decreased. Disparity is still seen within Developing Regions (DRs); specifically, it can be noted that only 16% of people in Sub-Saharan Africa (SSA) have access to piped water. The sanitation figures are equally disturbing for many regions of the world. In many instances in DRs, water is collected from unclean surface sources or purchased at unaffordable high prices from private vendors (UN-Habitat, 2012).

Table 1.1: Global access to sanitary facilities (Adapted from WHO & UNICEF, 2010).




Access to safe and adequate drinking water, developed sanitation methods, and modern energy are vital to human health, development, and well-being. A substantial number of the world's population, many living in the slums of urban and semi-urban areas, still lack access to these amenities (UN-Habitat, 1991). As a result, millions of lives are lost due to preventable illnesses such as diarrhea and cholera. These diseases often can be traced back to inadequate supply of safe, clean drinking water and a lack of appropriate means of treatment (UN-Habitat & UNEP, 1999; UN-Habitat, 2012).

Energy poverty has an adverse effect on economic development, industrial productivity, commercial accomplishment, and the delivery of educational services.

Furthermore, lack of adequate energy technologies, particularly those designated for electricity production, limits the amount and quality of modern and affordable healthcare provisions for the people who need it most. The preventable diseases previously mentioned, those which tend to incite minimal concern in more developed regions, can run rampant in developing regions without substantial healthcare to address them. Lack of electricity also limits access to modern technology and electronics; cell phones and computers need to be charged and powered by reliable energy sources.

Energy poverty is a globally widespread problem. The 2010 World Energy Outlook for the UN General Assembly on the Millenium Development Goals expects that an estimated 1.4 billion people lack basic access to electricity; 214 million and 1.2 billion of them being from urban and rural areas, respectively. Figure 1.2, below, displays these figures and their global distribution. Furthermore, assuming continued trends, we can estimate that this problem will not improve in the next 20 years. The 2010 World Energy Outlook estimates that 1.2 billion people will still lack access to electricity in 2030 (IEA, 2010). While this is a lower number and a lower percentage of the population, these conditions cannot be accepted when seeing how many people still lack electricity.

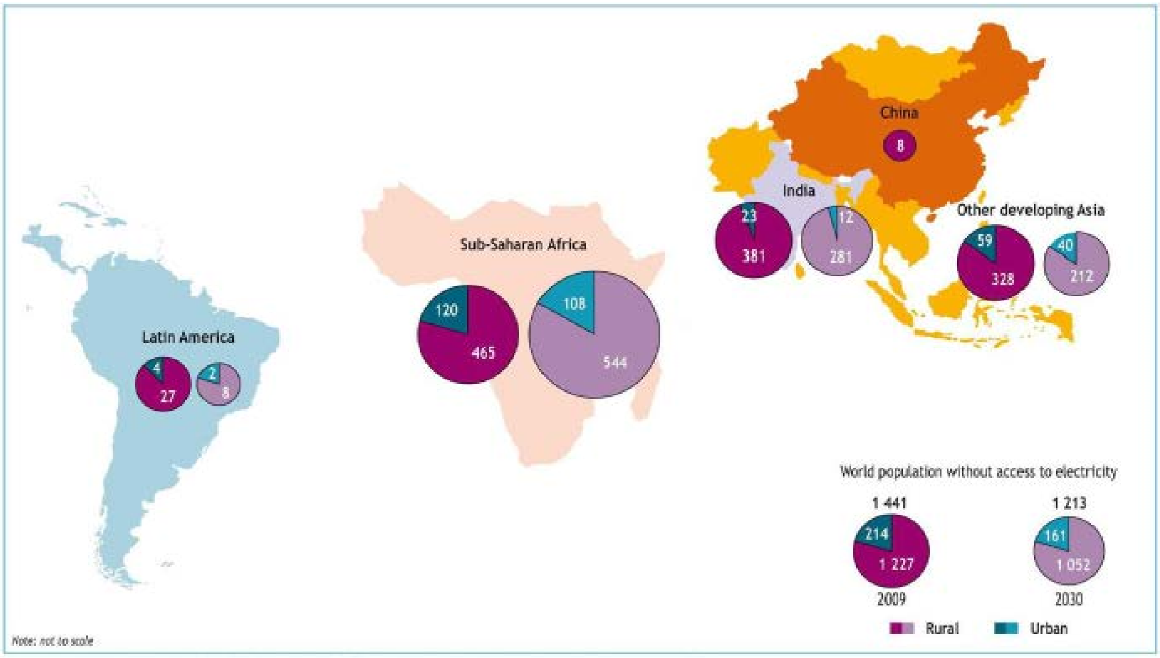



Figure 1.2: Number of people (Millions) without access to electricity in rural and urban areas (IEA, 2010).

Figure 1.2 is a map displaying trends of global energy poverty in relation to millions of people without electricity in the developing world. It can be noted that the main hub of energy poverty are located in Sub-Saharan Africa, where many people in other urban and rural locations lack access to electricity resources. In the other noted developing regions, a larger percentage of people who are without electrical resources live in rural areas. Areas like India and China are home to larger cities and urban areas with notably high population densities and have a smaller proportion of individuals living in rural areas. There are various factors contributing to the lack of adequate provision of basic services, particularly in urban slums and semi-urban areas. One factor is the lack of proper planning and resource allocation for establishing infrastructure. Other factors include; low-income levels within the concerned communities, poor institutional and legal frameworks, insufficient information on best practices, and scarcity of political will to offer affordable basic services (UNDP, 2007; UN & WHO, 2009). While little can be done to improve political institutions on the local level, much can be done in improving facilities for resource allocation and provision at this level.

Figure 1.3 relates the number of people without access to electricity to people without access to clean cooking facilities. While this term can be subjective, a clean cooking facility typically refers to an area with an atmosphere free of heavy smoke and with access to clean and safe water (IEA, 2011). Many of these areas rely on biomass and biomass products like firewood, charcoal, agricultural residue, and dried dung. Burning these materials indoors generates smoke which is not conducive to a clean cooking area. Likewise, without clean and adequate water sources, cooking and general sanitation also suffers. Preparation areas cannot be properly cleaned with contaminated water and food shouldn't be cooked with unsafe water (UN-Habitat & UNEP, 1999; UN-Habitat, 2012).

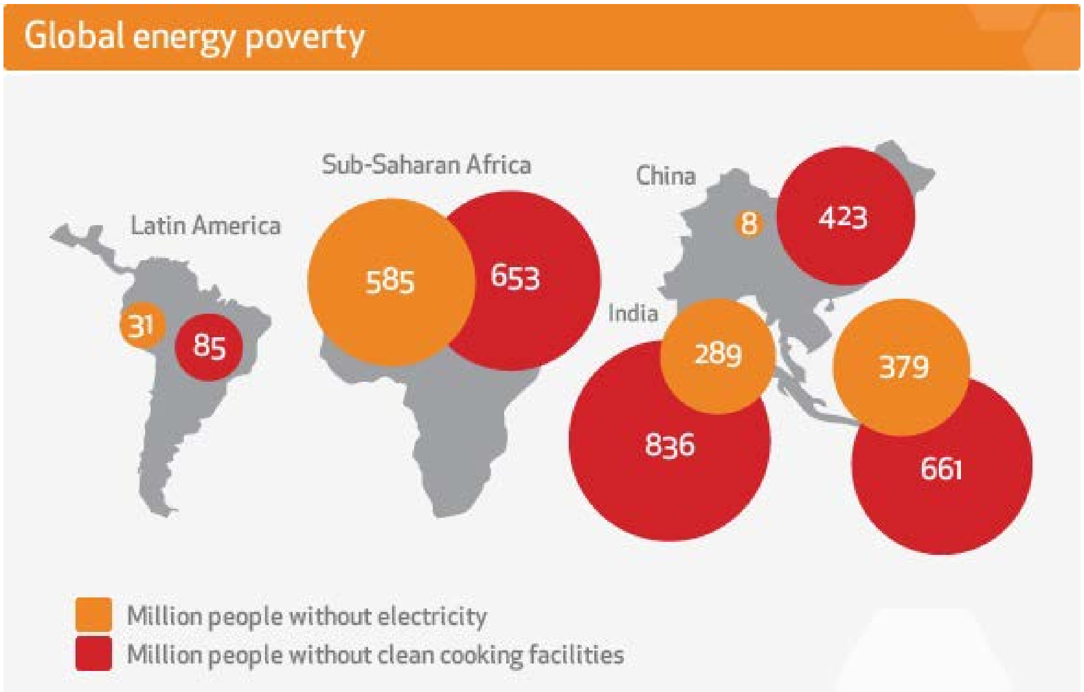



Figure 1.3: Access to modern energy sources by continent (IEA, 2011).

Rapid urbanization is creating a growing environmental strain in African urban areas which are hubs for growth in population, residences, and commercial and industrial activities. African cities like Nairobi, Cairo, Lagos, Dar-es-salaam, and Kampala are consuming huge amounts of energy and generating waste in a manner which is quickly depleting resources which are typically non-renewable. This is having detrimental effects on human health and economic development at all levels (UN-Habitat & UNEP, 1999). Critical problems involve a lack of urban basic services, particularly in the form of urban energy. In reference to the development of sustainable human settlements, Section 1 of Chapter 7 in Habitat Agenda 21 outlines some of the environmental interventions that are required to promote sustainable development of settlements. A majority of the African energy investments are directed at the urban population where not all segments are equally represented or receive benefits of the investments. The Kibera slum is one example of a location in Nairobi, Kenya where estimates of 800,000 to 1,200,000 people are living without or with limited access to modern energy resources. Energy prices are increasing due to the growing liberalization of the electricity sectors. These increases have a dramatic effect on the urban and rural poor in developing regions where modern energy resources are being made even more inaccessible for the poor (UN-Habitat & UNEP, 1999). It is important to address energy related issues as they relate to environmental impact, creation of stable jobs, supplementation of income, and improvement of energy services. It is suggested that energy from urban waste would result in a mitigation of negative environmental impacts while stimulating economic stabilization (UN-Habitat & UNEP, 1999). Anaerobic digesters can address the problems related to urban developing regions by acting as a tool for producing biogas energy and mitigating sanitation issues. Anaerobic digesters and tools related to their design will serve as a focal point for alleviating energy poverty in this thesis.

### 1.4 Anaerobic Digesters in Urban Developing Communities

Developing communities would greatly benefit from the implementation of anaerobic digesters. This is a valuable process when used in gas producing systems which has the advantage of addressing several problems when integrated into a community's waste management system. A practical example of a waste to energy process, AD biogas reactors have the advantage of being a sustainable method for producing cooking fuel, treating biological waste materials, generating nutrient-rich fertilizers, lessening the amount of energy demands from non-renewable and costly sources, and improving living conditions on various levels. When projects such as this are responsibly undertaken with the cooperation and involvement of the receiving community, positive results and ease of implement adoption and transfer are more readily achieved.

## 1.5 Research Objectives

The objectives of this research are:

1. Perform a critical Literature Review of anaerobic digestion technology in the context of developing regions and transdisciplinary research methods with respect to international development.
2. To design a worksheet tool which can be used to assess the energy potentials of biogas systems of various scales based on a continuous process.
3. To generate a construction and operation Manual for fixed-dome biogas digesters for use by the UN
4. To report Methods for advancing biogas technology and transdisciplinarity in project models in developing regions and on best-fit applications of improved biogas resources based on field observations.

## 1.6 Scope of Work

First, Chapter 2, sections 2.1-2.2 will include an intensive literature review exploring energy initiatives with their relation to a nexus discussion of engineering global grand challenges. It will focus on UN mandates to combating global poverty in the context of energy resource access and development. Chapter 2, sections 2.3-2.4 will discuss engineering development in the context of transdisciplinarity and sustainability. An in-depth analysis of transdisciplinary research as it relates to development programs between engineering disciplines and humanities will be performed. These sections will give case studies of academic and international programs actively engaging in collaborative development. It is important to engage with communities and assess problems from a multitude of perspectives to ensure a holistic and inclusive solution to a problem. Transdisciplinarity will be discussed in a context of producing quantifiable and real results and solutions to existing problems related to energy poverty.

In chapter 2, section 2.6, a literature review of the microbiology of anaerobic digestion will be performed. Furthermore, literature about different anaerobic digester designs, configurations, and technologies in the context of developing regions will be assessed. Important design parameters to consider include simplicity of the design, ease of operation and maintenance, ease of construction and availability of locally sourced resources, properties of available feedstocks, input requirements, and potential energy productivity. Benefits of this technology as well as methods to consider for improvement of effectiveness in operation will be explored.

Chapter 3 includes the Excel Spreadsheet Design Tool for sizing and estimating the biogas productivity of small scale reactors. Model inputs, internal calculations, and outputs will be reviewed. This spreadsheet would allow potential users to quickly estimate the potential productivity and give a rough reactor volume estimate when given a set of substrate inputs. The development of the construction manual is described in chapter 3.2 and outlines the processes involved in creating the manual and going about construction and operation. Section 3.3 is in conjunction with work done with the Urban Energy Unit on appropriate technology and applications as it relates to the use of biogas resources.

Chapter 4, section 4.2 evaluates considerations of increasing system efficiency in the context of sustainable development. Methods for improving operational efficiency, while limiting both user input and system complexities, should be considered to help advance biogas resources in developing regions beyond simple technologies. Chapter 4, section 4.3 will provide a commentary on the time spent by the author working as an intern over a period of three months with the United Nations in Nairobi, Kenya. Guidelines for the future recommendations for improvement of international aid projects and for the produced document and design model are important to explore. Guidelines should include methods of enacting and designing biogas projects in a more responsible and consistently sustainable manner.

# CHAPTER 2. LITERATURE REVIEW

## 2.1 Energy Initiatives: A Global Call to Action

Problems related to energy have been recognized for quite some time now, ranging from developing new sources and technologies to regulating amounts produced and used and methods for generating it. There have been a multitude of initiatives set in place related to energy. The United Nations Millennium Development Goals (MDGs) are eight goals which the General Assembly set in place in 2000 and consist of the following:

1. To eradicate extreme poverty and hunger
2. To achieve universal primary education
3. To promote gender equality and empowering women
4. To reduce child mortality rates
5. To improve maternal health
6. To combat HIV/AIDS, malaria, and other diseases
7. To ensure environmental sustainability
8. To develop a global partnership for development (United Nations, 2010).

While the goals are not specifically related to energy, and there are no target values or indicators of progress, energy can contribute to the achievement of many of the goals. The International Energy Agency (IEA) summarized how energy is involved in each of the

MDGs. Table 2.1 expands on some of the explanations set forth by the IEA. Furthermore, the UN Advisory Group on Energy and Climate Change has called for the addition of a goal including universal access to modern energy services (IEA, 2010). From this, it can be seen that a "global call to action" has been made in regards to improving energy resources and access.

Table 2.1: Impacts of modern energy on the MGDs (IEA, 2010).

| | |
|---|---|
| **1: Eradicate Extreme poverty and hunger** | Modern energy access enables economic development by providing efficient power sources. Energy allows for clean water to be pumped for drinking and methods for sanitation. |
| **2: Achieve universal primary education** | Children will be allowed more time for education if they spend less time collecting water and firewood. Electricity facilitates modern education tools like computers and communication tools. |
| **3: Promote gender equality and empower women** | Improving electricity access opens new opportunities for women by reducing the need to collect firewood and the like. Street-lighting can improve the safety of women at night and allows access to night schools. |
| **4, 5, and 6: Reduce child mortality; Improve maternal health; and combat HIV/AIDS, malaria, and other diseases** | Common cooking fuels produce harmful indoor conditions which electricity can improve for women and children. Improved electricity access expands access to modern healthcare services. |
| **7: Ensure environmental sustainability** | Energy production is a large contributor to environmental quality. Cleaner energy sources will have a large, positive effect on the environment. |
| **8: Develop a global partnership for development** | Electricity powers modern communication and information tools necessary for sharing technology application. |

Africa, in particular, is facing a serious energy crisis which is not due to a lack of sustainable energy resources, but rather a poor state of infrastructural support and implementation of appropriate technology. Large swaths of native forest lands are being cut to provide firewood for heating and cooking while soils are degrading from burning of crop residue in place of system reintegration. The world is focused on globalization, with aggressive drives towards economic development and trade liberalization (Bugaje, 2005). African energy needs must be addressed, lest the continent be further left behind in the name of global advancement. Energy development will usher a move in a direction of improving poverty rates, the poor state health and education systems, and environmental degradation.

The UN reports that roughly half of the MDGs have been reached or are on track to be completed by the time set in place, particularly in sub-Saharan Africa, Southern and Eastern Asia, and Oceania (United Nations, 2013). On the whole, progress looks promising when one considers the ambitious nature of such endeavors. However, this case can show how expectations and actual results differ after time. It is good to set goals for development, but very important to take into account the difficulties which will be involved. Often times in development work, any progress towards the goal is considered to be positive even if it doesn’t happen in the ideal timeline.

### 2.1.1 Sustainable Energy

Energy tends to be seen as a pivot point of economic and social development throughout the world. Advanced energy production improves the abilities a nation has to generate economic prosperity. However, the methods by which energy is produced and utilized can have a hugely detrimental effect on multiple scales regarding an environmental and sustainability perspective. Inefficient energy production and utilization methods contribute to a lack of system sustainability (ICSU, 2007). The definition of the term “sustainable energy” can be debated, but the breadth of this paper will assess it in the context of development. The International Council for Science adopts the agreement made by the $9^{th}$ session of the UN Commission on Sustainable Development and expresses sustainable energy as “energy for sustainable development”. It is further defined as the following:

> “Sustainable energy is defined as energy providing affordable, accessible, and reliable energy services that meet economic, social, and environmental needs within the overall development context of the society for which the services are intended, while recognizing equitable distribution in meeting those needs” (ICSU, 2007).

Based on this definition, it can be seen that the term sustainable energy refers to more than just abatement of environmental degradation. Economic viability, social concerns, reliability, and distribution equality should also be taken into account when seeking an energy source and production method with regards to sustainability.

Many initiatives have been made and goals outlined to try and decrease the amount of non-renewable energy resources perceived as environmentally unsound. In 1997, The Kyoto Protocol was adopted by members in the United Nations Framework Convention on Climate Change (UNFCCC), and went into effect in 2005. This was essentially an agreement between some developed countries to reduce greenhouse gas emissions (Jefferson, 2006). Several countries such as Canada, Japan, Russia, and the United States have discontinued their involvement in the commitment, citing damage caused to their respective economies and industrial capabilities. Included in this protocol are international emissions trading allowances, which raises questions as to whether or not this protocol is really effective. It has been suggested that cap-and-trade programs simply redistribute the "blame" and do not really alleviate the amount of greenhouse gasses emitted. Under the protocol, developing countries are "encouraged" to invest in renewables and decrease fossil fuel reliance, but are not legally bound to in the same manner as developed nations. On the whole, little has been achieved in curbing greenhouse gas emissions under the protocol (Jefferson, 2006). The UN Secretary-General's Advisory Group on Energy and Climate Change (AGECC) has made the following recommendations to achieve the goals of reducing global energy intensity and ensuring universal energy access:

1. A global campaign should be launched in support of "Energy for Sustainable Development."
2. All countries should prioritize the goals through the adoption of appropriate national strategies.
3. Finance, including innovative financial mechanisms and climate finance, should be made available by the international community.
4. Private-sector participation in achieving the goals should be emphasized and encouraged.
5. The United Nations system should make "Energy for Sustainable Development" a major institutional priority (UN-AGECC, 2010).

Realistic steps should be taken to increase the amount of renewable and sustainable energy sources employed. The goals previously listed are good ideas and references for accelerating the transition to sustainable energy systems. While many of the AGECC's recommendations use phrases like "all countries" and "global campaign" it is important to step back and analyze potentials for transitions on a country to country and situational basis. A plan that is economically sound and responsible for one country may not be for another. Broad range goals make for compelling and idealistic statements and rhetoric, but they must be taken in the right context.

Sustainability of energy development is more than just simply reducing greenhouse gas emissions. Summarizing the 1987 Brundtland Commission's Report of sustainable energy development, Jefferson seeks to express the concept in broader terms relative to realistic measures.  Sustainable energy development implies a growth in energy supplies so as to reasonably meet human needs, especially in developing regions where population and energy use are rapidly increasing. Sustainability means conservation by means of efficiency of technology use and design while employing effective use of available and appropriate technology. Furthermore, public health and safety as well as mitigation of pollution on applicable levels need to be considered (Jefferson, 2006). All of the previous considerations need to be made when discussing sustainable energy development; not just the environmental implications and not just the economic impacts. A top-down approach to transitioning to sustainable energy systems is often coupled with setting unrealistic target numbers and a lack of consistency of policies. These measures may appear appealing in their conception, but the often lack a fundamental and realistic understanding and assessment of feasibility. Jefferson asks the question as to why a few mature renewable energy technologies like wind and solar power are pushed and subsidized by governments when their costs are insufficiently regarded. Can technologies like this be considered sustainable when their costs are so heavily subsidized? Why are established and mature technologies still subsidized while less mature technologies with huge potentials for meeting global energy needs are not supported (Jefferson, 2006)? Policy makers need to remember economic viability of technologies and need to appropriate funds to newer technologies that show promise. Lessons on sustainable energy development impart a need in involving people at all levels with sound commercial and technical applications (Jefferson, 2006).

### 2.1.2 Waste to Energy Initiatives

Waste to energy technologies consist of the conversion of the calorimetric energy contained in waste materials to heat or electricity through burning and other methods. The methods by which this is achieved can include direct incineration, other thermal technologies, and non-thermal technologies. This study will focus on anaerobic digestion, a non-thermal energy production technology. This technology produces biogas which, through burning, is a form of energy achieved through direct incineration. Biogas, a methane rich gas, acts similarly to natural gas and can be burned in simple gas burners or lanterns and used as a fuel for electric generators. The non-thermal AD process produces a fuel which is directly incinerated to produce heat and light.

The proper management of urban waste, particularly municipal solid wastes (MSW), is a problem that is rapidly growing in sections of Africa. Urbanization is spreading faster than what the current practices and infrastructures are able to handle. Illegal dumpsites, irregular and inefficient collection configurations, and general buildup of refuse are all evidence of the ineffective waste management practices that are currently seen. It is estimated by the World Resources Institute and USAID that up to 30% of the budget in urban centers is allotted to refuse collection and disposal; a huge number in such an ineffective system. Furthermore, it is estimated that only 50-70% of the MSW is collected, most of it being disposed of in unsafe manners (UN-Habitat & UNEP, 1999). This is having a hugely detrimental effect on the abilities that the municipalities have in safely and effectively collecting and disposing both solid and liquid waste materials. Couple the problems of growing waste woes with the issues regarding a need for energy, and it can be seen why the waste to energy initiative is growing more attractive as a means to both treat waste and produce energy (UN-Habitat & UNEP, 1999).

"Ecological Sanitation" or "EcoSan" has been explored as a method that is a sustainable, closed-loop system for managing waste materials which helps close the gaps between sanitation, energy production, and agriculture. The EcoSan approach represents a holistic approach towards economically and ecologically sound treatment of waste water and MSW (Langergraber et al., 2004). Waste material can be treated in anaerobic digesters which produce an energy rich biogas while rendering the waste to a point where it is of use in agricultural fields. According to a study by Werner, EcoSan, as an approach, is meant to recognize waste as a resource and does the following:

1. Reduces the health risks related to sanitation, contaminated water, and waste.

2. Prevents the pollution of surface and groundwater.
3. Prevents the degradation of soil fertility.
4. Optimizes the management of nutrients and water resources (Langergraber et al., 2004).

### 2.2 Nexus Approach to Solving Water-Energy-Food Security Issues

The National Academy of Engineering (NAE) recognizes water, energy, food, and their related sectors as being three of the grand challenges in engineering (Kaplan-Leiserson, 2011). A nexus approach to analyzing water-energy-food seeks to recognize the interdependence that the factors have on one another; addressing one intersection of the nexus will affect the other in some manner (Hoff, 2011; Mohtar & Daher, 2012). The connections between water, energy, and food production are numerous and significant; the interactions that these resources have on multiple scales is not something that should be discounted when working with one specific facet. For example, water is used extensively when processing fossil fuels; from extraction and refining to residue disposal. Fresh water supplies are also used in growing feedstock for biofuels and it is heavily relied on for cooling in electricity producing power plants (Hoff, 2011). Water is a commodity whose use is demanded by both energy production and food production where a balance needs to be found to ensure efficient and effective practices. For example, commercial biofuel production is a huge consumer of water, using over 1000 gal/MMBtu, while we can see that food production agriculture is heavily reliant upon global fresh water supplies and accounts for 70-80% of fresh water use, often due to poor management practices. Agriculture and food production contributes to land degradation through changes in runoff and disruption of groundwater properties and levels; it also contributes to poorer water quality measures, often due to pesticide and fertilizer application (Hoff, 2011; Mohtar & Daher, 2012). Crops require large energy inputs when farming is mechanized and when food is processed. Figure 2.1 expresses some of the connections between these resources in a visual format (Mohtar & Daher, 2012).

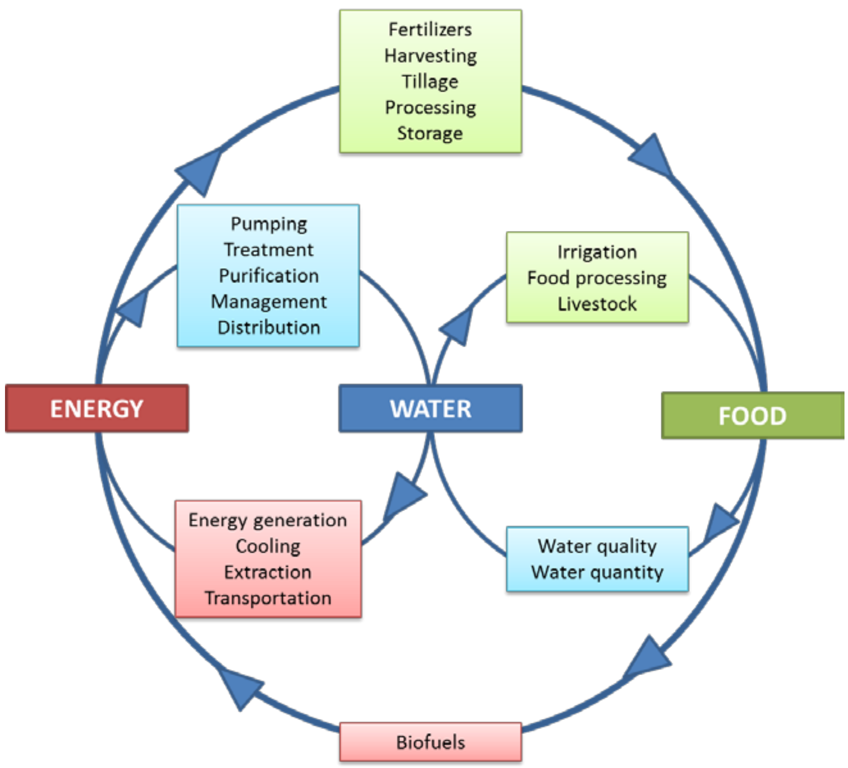



Figure 2.1: Connections in the Water-Energy-Food nexus (Adapted from Mohtar & Daher,2012).

In the context of sustainable energy development, this nexus must be considered. In this study's specific example of using anaerobic digestion to produce energy, its effects on water and food can be seen. Anaerobic digesters serve as a method to effectively treat waste water to a level where it is acceptable to be reintroduced into natural systems. Conversely, the optimal operation of anaerobic digesters requires a large amount of water; water availability must be considered when implementing these designs. One of the byproducts of the AD process is slurry which is rich in useful nutrients that can be directly applied to agricultural fields for watering and fertilization or dried out and used as a solid fertilizer (GTZ/GATE, 1998; Rowse, 2011). Food production practices can greatly benefit from energy production by AD.

## 2.3 Anaerobic Digestion

When biological materials such as municipal solid waste (MSW) materials are kept in an environment which is void of oxygen (anaerobic), specialized bacteria will grow which use the materials as a source for fermentative metabolic processes. These anaerobic bacteria digest the biological waste materials, resulting in a mixture of methane ($CH_4$) and carbon dioxide ($CO_2$) commonly referred to as biogas (Haandel & Lubbe, 2007). Biogas digestion typically takes place in locations like sewage plants, landfill gas sites, and specialty biogas plants. This process is also used in rural and urban developing regions to process biological waste materials and generate a clean, high grade fuel gas. Anaerobic digestion requires conditions which are void of oxygen and light and have moderately warm to higher temperatures between $20^oC$ and $55^oC$ (Fulford, 1988; Sasse et al., 1991). The process itself requires a population of anaerobic bacteria which secrete enzymes capable of digesting the waste material to the point where it is a usable energy source.

### 2.3.1 Microbiology of Anaerobic Digestion

There are four main phases, seen in figure 2.2, which the AD process consists of: hydrolysis, where macro molecules are broken down into water soluble molecules, acidogenesis, where molecules are further converted into even simpler molecules and acids, acetogenesis, a process where the products of acidification are converted into acetic acids, hydrogen, and carbon dioxide, and methanogenesis, where organic material is removed and methane gas is allowed to desorb from the liquid. This process generates useable end products in the form of bio-gas, the gas produced during the methanogenesis phase which primarily consists of methane and carbon dioxide gasses, and nutrient rich effluent slurry. Figure 2 is a visual representation of the decomposition of sludge through anaerobic digestion, including the percentage of Chemical Oxygen Demand (COD) at each step (Haandel & Lubbe, 2007).

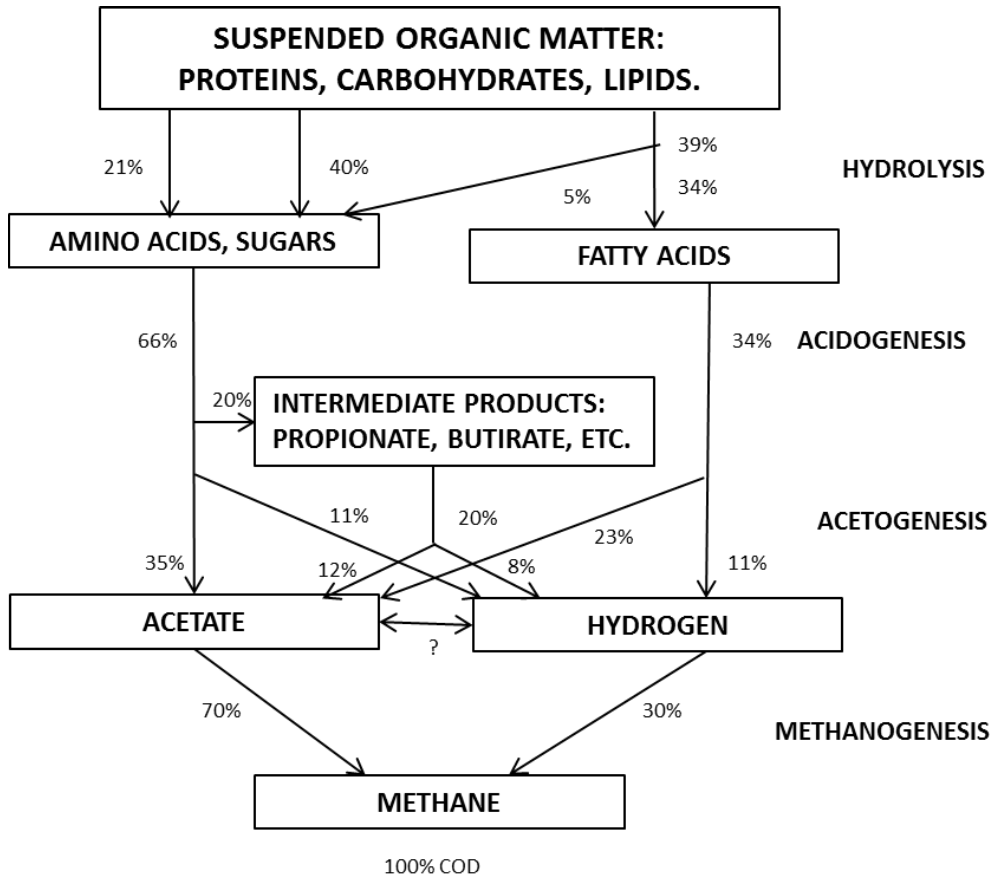



Figure 2.2: Representation of the decomposition of excess activated sludge by AD (Adapted from Haandel & Lubbe, 2007).

It is worth noting that some sources list a varied number of stages in anaerobic digestion, choosing to report three steps and include acetogenesis in the overall step of acidogenesis, or choosing to further breakdown steps into smaller sections of conversion (Gujer et al., 1983; Mata-Alvarez et al., 2000; Rowse, 2011). For example, the 1983 study by Gujer et al. and Zehnder chooses to note six different steps which occur in an anaerobic digester (Gujer et al., 1983).This summary will follow the study by Haandel and Lubbe, delineating four primary steps in anaerobic digestion (Haandel &

Lubbe, 2007). This process is also summarized by the Waste-to-Energy Research and Technology Council.

When an anaerobic digester is preforming ideally, it is typically observed that the conversion of the intermediary products seen in the first three steps is complete, therefore limiting the concentrations of these products at later times in the process. During the hydrolysis step, macro molecules which comprise the waste material, including proteins, carbohydrates, polysaccharides, and fats, are broken down by enzymes excreted by fermentative bacteria into smaller, water soluble molecules: peptides, saccharide, and fatty acids (Haandel & Lubbe, 2007). An example of a hydrolysis reaction can be seen in equation 2.1 where organic material and water is broken down into glucose, a simple sugar (Verma, 2002).

$$C_6H_{10}O_4 + 2H_2O \rightarrow C_6H_{12}O_6 + 2H_2 \qquad (2.1)$$

Retention time, or the time it takes for waste materials to be digested, is most effected by the hydrolysis step, as this step sees the most complex and time consuming process of the complete anaerobic digestion procedure. Factors which influence the retention time and methods for decreasing the time will be discussed more fully later.

Acidification relies heavily on an anaerobic system and is the step where the products of hydrolysis are further converted into smaller, simpler molecules such as short chain volatile acids, ketones, alcohols, hydrogen, and carbon dioxide (Ostrem, 2004). The acidogenic bacteria are responsible for the decay of the hydrolyzed products into volatile fatty acids (Rowse, 2011). While several products come from this step, the conversion to acetic acid ($CH_3COOH$) is the most prominently noted product of acidification. The conversion of glucose to acetic acid can be seen in equation 2.2 (Bilitewski et al., 1997). Other compounds produced in this step are propionic acid, butyric acid, and ethanol.

$$C_6H_{12}O_6 \rightarrow 3CH_3COOH \quad (2.2)$$

Acetogenesis is the process of the conversion of the acidified products into base components of acetic acids, hydrogen, and $CO_2$. This step is sometimes seen as an intermediate transition point of acidogeneis. This process encompasses the products of hydrolysis that are not converted into acetic acid, hydrogen, or carbon dioxide in the acidogenesis step and include the alcohols, ketones, and other acids. Hydrogen is a vital element in this step which will only occur if the partial pressure is low enough, thermodynamically, to allow the total conversion of the remaining acids. Therefore, measuring the amount of hydrogen present in a digester can serve as a fair representation of the performance of the system (Mata-Alvarez et al., 2003). Ethanol, one common product of the acidogenesis stage, is one such alcohol which is broken down into acetic acid. This process is described by equation 2.3 (Ostrem, 2004).

$$CH_3CH_2OH + 2H_2O \leftrightarrow CH_3COO^- + 2H_2 + H^+ \quad (2.3)$$

The first three steps, hydrolysis, acidogenesis, and acetogenesis, are typically grouped together into a group comprising the acid fermentation process. During this process, organic material remains in the liquid phase and is simply processed into a substrate which can be utilized during methanogenesis; the creation of methane and other gasses. Methanogenic fermentation sees the conversion of the primary product of acetogenesis, acetic acids and hydrogen, into methane and carbon dioxide by the appropriate microorganisms, as illustrated in figure 2. Methane is produced from two pathways during methanogenesis. One pathway takes hydrogen and carbon dioxide and forms methane through hydrogenetrophic methanogenesis while the remaining pathway converts acetic acid into methane and carbon dioxide through acetotrophic methanogenesis (Rowse, 2011). Equation 2.4 shows the conversion of carbon dioxide and hydrogen to methane and water. Equation 2.5 is an illustration of acetic acid converting into methane and carbon dioxide, the gases which primarily make up biogas (Verma, 2002).

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O \qquad (2.4)$$

$$CH_3COOH \rightarrow CH_4 + CO_2 \qquad (2.5)$$

Up to this point, the large majority of organic material in the liquid phase is transformed and desorbed into the methane gas. From that, we have a measure of waste stabilization where the initial biological waste material has degraded to base compounds. The gas resulting from methanogenesis is the biogas which was desired from this process. The resulting slurry primarily consists of water and nitrogen and phosphorus compounds, and is void of most volatile organic compounds. A simplified, chemical equation for the processes described above can be expressed in equation 2.6; the split of glucose into methane and carbon dioxide. Essentially, that is the overarching equation which should be considered in the microbiology of anaerobic digestion (Onojo et al., 2013).

$$C_6H_{12}O_6 \rightarrow 3CH_4 + 3CO_2 \qquad (2.6)$$

### 2.3.2 Operational Configurations of Anaerobic Digesters

The type and configuration of anaerobic digester is largely dependent on the specific situation in which it is implemented. A small scale rural operation will use a different system and scale than a municipality or an industrial complex. Beyond the location and scale of the operation, the intended use of the biogas is important. Will the gas be burned in a stove top burner? Will the gas be used to fuel gas engine generators? Furthermore, anaerobic digesters also perform an important process of safely treating waste materials. While this research will focus more on small scale technologies, it is important to recognize the influence of the various anaerobic digester technologies.

The knowledge that an operator of a biogas plant has or does not have is one of the key factors influencing the overall effectiveness of a biogas program. It is relatively easy to build a biogas plant that will produce gas, treat waste, and generate fertilizer; but designing a program that is both effective, cheap, and easy to operate and maintain can be a challenge when one considers the human element. Conditions which affect the productivity of a digester can change, meaning that an operator could run into difficulties if that person is not properly trained in an array of operational procedures. In the context of development projects, biogas reactor designs should be conscientious of the knowledge of the operators and the project should include training for the users. It is important that a technician or specialist in AD design, or similar practices, be available should problems beyond the skill of the normal operator be available in the area; else the operator should be trained to a level where he or she would have the competency to address problems (Fulford, 1988; Sasse et al., 1991; Rowse, 2011).

Single Stage Reactors

Single stage reactors are the “classical” design for anaerobic digesters. These reactors are popular in use due to their simple operation, construction, and wide applicability to various situations. In single-stage reactors, anaerobic digestion, sludge thickening, and the formation of a supernatant take place all in one contained reactor space (Rowse, 2011). Inherently, these reactors see a high level of inefficiency in conversion. The functions described are carried out in a single reactor despite the fact that the optimal conditions for each process are very different. For this arrangement to operate efficiently, the contents of the reactor must be stirred, an action that is uncommon in DRs because of the added costs and complexities. As such, longer retention times are used to compensate for the inherent inefficiencies which allow for greater separation and to provide the anaerobic bacteria with more time to digest the material. Furthermore, as the digester is not very efficient in either digestion or phase separation, larger digester volumes are needed to produce a properly stabilized sludge (Haandel & Lubbe, 2007). This arrangement, also called standard-rate digestion, includes batch, continuous flow, and plug-flow reactors, to name a few. In vertical configurations, there are distinguishable layers which form and can be seen in figure 2.3 and described thereafter (Haandel & Lubbe, 2007).

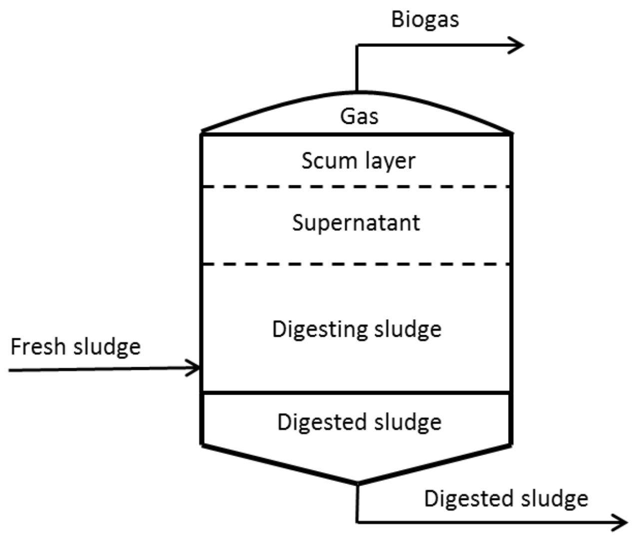



Figure 2.3: Stratification in a single-stage anaerobic digester (Adapted from Haandel & Lubbe, 2007).

1. Scum layer- this top layer is comprised of materials which decay at slowed rates yet have a lesser density than the rest of the substrate.
2. Supernatant liquid layer- this layer is a liquid phase largely free of solids.
3. Active digestion zone- where the conversion of organic substrate into biogas takes place; also where fresh biological material is introduced into the system.
4. Digested sludge or stabilized sludge zone- the bottom of the digester, where fully digested substrates or “biosolids” settles (Haandel & Lubbe, 2007).

Batch Reactors

Batch reactors are a type of single-stage reactor operated by filling the reactor with the desired substrate, sealing it, and then leaving it undisturbed to allow the AD reaction take place in its entirety. Once the material is digested and the remnants removed, a new batch of waste material is introduced into the digester to begin the process again (Rittmann et al., 2001). Figure 2.4 shows a common batch reactor configuration. Biogas, which is generated in the layer of actively digested sludge and passes up through the liquid slurry, is stored above the layers of substrate and its storage should typically count for roughly 50% of the total reactor volume (Rowse, 2011). To catalyze digestion, some biosolids rich with AD microbes from the previous batch may be conserved to seed the following and increase the speed of the microbial reaction. As material is only introduced at one time during the process, stirring the substrate to promote uniform mixing is not necessary. Advantages of a batch configuration include: lack of an external stirring mechanism, high contaminant removal rates, and ease of operation (Rowse, 2011). True batch reactors are less common in developing regions as the users typically prefer a method which allows them to add material at their convenience.

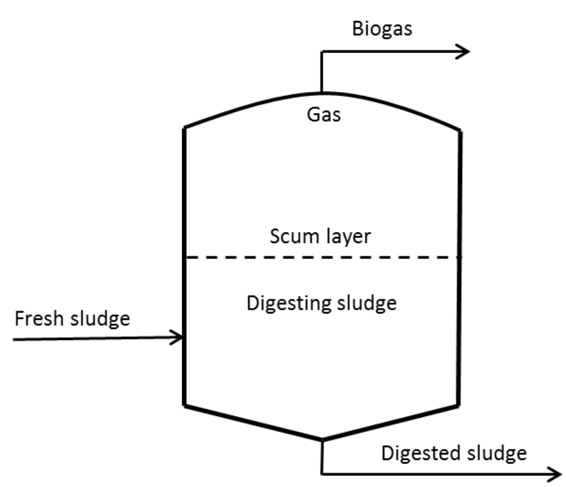



Figure 2.4: Batch anaerobic digester (Adapted from Haandel & Lubbe, 2007).

Continuous flow reactors

These types of digesters, also called continuously stirred tank reactors (CTSR) or continuously mixed reactors, typically include continuous introduction of waste materials into the reactor and continuous removal of the liquid contents from the reactor (Rittmann et al., 2001). Though ideally configured for continuous inflow and outflow (figure 2.5), the deposit of material is typically more intermittent. Intermittent depositing of waste materials can result from daily animal stall cleaning, daily collection of manure from feeding areas, visits to the toilet, and other time related instances. In a continuous flow reactor, microorganisms in the reactor continuously reproduce and replace microorganisms that are removed with the effluent. Ideally, the concentrations of the substrate and microorganisms are uniform throughout the reactor because of mixing that occurs (Rowse, 2011). More commonly there is a level of substrate settling that occurs as many systems elect to forgo a mixing apparatus in favor of a cheaper, simpler design.

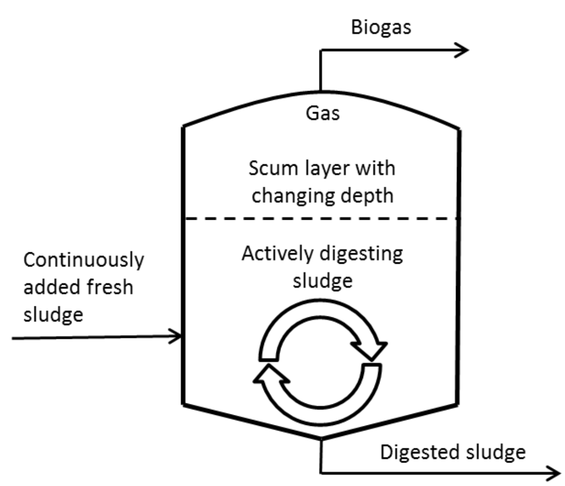



Figure 2.5: Continuous flow anaerobic digester (Adapted from Haandel & Lubbe, 2007).

This type of configuration is common in developing regions as it is easy to maintain and simple to operate. In instances where no heat other than the ambient temperature is added, reactor performance can vary with the temperature fluctuations. Climates which can maintain a mesophilic or thermophilic temperature range are therefore ideal when the reactor is not heated. Therefore, some configurations include external heating and stirring mechanisms. More commonly, developing regions employing this type of reactor design for longer retention times because they elect not to include a heating and stirring system. A large amount of water must be added to the digester so as to permit proper material digestion and allow for the outflow of digested material. In instances that a continuously stirred tank reactor (CSTR) is used, a substrate concentration of 3-8% total solids (TS) is ideal, while a TS concentration of 16-22% is ideal when there is no stirring mechanism (Gunaseelan, 1997). Water used to flush toilets, shower water, water for cleaning out animal stalls, and cleaning water are examples of wastewater which can be used to help reach the ideal TS concentration. The large amount of added water typically requires the use of larger digester volumes at well as an outflow point where the slurry can be collected and reintegrated into the environment responsibly.

Plug-flow reactors

A plug-flow digester (PFR) is often called a tubular digester and operates with influent continuously entering at one end and effluent slurry exiting continuously at the opposite end. In an ideal PFR, material moves through the tube in a single “plug,” that does not mix as raw material enters and digested material exits (Gunaseelan, 1997). Because of this, microbial concentrations vary throughout the tube. This arrangement (figure 2.6) is common in rural developing regions, and is often built as a flexible plastic tube and used in single family scenarios that may have a few animals adding biological materials in addition to their own.

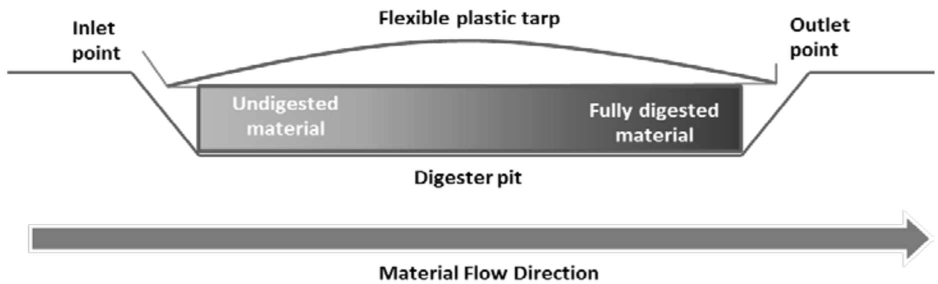



Figure 2.6: Plug flow anaerobic digester.

Reactors in Parallel

Operating reactors in parallel is a method more regularly used in large scale wastewater treatment facilities. By this manner, overflow situations can be contained by distributing the water inflow among the reactors. Digestion takes place at the same rate within the digesters that share the inflow load. Parallel configurations (figure 2.7) are also used in large scale agricultural operations in developed countries. In this setting, digesters are similar in construction to grain silos and are typically stirred and heated. The resulting gas is usually used as fuel in gas engine generators (US EPA, 2010). When maintenance is required on a reactor, those remaining can continue to operate and make up for the downtime (Rittmann et al., 2001). In small scale operations common in developing regions, it is typically not practical for a parallel operation due to the scale involved. These systems are very costly to install and maintain and should be relegated to large scale operations where capital costs are not prohibitive to development of the technology (Rowse, 2011).

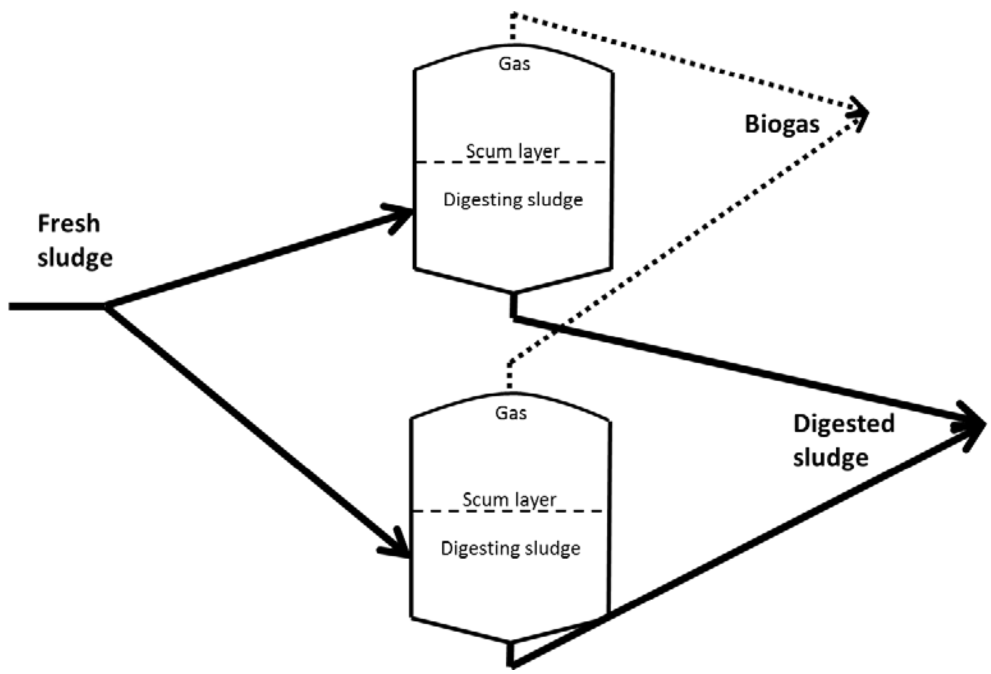



Figure 2.7: Anaerobic digester in a parallel configuration.

Two-Stage and Phased Anaerobic Digestion

A two-stage digester consists of two digesters acting in series, where the first digester carries out the acidogenic processes. The acidogenic reactor is followed by a second one which operates in the methanogenic stages of AD. To catalyze the processes in the acidogenic reactor, sludge from the methanogenic reactor can be added to the influent (Rowse, 2011). Biogas generation primarily occurs in the methanogenic tank. Because the material is already reduced in the first digester, the retention time in the second digester is typically shorter. In configurations which optimize conditions of digestion by stirring, adding heat, or using quickly fermenting materials, a two-stage digester can have a lower overall retention time than a single-stage reactor (Gunaseelan, 1997). Because of this, two-stage digesters are often referred to as "high-rate" digesters. A typical layout can be seen in figure 2.8; stratified layers in this configuration have their counterparts in single-stage digesters and can be described similarly (Haandel & Lubbe, 2007). As substrate is added and digested in the first chamber, the partially digested slurry flows into the next digester when AD is completed.

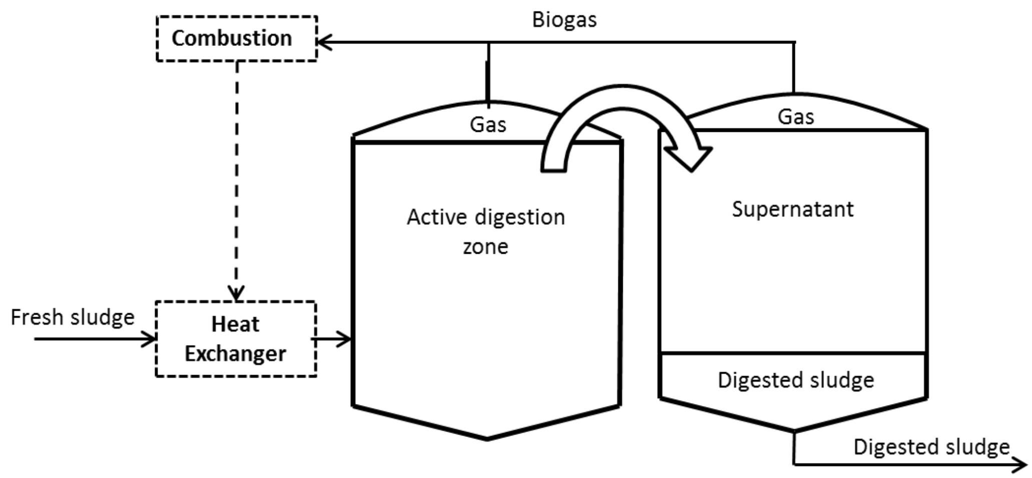



Figure 2.8: Two-stage digester configuration (Adapted from Haandel & Lubbe, 2007).

A phased digester is similar in configuration in that it also consists of a series arrangement in which one reactor is designated for fermentation and the other for methanogenesis. Little difference is seen when compared to a two-stage digester aside from the mechanism that separates the two reactors. Phased digesters separate the processes by using different hydraulic retention times. Tank volume and designed flow rates help to dictate this differentiation (Gunaseelan, 1997).

These arrangements are rarer in development situations as they are cost prohibitive. This method typically boasts a more efficient and stable conversion process as opposed to single-stage reactors. Two-stage reactors also appear to be more effective at destroying pathogens, by comparison. However, the improvements do not typically justify the increased expense (Rowse, 2011). In situations limited by area available, materials, and capital, cheaper and easy to operate single-stage configurations are more common and practical.

### 2.3.3 Reactors used in Developing Regions

Developing regions typically feature small scale applications of anaerobic digesters whose operation can typically be described by the following process. These smaller scale reactors are often operated so that waste material is deposited into the reactor at its convenience; when animal waste is collected, night soils are deposited, and when similar activities take place (Ni et al., 1993). Water must be mixed with the substrate so as to allow effective material flow into the reactor and to allow from proper digestion and operation of the reactor as a whole. Gas is generated and stored within the reactor while digested materials are allowed to flow out of the reactor, driven by gas pressure differentials and relatively consistent material inflow rates. The slurry outflow is nutrient rich liquid slurry which is applied directly to fields as a fertilizer, or dried out and used as a solid fertilizer or animal bedding. The AD process is effective at removing harmful pathogens, though the exiting slurry is clearly not fit for many applications beyond agricultural use (Sasse et al., 1991).

Commonly, there are three types of anaerobic digesters that are seen used in developing regions including fixed-dome digesters, floating-drum digesters, and polyethylene tubular digesters. Fixed-dome and floating-drum digesters are very similar in their operation and production of gas. As can be deduced by the name, fixed-dome digesters are a single compartment of a fixed volume while floating-drum reactors have a separate gas collecting container which sits atop the digesting section. Both of these arrangements feature a fixed volume for containing gas, meaning that system pressure would increase as gas is produced. When gas is extracted for use at a set rate and gas producing materials are introduced at a set rate, equilibrium can be reached which results in a relatively constant system pressure. Polyethylene tube digesters are also operated in a semi-batch manner with a model of a plug-flow digester. Similar to the other two, system pressure can equalize when inflow and outflow rates are stabilized.

With temperature being such a large component influencing hydraulic retention times and therefore digestion rates, climate must be taken into consideration. Temperatures of 20$^oC$ to 55$^oC$ are ideal ranges for anaerobic digestion, with the optimal mesophilic range at 30$^oC$ to 38$^oC$ (Fulford, 1988). Ambient temperatures need to be in an appropriate range to support anaerobic digestion, or the digesters themselves must be insulated or have other means of heating them. In developing regions, it would seem counterproductive to use energy to produce heat to generate energy, so passive heating methods such as installing greenhouses or shed roofs atop the digester can be used. In larger scale operations, heat is more practical to add; cooling systems from gas engines can be used to warm digesters.

Any construction project must take into account the resources that are at hand and locally available. Availability of appropriate construction materials, skilled labor, and user knowledge need to be accounted for in construction of biogas reactors. Likewise, the ease of operation also must be considered. Complicated designs and operational procedures should be avoided when introducing technologies of this kind in developing regions. Engineers must be aware of what parts can be sourced in areas so they can better design reactors. Furthermore, these reactors require a great deal of skill to build properly. Fixed-dome and floating-drum digesters have masonry components that must be sealed gas tight so as to prevent leakages. When components breakdown and maintenance is required, local personnel need to be able to make repairs; it is not reasonable for a foreign specialist to come in and repair something of this scale. What parts are available? Even if a person has the knowledge of how to operate or maintain a digester, can a mechanic or mason repair the reactor with the materials that are locally available? This example shows the importance of integrating local knowledge, personnel, and resources into a design.

The amount of waste or usable substrate that is generated in a situation needs to be adequate to justify the installation of an anaerobic digester. A small family with a few animals would require a digester which is very different in size than a community of several households and their animals. How much biological material that is available in an instance will affect the gas that can be produced and the volume of a digester required. Also, large amounts of water are needed to be mixed with the substrate to allow proper settling and flow into the reactor. Therefore, regions which have scarcity of water would be advised against using anaerobic digesters.

To summarize digesters in developing regions, Fulford states that a biogas plant should be:

1. Strong
2. Leak-tight
3. Built of local materials
4. Cheap to build
5. Easy to use
6. Easy to maintain
7. Easy to insulate and heat
8. Reliable (Fulford, 1988).

### Fixed-dome Digesters

Fixed-dome digesters first appeared in China in the 1800s, and are often referred to as Chinese dome digesters. Based on a simple design model, dome digesters are essentially an underground masonry chamber with a dome fixed atop it. The chamber is typically constructed using brick or concrete, depending on the availability of material and appropriate personnel and equipment. Gas is stored above the digesting substrate, as described in section 2.3.2 and is sealed by a cover on top of the dome which is held in place by dirt placed on top of the digester (Fulford, 1988; Sasse et al., 1991; Rowse, 2011). The basic layout of a fixed-dome digester can be seen in figures 2.9 and 2.10.

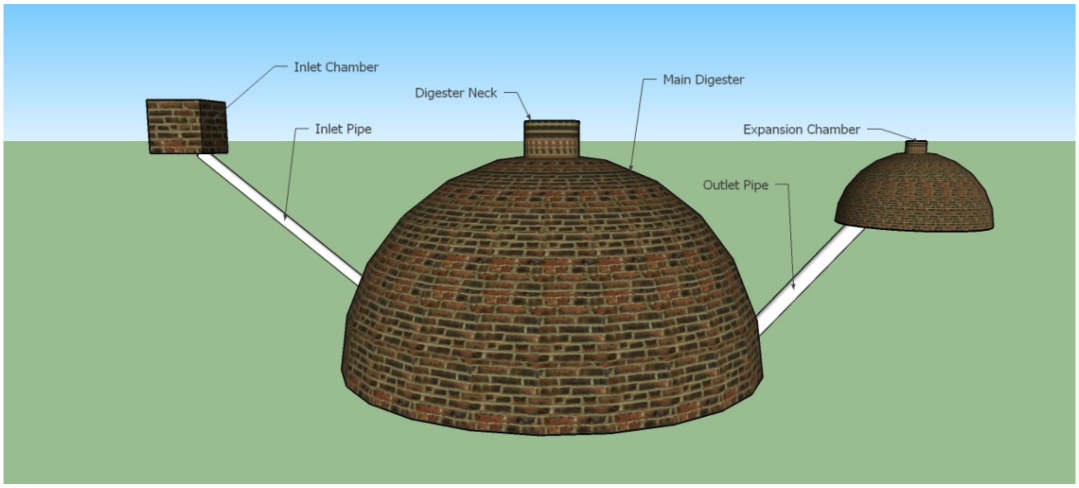



Figure 2.9: Fixed-dome digester.

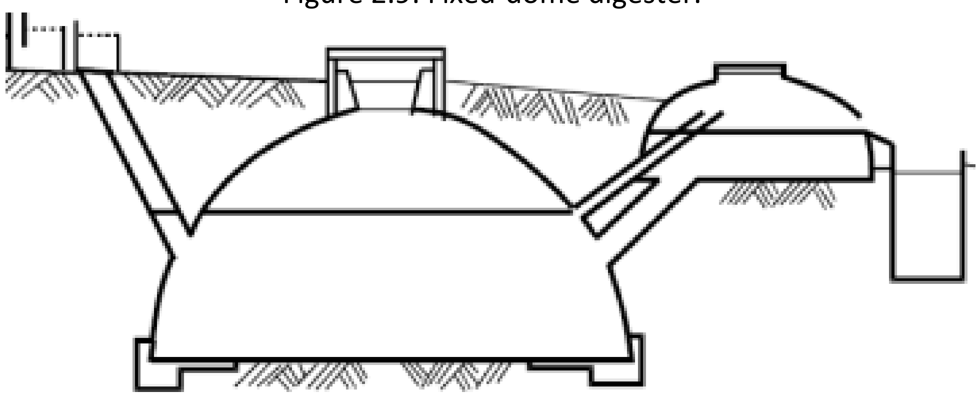


Figure 2.10: Cross-section of a fixed-dome biogas digester.

Commonly, the digester pit is of a cylindrical shape with a dome on top of it. The dome design is used because when in compression, domes are self-supporting so little extra reinforcement is needed. The Chinese design also experimented with rectangular configurations, though difficulties with sealing corners prevented this idea from gaining ground. Substrate is mixed in a mixing pit and fed into the digester. The inlet point should be in the actively digesting layer of the reactor (Fulford, 1988). A second chamber sets adjacent to the main reactor where digested material flows out. The lower image of figure 2.10 shows how as pressure from the produced biogas builds up, it forces digested material into the overflow slurry reservoir by the displacement principle. This chamber needs to be cleaned out periodically and can be used as a fertilizer. The outflow point must be higher in relation to the depth of the inflow point to prevent backflow of material into the mixing basin.

This type of digester has the benefit of being subterranean, meaning it takes up less space on the surface than other types. It is also has the advantages of having no moving parts, relatively low construction costs, and long operational life spans when maintained properly. Being subterranean, some problems arise with users being unable to physically observe the amount of gas in the tank, system pressure gauges would need to be included. Also, construction requires precision and expertise to ensure structural integrity and adequate sealing (Sasse et al., 1991; GTZ/GATE, 1998). These digesters are widely used in China as well as developing nations. When built properly and maintained accordingly, fixed-dome digesters can be used to great effect for 20-50 years (Fulford, 1988).

Floating-drum Digesters

Floating-drum digesters were first developed in India and differ from fixed-dome in that a gas holding camber sits on top of the digester.  The gasholder floats either directly on the fermentation slurry or in a water jacket of its own, which separates it from the potentially corrosive substrate (Fulford, 1988). The gas is collected in the gas drum, whose height relative to the digester changes based on the amount of gas stored. Similar to the fixed-dome digester, floating-drum digesters are operated in a semi-batch manner by feeding the water mixed substrate into digester inlet pipe, which flows down the inlet into the active digestion zone of the digester (Rowse, 2011). Figure 2.11 is a representation of a typical floating-drum digester (Fulford, 1988; Rowse, 2011).

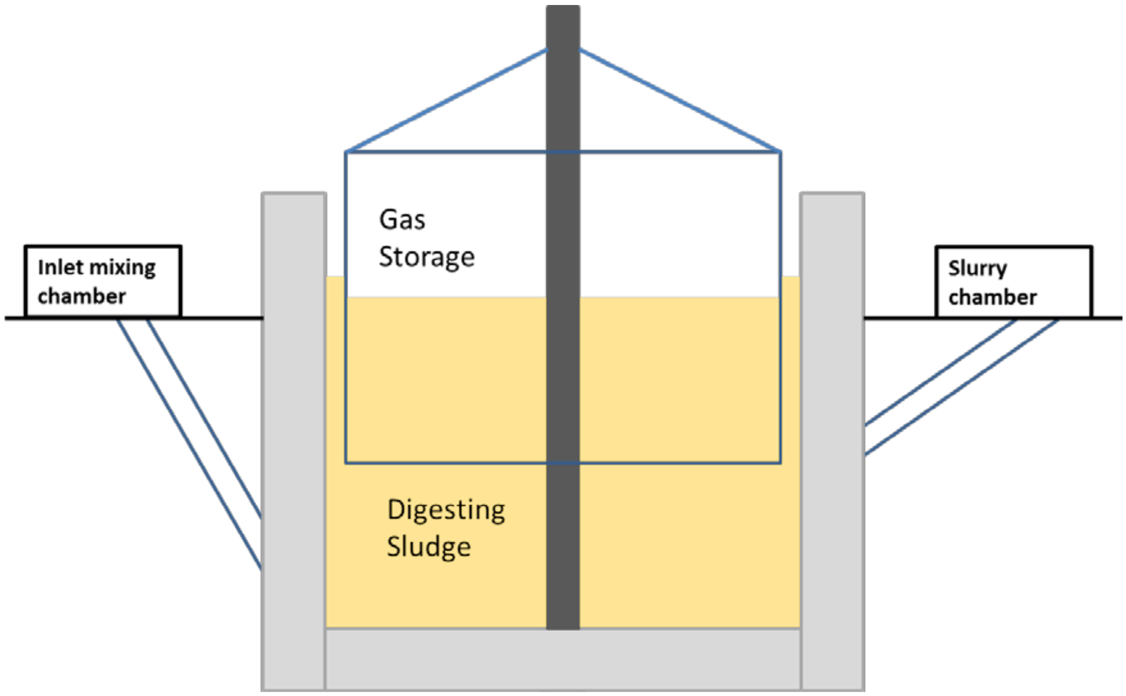



Figure 2.11: Cross-section of a floating-drum biogas digester.

The digester consists of a pit, constructed of brick or concrete, which is built into the ground. As seen, the gas accumulates in a cylindrical steel gas drum that floats open end downwards in the slurry. As biogas accumulates the pressure from the volume raises the drum which falls as gas is consumed. This action allows users to physically observe the amount of gas available for use. The gas drum is secured by a guide frame which keeps the drum properly aligned while moving up and down and allowing for it to pivot about its central axis. This system prevents the drum from moving sideways or moving off center and jamming against the walls of the digester pit (Fulford, 1988).

The Indian design has the advantage of being simple in operation and construction when properly cared for. Construction precision, while it should be strived for, is less critical in comparison to the fixed-dome design. Another large advantage is the fact that the level of gas produced and stored is directly visible based on the depth level of the drum. Furthermore, gas pressure remains constant and is based on the mass of the drum itself (GTZ/GIZ, 1999).

The main drawback in this design comes with the floating drum which is usually made from mild low carbon steel welded around a frame of angle iron bars or rebar. Plastic is not widely used because locations which are suited for floating-drum digesters are typically quite sunny and hot and these conditions can quickly degrade plastic. Furthermore, the convective heat properties of steel allow the drum to contribute heat that it receives from the sun’s radiation to the AD process. The use of steel presents a relatively high material cost and accounts for a fair amount of the maintenance involved in the operation of floating-drum digesters. Low carbon steel is susceptible to rust and corrosion; this drum sits on top of biological waste material, a substantially corrosive material (Rowse, 2011). Ideally drums should be painted annually or biannually and need to be cleaned of substrate, which presents a recurring maintenance cost. Because of the susceptibility of the drum to corrosion, floating-drum digesters usually have a shorter operational life span of 5-15 years (GTZ/GIZ, 1999). Floating-drum digesters are common in developing regions that have access to material for the drum and its maintenance.

Balloon Digesters

The design on these digesters, which were originally designed in Taiwan, can vary to some degree, though the concept remains the same throughout. Digested biogas is stored within a polyethylene bag. In a balloon pit design, a lined trench is constructed which serves as the main digestion chamber. A plastic tent, or "balloon", sits atop the trench and inflates as gas is produced. The trench is dug at a slight angle to enable flow of digested material out of the trench. This method is modeled by a plug-flow design (Fulford, 1988). The basic layout of a balloon digester can be seen in figure 2.12.

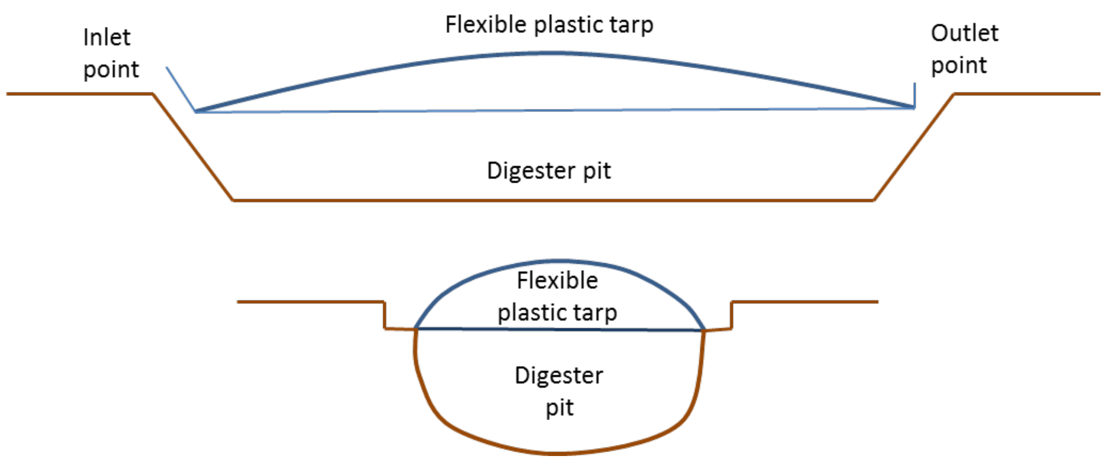



Figure 2.12: Balloon anaerobic digester.

Similarly, some balloon digesters are constructed in a tubular design and use a plug flow configuration. Polyethylene tubular digesters function in the same manner, but instead of having a lined digester pit with a tent on top of it, they are a single tube of plastic which contains the entire AD process (Rowse, 2011). As materials have improved, and prices have decreased, this design has increased in popularity. System pressure is maintained by the elasticity of the material used. Weights can also be put on the bag to regulate pressure relative to the volume available.

These digesters are the easiest expensive and easiest to construct of the three discussed. Materials have improved over the years as well; red mud plastic (RMP) is a polyvinyl chloride plastic which has gained popularity and shows evidence of an up to ten year life span (Fulford, 1988). RMP bag digesters have been used in large scale industrial operations in some Chinese locations. Ease of construction, low capital investment, simple maintenance and operation are the main advantages of balloon digesters. However these digesters have a comparatively short life span of 2-10 years and are ill-suited to configurations featuring larger input quantities when in developing regions (Rowse, 2011). Furthermore, balloons are much more susceptible to damage than fixed-dome and floating-drum digesters; a cow stepping on the bag, a child jumping on it, heavy debris falling can all damage the digester. Because of this, roof structures are sometimes built over the digester to both protect it and insulate it to increase heat through convection. Balloon digesters can also have a larger footprint than the other two as it is not underground or partially underground. Balloon digesters can easily be applied and often are in places with even and consistent climates (GTZ/GIZ, 1999). Their low cost and simple installation and maintenance make them viable methods for treating waste and generating energy in developing regions.

### 2.3.4 Organic Substrate Sources

Waste materials and substrates refer to the carbon based biological materials which are introduced to anaerobic digesters to be fermented. A substrate functions as an electron donor during the biochemical reactions taking place during methanogenic fermentation (Rowse, 2011). These can come from any biological material that contains substances such as fats, carbohydrates, and proteins. The form in which these substances exist has a large effect on its digestibility. For example, cattle dung is one substrate that is typically easier to digest as it has already been digested by a ruminant and it already contains the bacteria which permit anaerobic digestion. Raw plant material on the other hand, is more difficult to break down as its carbon substrates are locked up by cellulosic and lignin materials which are hard to digest (Fulford, 1988). Human waste is easily added to digesters by connection to flush toilets, pour-flush latrines, and pit latrines. Additionally, the water that is used to flush also serves at mixing material to increase the effectiveness of the AD process while facilitating particle flow into the reactor. This method can be especially effective in larger scale centers like community washrooms, hospitals, schools, prisons, and universities.

Plant material and food waste can be a viable substrate source in anaerobic digesters. Table 2.2 represents some of the more common biomass sources for methane production. The amount of methane produced per kilogram of volatile solids (VS) can be seen. Volatile solids refer to solid materials which are able to be digested by the anaerobic digestion process (Gunaseelan, 1997). Plant materials typically need to be preprocessed before deposited into a reactor. This can be done in a number of ways including, but not limited to, mechanical chopping, composting, screening, and chemical treatment. Composting plant material for a few days prior to addition to the digester is a good method to use because aerobic bacteria are better at breaking down cellulose than anaerobic (Fulford, 1988).

Table 2.2: Methane yields from various biomass resources (Gunaseelan, 1997).

| **Biomass Source** | **Methane Yield (m3/kg VS)** |
|---|---|
| Organic Fraction of Municipal Solid Waste | 0.390-0.430 |
| *Fruits and vegetables* | |
| Fruit and Vegetable Solid Waste | 0.51 |
| Tomato processing waste | 0.42 |
| Banana waste | 0.409-0.529 |
| Potato waste | 0.426 |
| *Grass* | |
| Corn stover | 0.36 |
| Wheat straw | 0.0383 |
| Sorghum | 0.42 |
| Millet straw | 0.39 |
| *Woody Biomass* | |
| *Ipomoea* (Sweet potato) | 0.361-0.429 |
| Poplar wood | 0.33 |
| *Land Weeds* | |
| *Ageratum* (Whiteweed) | 0.241 |
| *Parthenium* | 0.236 |
| *Lantana* | 0.236 |
| *Marine and Freshwater Biomass* | |
| *Ulva* | 0.330-0.480 |
| *Macrocystis pyrifera* | 0.31 |
| *Pistia* (Water lettuce) | 0.41 |
| Water hyacinth | 0.362 |

In general, animal dung is a very good substrate source for anaerobic digesters. Collection methods should be taken into account when considering anaerobic digesters. Manure from pastured animals will need to be physically collected while that from penned animals is much easier to collect. Different animals are able to process fibrous materials more or less effectively while others so retention times and gas removal efficiency can vary. The physical properties and characteristic of the dung from several different animals is seen in table 3 (ASAE, 2005; Fulford, 1988). It should be noted that the figure and reference to human waste was adjusted to reflect the waste properties of both fecal matter and urine. Dung needs to be mixed with water to at an approximate 1:1 ratio by mass (Fulford, 1988). This allows for ease of material flow into the reactor and also promotes proper settling and digestion within the reactor.

Table 2.3: Amounts of waste materials from various animals (Fulford, 1998; ASAE, 2005).

| Animal | Total Manure (kg/day) | Total Solids (% of Total Manure) | Volatile Solids (% of total solids) | Resource |
|---|---|---|---|---|
| Cattle- Beef | 29 | 8 | 79 | (ASAE, 2005) |
| Cattle-Dairy | 68 | 13 | 84 | (ASAE, 2005) |
| Poultry- Layer | 0.09 | 25 | 73 | (ASAE, 2005) |
| Poultry- Broiler | 0.1 | 27 | 74 | (ASAE, 2005) |
| Swine- Gestating Sow | 12 | 10 | 83 | (ASAE, 2005) |
| Swine- Boar | 3.8 | 10 | 89 | (ASAE, 2005) |
| Human (feces and urine) | 1.3 | 10 | 79 | (Fulford, 1988) |

### 2.3.5 Factors Influencing Reactor Effectiveness

A few general factors should be considered when describing the operation of an anaerobic digester. The factors that will discussed in this study affect all types of digester regardless of the configuration or feedstock and include; hydraulic retention time (HRT), solids retention time (SRT), temperature, pH, toxins, and safety factors. All of these factors can be influenced by operator inputs. Mixing and heating reactors improves HRT and SRT while the kinds of substrate used and substances present in them can influence the pH and toxin levels.

Hydraulic Retention Time

Hydraulic retention time simply refers to the amount of time that a reactor substrate remains in the reactor. Numerically, this is seen in equation 2.7 (Rittmann et al., 2001).

$$\theta = \frac{V}{Q} \tag{2.7}$$

Where:

Θ = Hydraulic retention time measured in days

*V* = Volume of the reactor in cubic meters

*Q* = volumetric inflow rate

The HRT defines the overall amount of time that the substrate will stay in the reactor. This affects how long it will take for biogas to be produced and well as the time in which pathogens will be neutralized. Typically, the methanogenesis step dictates the amount of time a substrate will take to digest. HRTs can range between 10 days in ideal heated and stirred conditions and 100 days in cryophilic and non-stirred conditions (Fulford, 1988; Rowse, 2011). HRTs need to be designed based on the conditions of the digester. Taking into account digester storage volume, influent rates, and temperatures, an appropriate HRT can be deduced which will result in an effective design.

Solids Retention Time

Rittmann and McCarty define solids retention time as, “the mass of organisms in the reactor divided by the mass of organisms removed from the system each day” (Rittmann et al., 2001). This factor refers to the rate at which anaerobic organisms reproduce in relation to the stabilization of sludge materials. Equation 2.8 is represents this relationship in a numerical manner (Rittmann et al., 2001; Rowse, 2011).

$$\theta_c = \frac{V*X}{Q_o*X_o} \qquad (2.8)$$

Where:

$\Theta_c$ = Solids retention time in days

V = Volume of the reactor in cubic meters

X = Anaerobic bacterial concentrations in the reactor

$Q_o$ = Volumetric outflow rate

$X_o$ = Anaerobic bacterial concentrations in the outflow

It is important to optimize the SRT, as one which is too short will result in bacterial outwash. Outwash of digestive bacteria is detrimental to the effectiveness which a digester will have. SRT dictates the growth conditions of the desired bacteria and a longer time allows for stabilization of fermentation and an increase in the effectiveness and efficiency of biogas production (Rittmann et al., 2001). Rittmann and McCarty maintain that the SRT for a reactor in the mesophylic temperature range should be at least 10 days (Rittmann et al., 2001).

Temperature

Some AD systems feature a heat exchanger or other mechanism for increasing the temperature within a reactor (Fulford, 1988). Temperature dictates what types of bacteria will be present in a digester. This affects both HRT and SRT which indicates the effectiveness of biogas production. In the context of developing regions which mostly operate relying on ambient temperatures, the mesophylic temperature range of 30$^{o}$C to 40$^{o}$C is of concern. Gas production rates are heavily based on temperature as a 10$^{o}$C increase can result in a doubling of the production rate (Fulford, 1988). Furthermore, the amount of gas produced per unit of feedstock also increases as temperatures rise. High, consistent temperatures are ideal for AD situations. Consistency is especially notable as it can be observed that sudden temperature fluctuations can 'sour' a digester (Fulford, 1988). The souring of a reactor refers to the dramatic increase in acidity and eventual failure of a reactor. In conditions of temperatures in the mesophylic range, HRTs can be in the range of 20-40 days; shorter HRTs result in a faster cycle of new materials being digested (Fulford, 1988; Rittmann et al., 2001).

pH

Normally, an anaerobic digester should operate in a zone of neutral acidity (Fulford, 1988; Rittmann et al., 2001). When a plant is first started, the acidic bacteria are the first to take effect, meaning the overall pH will initially be lower than what is ideal. However, once the methanogens start to grow and react, the pH will balance itself out. That being said, pH is a good indicator of the overall health and effectiveness of a mature reactor. Too low of a pH decreases methane production and can cause a reactor to sour (Fulford, 1988; Rittmann et al., 2001).

A properly functioning biogas reactor is naturally buffered and pH is regulated by the processes that are occurring within. The measure of carbon dioxide is an important in a digester as it can function as a cause of acidification. $CO_2$ can dissolve in the water inside the reactor which will create bicarbonate ions which can increase the alkalinity of a digester (Fulford, 1988). Therefore, $CO_2$ measurements in the outgoing biogas can help to serve as an indicator of the health of a digester with respect to pH levels.

## Toxins

A large contributor to the souring of reactors is the presence of certain toxins in the forms of disinfectants, antibiotics, pesticides, chlorine, and other compounds which have the purpose of killing bacteria. Therefore, care must be taken to avoid depositing waste materials which may contain these substances (Fulford, 1988). If animal stalls are cleaned with detergents and disinfectants or if digesters are connected to greywater outflow points, care must be taken to avoid transmission of substances which can harm the desired bacteria. Waste from animals and people on antibiotics should ideally not be deposited into a reactor.

## Safety Factors

As in all engineering designs, some manner of a factor of safety must be considered in designing a biogas reactor which uses waste materials. Safety factors in these situations are meant to address problems and issues such as a lack of operator maintenance or oversight, variability in waste input amounts, fluctuations in temperatures and HRTs, and changes in operational conditions. Additionally, a safety factor can account for growth of a family or of a farming operation without necessitating the immediate expansion or replacement of an existing digester. Safety factor figures can be somewhat subjective in biological systems as opposed to more "traditional" engineering designs of structures or vehicles. Rittmann and McCarty suggest a broad range of a factor of 10-30 for a factor of safety, though this figure is ultimately dependent on factors related to consistency of operation, quality of construction, and competence levels and responsibility of operators (Rittmann et al., 2001). Safety factors in an AD typically denote a larger total volume and a designed HRT which is longer than what conditions might otherwise require. Failure of a technology has a different effect when in a developing situation as it can result in a degradation of the reputation held by a technology and those implementing it.

### 2.3.6 Methods for Increasing System Efficiency

Stirring

Simply stirring or agitating the digesting substrate in some manner can increase the rate at which the material breaks down and produces biogas. Stirring stimulates the digestive bacteria while also mixing the substrate and producing a more uniform digestion profile. This also breaks up the scum layer that often forms in a stagnant reactor. Automated stirring mechanisms are almost exclusively seen in large scale digesters in industrialized countries; they are not typically feasible in development situations because they are comparatively expensive and involve another layer of maintenance. However, simpler manual stirring mechanisms can be included in more basic digester configurations (Fulford, 1988; Rowse, 2011).

Heat cycling

The anaerobic bacteria involved in the production of biogas function better under mesophylic temperature conditions of 30 to 40˚C. While digesters will certainly function under lower temperature conditions, the amount of gas produced per unit of feedstock digested also increases as the temperature does. Warmer, consistent temperatures are ideal in AD programs to maintain effective biogas production. The types of heating mechanisms that can be used vary greatly to suit the conditions of the location in question. In some situations, the biogas produced by the reactor is directly used to heat it; boilers recycling water used for cooling, heat exchangers, and other similar mechanisms are commonly used (Fulford, 1988). Figure 2.13 shows a possible configuration for recycling the cooling water for a gas engine to a digester. The water which is warmed by the heat exchanger on the gas engine is pumped into a pipe system in the digester; this warming increases the biological activity and digestion rate in the biogas reactor.

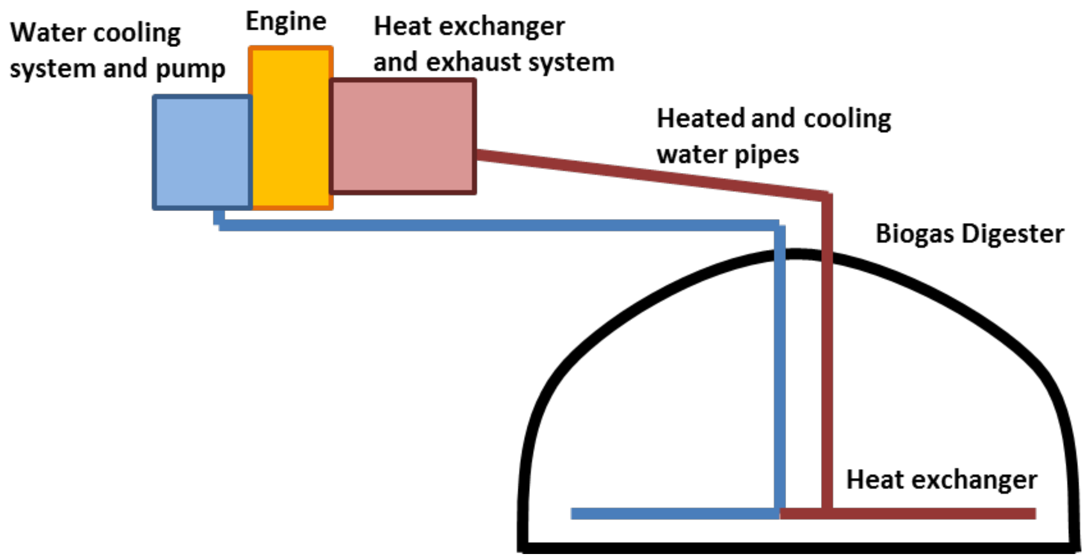



Figure 2.13: Heating a fixed-dome digester with engine cooling water.

When applied, an increase of biological activity in the sludge occurs coupled with a decreased HRT. In instances where digesters are used in developing regions, heating is attractive at low temperatures where a digester would not function well otherwise. Typically, the temperatures in tropical and sub-tropical developing regions are adequate for anaerobic digestion without heating. Other steps can be taken to heat the system beyond the addition of heat sources. Methods like insulating the digester and using warm water for the input mixture can increase the system, temperature (Fulford, 1988).

Pre-treatment

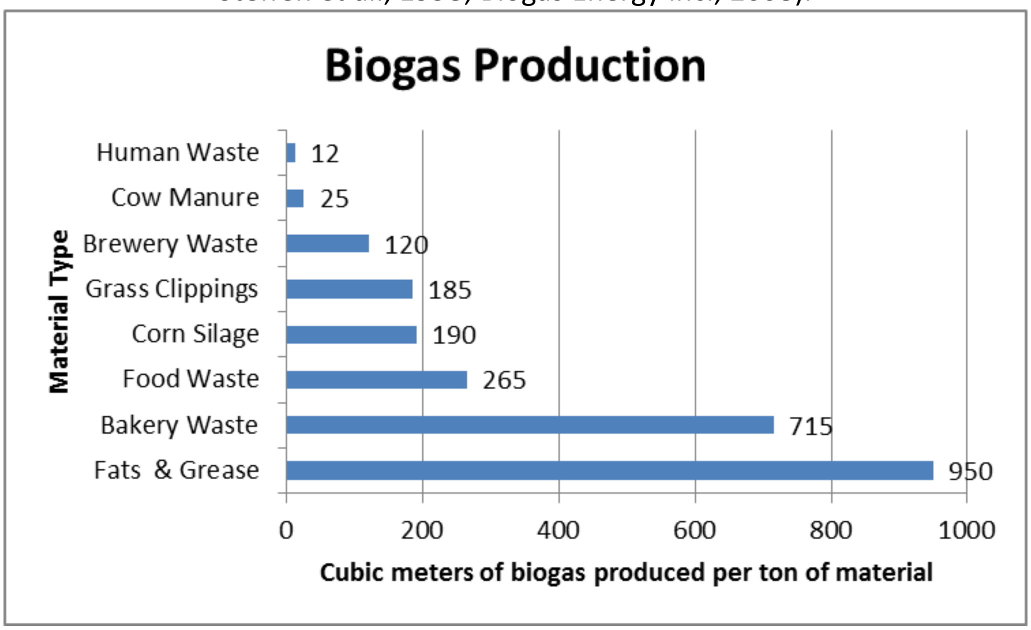
Pre-treatment describes types of handling of the input substrate that can be done prior to the addition of the materials into the digester. These treatments can be as simple as chopping or grinding the feedstock or as involved as undergoing chemical treatments. Some common pre-treatment methods include mechanical treatment like chopping and grinding, acid treatments, thermal treatments, pressure and de-pressure treatments, and freeze-thaw treatments (Ma et al., 2010).

In general, pre-treatment methods work to degrade the physical bonds holding together the substrates or otherwise break the material into smaller components. Mechanical pre-treatments include different methods of physically breaking down the feedstock into a substance which is more easily digested within a reactor. Acid pre-treatments wash the waste with an acid (such as HCl) mixture to breakdown the materials. Thermal treatments generally include heating the substrate to temperatures upwards of 100˚C; the increased temperature breaks down the material by destroying the cell walls of plant constituents and increasing biological activity. Similarly, freezing and thawing the material destroys cell structures and increases digestion rates. Quickly pressurizing and depressurizing the system can help to promote an increase in substrate solubility and enhance biodegradability (Ma et al., 2010). With specific regard to biogas programs in development, some pre-treatments are more feasible than others. Thermal and chemical pre-treatments would seem less feasible than mechanical pre-treatments. Chopping or grinding can be done more simply and at a lesser cost, comparatively speaking.

## Variation of Substrates

Various feedstocks digest to produce differing amounts of biogas based on the volatility of their chemical make-up (Steffen et al., 1998). Digesters can run quite effectively when fed by manure alone, but because of the dramatic effect that they have on methane production, digester effectiveness can benefit from using a mixture of feedstocks. Food waste, kitchen refuse, cooking byproducts, spent cooking oils and greases can be accrued from restaurants and cooking areas. These, and other materials, can be included in a digester without significantly altering retention times while dramatically increasing the amount of biogas produced per unit of mass introduced (Table 2.4) (Steffen et al., 1998; Biogas Energy Inc., 2008).

Table 2.4: Biogas produced by the digestion of different substrates (Adapted from Steffen et al., 1998; Biogas Energy Inc., 2008).




Timing and quantity control

Maintaining a consistent schedule of adding waste material, using the produced biogas, and allowing treated waste to flow out can help to promote a stable and dependable anaerobic digester. This can be done by using a form of timing and quantity control; optimizing the amount of material added to the digester based on its designed

HRT and volumetric characteristics. Ensuring that the quantities involved are within the designed capabilities and planning for the appropriate time intervals makes sure that the operation of the digester is smooth and consistent. Operating in an inconsistent manner can shock the system and disrupt the level balances between pressure generated by the produced biogas and the slurry outflow (Fulford, 1988; Rowse, 2011).

### Optimizing retention time

The hydraulic retention time of a digester should be designed to take into account the ambient temperature, feedstocks used, amount of substrate used, water availability, pathogens present, and design safety factors when designing the desired rate. It is important to optimize the time in which the substrate will be digesting; too short of an HRT, and the substrate will not be adequately digested, wasting the potential energy contained in the volatile solids and potentially releasing unsafe materials while too long of an HRT limits the amount of fresh material that can be introduced into the system. Using a design which optimizes retention times in reactors is a step that can be taken to improve the overall efficiency and effectiveness of the technology (Rowse, 2011).

### Monitoring systems

Monitoring different parameters of a system, such as the TS and VS in the feedstock, the HRT of the digester, the pH, and the internal temperature can improve the overall effectiveness of a reactor by allowing the operator to be able to observe the reactions taking place within the digester (Fulford, 1988). If a digester is having issues, monitoring systems can help to indicate where improvements in operation can be made. It is also beneficial to have an indication of the digester's productivity so that adjustments of the operational configurations can be made to improve effectiveness.

The majority of biogas programs in developing countries lack any method of monitoring the digesters. Digester monitoring systems could be something as simple as including a flow or pressure gauge. Flow gauges can measure the amount of gas flowing out of a digester as well as the amount of material being fed into the digester and the amount of slurry flowing out. Measuring the flow in and out of the digester can help to ensure that the internal biological activities and balance of the digester is appropriate. A method of quantifying the productivity of a digester will help to display the output so that observers can emphasize the benefits of adopting a biogas digester program.

### 2.3.7 Benefits of Anaerobic Digesters in Communities

The use of anaerobic digesters in the context of developing regions presents a multitude of benefits. The positive impacts which digesters can have are addressed by the following (GTZ/GATE, 1998; Ni et al., 1993; Rowse, 2011):

1. Energy production in the form of biogas as a fuel source
2. Safe treatment of biological waste materials
3. Production of a nutrient rich fertilizer from the digested effluent
4. Mitigation of unstable deforestation of hardwoods used cooking fuel
5. Improving indoor air conditions

## Energy Production

Energy in the form of clean-burning biogas is the primary byproduct of the process of anaerobic digestion. Biogas is readily burnable in its current state. Commonly, it is used in burners for cooking stoves as well as in gas fueled lanterns and heaters. For this to be effective, a proper air mixing ratio must be achieved. Biogas is similar to natural gas and liquefied petroleum gas (LPG) in its properties as a burnable fuel (Chynoweth et al., 2001). The calorific value of biogas can be measured at about 6 $kWh/m^3$; similar in energy content to half a liter of kerosene, one kilogram of firewood, or 2 kWh of electricity (GTZ/GATE, 1998). Biogas can also be used as a fuel source in gas engines. Gas engine generators can be used to generate electricity, which is often unreliable in its availability and unsustainable in its production in developing regions. As a sustainable and cleaner burning fuel source, biogas offers a viable source of alternative renewable energy (Ni et al., 1994; Rowse, 2011).

## Treatment of Waste

Anaerobic digesters are often components of western style waste water treatments plants and represent a proven and sustainable technology for these purposes. One reason is because instead of consuming energy to treat waste materials, this process generates energy. Pathogens and harmful organisms are naturally and effectively broken down by the AD process (Lettinga, 1995). When not collected, treated, and addressed, waste materials present a very unsafe condition to those concerned both from a general sanitation and an environmental standpoint. In agricultural settings, water runoff can often be full of nitrates and phosphorus from manure and biological residues. Allowing this runoff into waterways is harmful to the ecological health of the system by presenting hypoxic zones or stimulating algae blooms (Rowse, 2011). Additionally, waste materials can be full of dangerous pathogens which can be quite harmful to life. When in an anaerobic environment, pathogens commonly found in human and animal waste material is broken down and neutralized in a safe and effective manner through immobilization (Fulford, 1988). Anaerobic digesters offer a method for treating materials and reintroducing them into natural systems more responsibly.

## Fertilizer Production

Biological waste materials inherently contain a high amount of nutrients which are usable by plants. Synthetic fertilizers require high energy inputs to convert nitrogen into a usable form through the Haber-Bosch process. Organic nitrogen is mineralized and converted into a form such as ammonia ($NH_3$) which plants can use. As most plants grown for agriculture are unable to fix atmospheric nitrogen on their own, fertilizers are a key component to high yields and effective eland management. Additionally, phosphorus is found in high concentrations in biological waste. Most phosphorus used in commercial fertilizers is sourced from mines, where the resources are limited. Commercial fertilizer prices have risen globally in the past years (Rowse, 2011). Anaerobic digestion produces a safe quantity of fertilizer in its effluent. This effluent can be dried and applied to fields or spread as a slurry to provide water and nutrients.

There exists a direct link between soil degradation, deforestation, and fertilizer needs in developing regions. Many rural locations rely on dung and crop residues for heating a fuel needs; these resources would serve a much greater good on the field as opposed to the fire. The nutrient losses in burning biological materials are great and detrimental to agricultural production. Ideally animal waste would be digested to generate energy and fertilizer while crop reside would be reintegrated into the soil; presently, both are widely used as fuel. Economically, this practice creates a huge strain as funds can be sapped by commercial fertilizers. Fertilizers are in great need, yet farmers are often forced to burn valuable fertilizer sources (Sasse et al., 1991; GTZ/GATE, 1998; Onojo et al., 2013). Biogas technologies can offset this by providing a fuel source along with quality fertilizer; all from the same resource.

Mitigation of Deforestation

As alluded to previously, many households in developing regions rely on firewood for heating and cooking needs. This, coupled with agricultural expansion, has led to widespread and rampant problems of deforestation, particularly in savannah regions of Africa which have limited woody resources to begin with. AD provides an alternative cooking fuel source so less firewood needs to be cut. AD also provides quality fertilizers so less land needs to be cleared and converted to farmland because of soil degradation and exhausting of nutrients.

Indoor Air Quality

Under most circumstances, methane burns as a comparatively clean fuel. Compared to other fossil fuels, burned methane generates less atmospheric pollution and carbon dioxide per unit of energy (Chynoweth et al., 2001). Indoor air pollution is a growing and critical respiratory health issue in developing countries. Burning of solid fuels such as coal, charcoal, firewood and other biomasses emits black carbon in the form of smoke and particulate matter. This is neither ideal nor advisable indoors as it is detrimental to respiratory health; nor is it ideal to release smoke to the atmosphere when it can be avoided. Four major illnesses have been documented as a result of poor indoor air quality in developing nations and include childhood respiratory infections, adverse pregnancy results, chronic lung and heart disease, and cancer (Rowse, 2011). Cooking with solid fuel sources, especially in enclosed spaces is a problem which can be addressed by integrating biogas resources into cooking systems. Methane in the form of biogas has shown great potential as a cleaner source of energy and cooking fuel.

## 2.4 Discussions of Transdisciplinarity and Development Engineering

The concept of transdisciplinarity in regards to development project design can find roots in transdisciplinary research models. It is important to look at both the research and design models of transdisciplinarity when discussing it. Academic researchers are generally interested in transdisciplinary research because of its focus on merging the ideas of different specialties in a way which improves upon the shortcomings of a single discipline. Development endeavors need to be aware of the potential benefits that taking an approach with transdisciplinary perspectives can have. It's essential to be able to take the lessons that can be learned in transdisciplinary research and translate it into practical development actions.

### 2.4.1 Transdisciplinary Research

The idea of collaborative research between a physical scientist and a social scientist implicitly assumes that the distinctive benefits of their combined work are relevant in a problem-driven research scenario. Often times, we assume that researchers of differing specializations will fall into specific roles within a project model. This observation can divulge into a discussion involving the "Engaged Problem Solvers vs. Detached Specialists". With respect to development, the engaged problem solver is seen as one who is involved with solving quantifiable problems through integration of technology systems while the detached specialist provides a position of expertise and specialty in researching and understanding the complexities of issues. An engaged problem solver does not look at problems in an abstract manner; instead this person views them in a given problem context. Detached specialists will discuss and research issues in an abstract, context-free manner. To simplify this discussion, it is appropriate to think of these two groups in terms of physical and social scientists. Physical scientists can often be described as being focused on the question of "what" to implement to solve a problem. Social scientists, however, can often be more concerned with the question of "how" to implement a solution.

Transdisciplinary Research is a means to address large societal challenges while not compartmentalizing scientific and professional knowledge. According to Christian Pohl of the Swiss Academy of Sciences, on the subject of Transdisciplinary Research (TR), it is suggested that if challenges are reformulated and defined properly, "TR can be defined as research:

- That takes into account the complexity of an issue, meaning the complex system of factors that together explain the issue's current state and its dynamic,
- That addresses both science's and society's diverse perceptions of an issue, and
- That sets aside the idealized context of science in order to produce practically relevant knowledge.
- When the motivation for TR is based on socially responsible research, TR can also be defined as research that deals with the issues and possible improvements for the status quo that are involved in balancing the diverse interests and inputs of individual stakeholders and disciplines." (Pohl, 2005).

In regards to development, environmental research is a topic that often comes up. Quinlan outlines that the general idea of this is to identify and substantiate different ways to go about development by looking at the interactions between natural and social sciences. The idea is to generate a combination of thought and expertise of different scientists with respect to research methods, field work, and development (Quinlan et al., 2004). This is a classic model for the crossing and transcendence of traditionally perceived disciplinary boundaries.

### 2.4.2 Transdisciplinary Project Models

Transdisciplinary project models commonly feature design teams consisting of members with varied technical and educational backgrounds. A water resource development team may involve an environmental engineer, a water chemist, an anthropologist, and a few other specified team members. Often times, teams like this are better described as being interdisciplinary or multidisciplinary teams; the members making up the group work together and coordinate their efforts, but each specialty is specifically tasked with one aspect of the project. The difference between this organization and a transdisciplinary one is the emphasis of transcending the technical boundaries seen between the different team members. This does not mean that every member is fully involved in all aspects of the project, but it does imply more in-depth participation from each member in areas outside of their particular field of expertise.

One example of a program that successfully displays some levels of transdisciplinarity is the AMPATH group; a partnership between the Indiana University School of Medicine and Kenya's Moi University and Teaching and Referral Hospital which began in 2006 (Inui, 2007). AMPATH represents the effect that an academic medical partnership can have in response to the HIV/AIDS pandemic ravaging sub-Saharan Africa. This partnership had small beginnings as a group generally focused on general internal medicine of the problem and expanded to include several other outlets like agriculture and food services. Like all programs which make a long-term commitment, AMPATH knew that it must have a holistic project plan with visions and actions of sustainability (Einertz et al., 2007). Furthermore, AMPATH maintains a model which fully integrates the foreign and host groups with the local clients in a manner which is both transdisciplinary and transparent. By disclosing plans and the administrative arrangements to those receiving aid, AMPATH is able to address problems while remaining sensitive to fluctuations in the profile of those in need

(Einertz et al., 2007; Inui, 2007). Other groups involved in international aid can take heed of AMPATH's experiences and try to exude a transdisciplinary model to meet grand challenge be they health, energy, environment, water, or resource related.

A model which conveys aspects of transdisciplinarity is one which tries to address problems from multiple view-points. This model must integrate host communities and address the needs of the individual receiving aid from the perspective of said individual. Those receiving aid must truly come to "own" whatever form of aid that they are receiving; if a community is receiving a tractor, its members must be trained on how to operate and maintain it, if a community is receiving a fixed-dome biogas digester, its members must be involved in the planning and construction and be trained on its proper operation and maintenance. Simply giving a community a piece of technology, without attaching a program for learning and imparting a sense of responsibility for said piece of technology, is neither sustainable nor ethically responsible.

### 2.4.3 Inhibitors to Transdisciplinarity

It is often presumed that the differences between various sciences and disciplines are what get in the way of successful integration of ideas. While this is true to some extent, it can be suggested that larger problems lie within the inherent academic research model, including the organization of educational systems and funding agencies.

Contrasts between the approaches that different disciplines take in problem solving and research can contribute to difficulties in integration. Communicating ideas and concepts to people with differing educational and technical specialties can certainly prove difficult. Drawing from experiences with the United Nations, difficulties and hurdles arose when discussing different ideas and concepts regarding biogas resources. A majority of the staff and consultants working with UN-Habitat are professionally trained as architects. During a discussion with Sebastian Lange, a UN staff member of the Urban Energy Unit, the difficulties that a trained architect has with addressing topics such as biogas resources came to light. Sebastian referenced the initial problems that arose when discussing previously unfamiliar topics such as the biochemical processes of anaerobic digestion and engineering design of biogas reactors. Admittedly, this initially proved a problem when discussing maters with biogas technical specialists and advisors used by the organization. However, Mr. Lange expressed that communicating with people of different technical backgrounds should not be considered an obstacle in development; after all, learning how to communicate is simply part of human interaction and the challenges involved should not be used as an argument or excuse against cross disciplinary collaboration (S. Lange, Personal Communication, 11 April, 2014). Sharing ideas and concepts across educational and technical barriers is simply part of the human aspect of development; while it can be difficult, when one recognizes the importance of utilizing various analytical perspectives while addressing a particular problem or issue, one can see how critical it is to move past boundaries.

With regards to research methods, the academic model on the university scale is often blamed for difficulties in cross disciplinary cooperation. Class arrangements and categorizations during the semester is one of the factors which affects the prospects of transdisciplinary research; other factors also affect the ease of interdisciplinary cooperation, but those listed will be the points of concern in this discussion. The way that the academic model is organized compartmentalizes students, which naturally places barriers between students in different programs; barriers which are difficult to circumvent in a manner which is convenient while still remaining effective. In the university setting, classes need to be developed and hosted by a specific department; allowing classes to be open and available to students of many different disciplines is difficult, and can often limit the scope of the class (Nolan, 2002). When classes are limited to “Interdisciplinary” departments or designations, the ability to attract effective and pertinent professors and students can be difficult. Likewise, the semester schedule does not often allow for and coincide with effective student management with regards to project and research development. The organization of curriculums for certain majors also adds to the complications associated with opening up cross disciplinary courses.

### 2.4.4 Development Engineering

In the context of development engineering, an inclusive approach to problem solving as well as an understanding of the importance of varied perspectives on problem assessment is important to have. Development engineering can be seen as the employment of engineering principals in addressing problems found in developing regions and communities. Often times this manifests itself in the form of engineers attempting to solve problems which are prevalent in DRs in a manner which differs from traditional engineering practices. Engineers involved in development projects will need to recognize the connections between challenges because the contributions that they will potentially make are paramount in advancing civilization past them. With such a complex level of interconnectivity, engineers will need to recognize and embrace a method of analyzing problems from varying perspectives; a transdisciplinary model in analyzing and solving problems is important to adopt. By understanding in the intricate web of research spanning these sectors, engineers involved in international development will better grasp the implications inherent in the interactions between the sectors. It is important to note that engineering education programs need to adopt an idea of promoting the interconnectedness of challenges and  showcase how varied perspectives in the problem solving approach is necessary for a globally competent engineer (Bland, 2008; Downey et al., 2006; Allert et al., 2007; Lohmann et al., 2006).

There are a multitude of initiatives, councils, committees, boards, and organizations set in place making strides to assess and discus development plans and engineering solutions in developing regions, yet an equally fervent push towards initiating projects and generating actual solutions is not being made. It is one thing to set goals and numbers for development, yet another to make real, quantifiable progress to those goals. Policy makers are coming up with great ideas for improving the plights of energy poverty in developing regions, but the number of actual boots on the ground is not representative of the amount of talk that is happening. United Nations programs, ICSU initiatives, and programs from other similar groups are meant to serve as models for methods by which communities can develop their own resources (ICSU, 2007; UN-Habitat, 2012). These programs are not meant to come in and completely take over the development of a community's resources; those communities are meant to follow the examples and models which have been set in place to develop their own.

With that model, therein lie the shortcomings of development programs as their perceived purposes can differ from their actual purpose. This was addressed in a conversation with Fred Ochieng, the biogas resource specialist in the Urban Energy Unit of the UN-Habitat's Nairobi Urban Basic Services Branch. Mr. Ochieng iterated that UN-Habitat projects in general are not designed or purposed to be all encompassing solutions on a large scale operations. In Kibera and other large scale locations, projects like Multifunctional Clean Energy Centers need to be viewed as starting points, models for future development to be carried out by NGOs and the communities themselves and not by government organizations like the UN (F. Ochieng, Personal Communication, 14 February, 2014). Development engineering cannot be seen as an aid group coming in and fixing problems by providing technology or infrastructure or programs. Instead, such endeavors need to be accompanied by and really highlight education and training programs designed to teach the recipient communities to take ownership of their problems and the solutions for them.

## 2.5 Example Programs Promoting Sustainability and Collaboration

It is a known quantity that for community development to be effective, the community needs to be actively engaged. University academic teams, Non-Government Organizations, The United Nations, and other state supported groups are actively pursuing project implementation models which engage with and enlist the support of host communities. This section will make reference to a few groups and programs making these efforts so as to provide a context for the kind of atmosphere that projects in sustainable development are being formed in.

### 2.5.1 Purdue University International Awareness Involvement

Purdue University has a multitude of international partnerships ranging from traditional international study abroad institutional relationships to personal level relationships. This section will focus primarily on Purdue's community level engagement through international development projects with foreign universities and non-government organizations (NGOs). Purdue's international development projects are typically centered on engineering themed projects related to water and energy resources as well as mechanization and general development of agricultural systems. With the growing concern over long term project effectiveness, Purdue has made a few notable shifts towards managing its international teams with a greater emphasis on transdisciplinarity. As discussed, the university is involved in an array of development projects. A notable tendency in international development is the failure or discontinuance of a project solution after a few years. This can often be attributed to the tendency to simply "cut and paste" existing solutions into a system which may not be the same as the original. While successful design models should be referenced when working in different areas, it is important to remember that solutions must be specifically tailored to the location and specific situation. Purdue's teams have noted this trend and are working to reverse it by enabling its students to have a more broad range appreciation for project scope, analysis, and solution design. A method for achieving this is to underline the importance of recognizing multiple perspectives through a transdisciplinary design model.

Purdue's international programs and groups help prepare students for work in different nations and make efforts to include collaborative design models. Purdue's Global Engineering Program (GEP) has a model that encourages and promotes international collaborations through service-learning projects by bringing together graduate and undergraduate students from engineering and other pertinent majors to work with international partners that are addressing real world problems (Mohtar & Dare, 2011). In the spring semester of 2013, Purdue University piloted a new course focused on the discussion of sustainable global collaborations. The course, IDIS 590/491: Sustainable Global Collaboration, sought to explores the intersection of human interactions in social, technical, scientific, cultural, political, economic, and historic systems using a holistic approach to sustainable human experience (Alter et al., 2013). Dr. Riall Nolan, a Purdue professor in Anthropology, piloted a series of Engineering and Anthropology Workshops for students. The idea was to help disseminate some of the ideological differences between engineers and anthropologists with respect to development to improve the effectiveness that transdisciplinary teams can have when working together in development settings. Nolan brings recognition to the importance of using local knowledge to promote cultural sensitivity and increase a project's success in a global setting, stating that, "Until quite recently, the development industry has not really recognized this need to learn [about cultural worlds], but has concentrated instead on trying to impose an essentially ethnocentric view of progress on other countries, with highly valuable results" (Nolan, 2002).

### 2.5.2 UN-Habitat: Multifunctional Clean Energy Centers

Vincent Kitio, the director of the Urban Energy Unit of the Urban Basic Services Branch within the UN-Habitat, expressed the purpose of UN development programs as being a demonstration to the member states and their citizens of how issues and problems can be addressed in a responsible and appropriate manner. He implied that United Nations development programs, as opposed to programs run by private firms, are not meant to be capital generating operations; they are meant to be examples of development strategies. Solutions that are generated in one location to address a specific and widely distributed problem can serve as a basis for how the same problem can be approached and addressed in another, similar location. (V. Kitio, personal communication, January 30, 2014).

Multifunctional Clean Energy Centers are an example of a program which is generating results. MCECs are community service centers purposed for the provision of modern basic facilities including sanitation, safe water, and energy, particularly in urban and semi-urban slum areas with otherwise limited access. The MCEC and bio-center initiative brings together the resources and expertise of several groups that share common interests in ecological sanitation, waste management, energy access, and slum upgrading to build multi-purpose service points which are designed to improve access to adequate and affordable basic services. The centers are designed to utilize locally available energy resources such as human waste, solar, wind, and hydropower using Renewable Energy Technologies (RETs).The main components of these centers are the biogas digesters which are fed by human waste which comes from the latrines which are made available to the community within the bio-centers (UN-Habitat, 2012). According to Dr. Kitio and Mr. Ocheing of the UN-Habitat's Nariobi Urban Energy Unit, UN sponsored MCEC project are planned, constructed, and operated in full cooperation with the recipient community so as to ensure long-term acceptance of and sustainability of the project. These centers serve as instructional prototypes to the communities and other organizations can replicate and improve upon the designs (V. Kitio, F. Ochieng, personal communication, January 30, 2014)

# CHAPTER 3. DESIGN TOOL AND CONSTRUCTION MANUAL DEVELOPMENT

## 3.1 Design Model

In any biogas design program, it is important to have a method of estimating the amount of biogas that can be produced at a site. Additionally, biogas programs in development situations need to have an easy and effective method of estimating the necessary size of a digester. Too often, digesters are sized based off of the familiarities and preferences of the designer and not on the amount of inputs available and the existing resources in an area. The UN-Habitat's Nairobi Urban Energy Unit expressed an interest in the development of a worksheet tool that can be used to estimate the size of a digester based on the amount of inputs available. It was also necessary for this tool to estimate the amount of biogas that could be produced in a particular situation. The development of this worksheet will be explained in the following sections. It should be noted that the equations used for generating these figures were collected by the biogas resource specialist in the unit, Fred Ochieng. Mr. Ochieng had previously attempted developing a model which achieved the results stated above; however, this model was limited in its abilities and had an ungainly user interface (F. Ochieng, personal communication, 29 January, 2014). The development of the new model used lessons learned from the one previously worked on including reference equations, animal input types and material amounts, and retention times. The model is a Microsoft Excel worksheet. MS Excel was chosen because of its wide availability the ease of understanding its operation.

### 3.1.1 Model Inputs

There are two inputs which the user of the model is required to provide and include the type and number of animals whose waste will be collected and added to the digester as well as the average temperature in the region during the operation of the digester. The type of animal is important because it dictates the amount of material that will enter the digester. Furthermore, the waste from different types of animals has differing amounts of solid materials which are available for anaerobic digestion. Table 3.1 describes the physical characteristics of the waste from several different sources. The animals chosen; include the following: cow, pig, sheep, goat, horse, chicken, and human. The physical properties of the waste from these animals were collected by Mr. Ochieng from several different sources (Karki, 1984; Fulford, 1988; Steffen et al., 1998; ASAE, 2005). These animals were chosen by the Urban Energy Unit and are commonly seen in Africa and other developing regions.

Table 3.1: Animal waste physical properties (Karki, 1984; Fulford, 1988; Steffen et al., 1998; ASAE, 2005).

| **Input Source** | **Avg Daily Discharge (kg)** | **Total Solids (TS) (% by weight)** | **Volatile Solids (VS) (% of the TS by weight)** |
|---|---|---|---|
| Cow | 14 | 18 | 77 |
| Pig | 6 | 25 | 80 |
| Sheep | 3 | 14 | 76 |
| Goat | 4 | 15 | 77 |
| Horse | 10 | 37 | 84 |
| Chicken | 0.1 | 20 | 77 |
| Human | 1.3 | 10 | 79 |

UN-Habitat is most concerned with the potential biogas productivity in human settlements, using human waste resources, yet quantifying the properties of multiple waste sources is prudent. Additionally, the method by which waste is collected is a factor in estimating waste amounts. In this study, it is assumed that all of the waste from a particular source is available for digestion in an anaerobic digester. Take the properties of cow waste for example; an average sized cow is reported to generate 14kg of waste (reported as wet feed) per day, of that 14kg, 18% of the material, by weight, is solid with 77% of the solids being volatile solids. Volatile solids are those which are available for anaerobic digestion and are used to quantify the amount of biogas that will be produced (Fulford, 1988; Steffen et al., 1998; Rowse, 2011). Users are responsible for indicating the type of animal as well as the number in the population as the first step. The user interface (UI) for this step can be seen in figure 3.1. Users simply select the type of animal from a dropdown list and indicate the number of individuals in the population. Figure 1 shows a theoretical scenario of how a user could fill out this section.

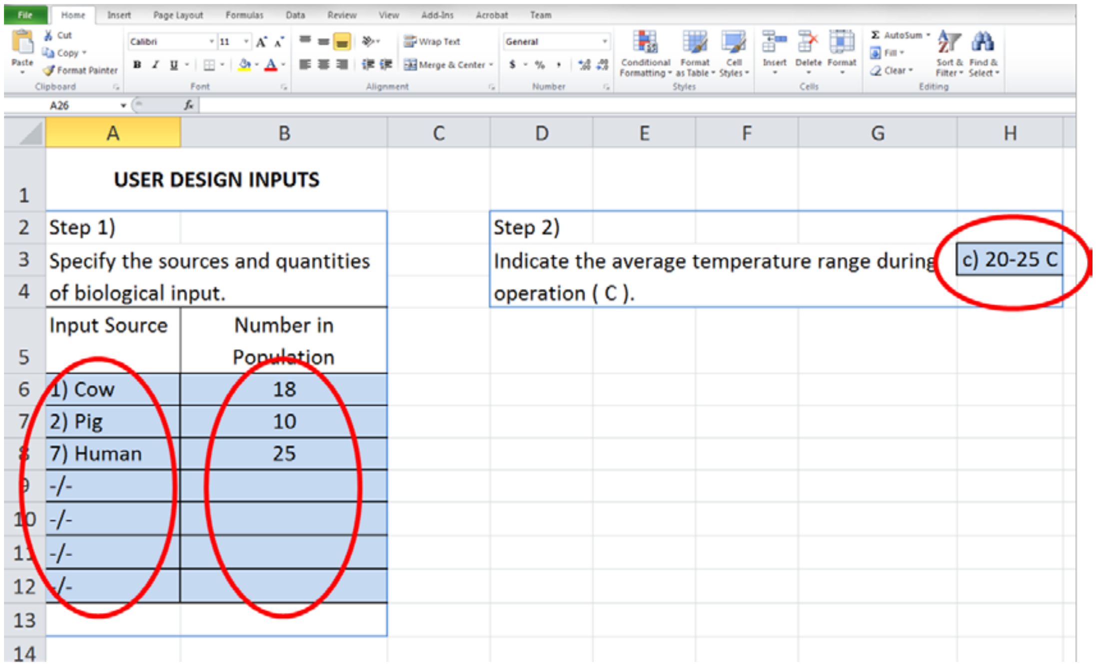



Figure 3.1: User interface, input sections.

The other user input for the model is the average temperature in the area during the operation of the digester program. Users indicate the temperature range for the desired area by selecting a range from a dropdown list. Temperature is a factor that affects the % and rate of VS degradation and coincides with a particular HRT. In the model, the temperature ranges, given in degrees Celsius, available for selection coincide with a designated HRT, in days, that the model will use to calculate digester size and the volume of biogas produced. Table 3.2 outlines the temperature ranges that can be selected and the HRTs that coincide with the ranges (Fulford, 1988; Karki, 1984).

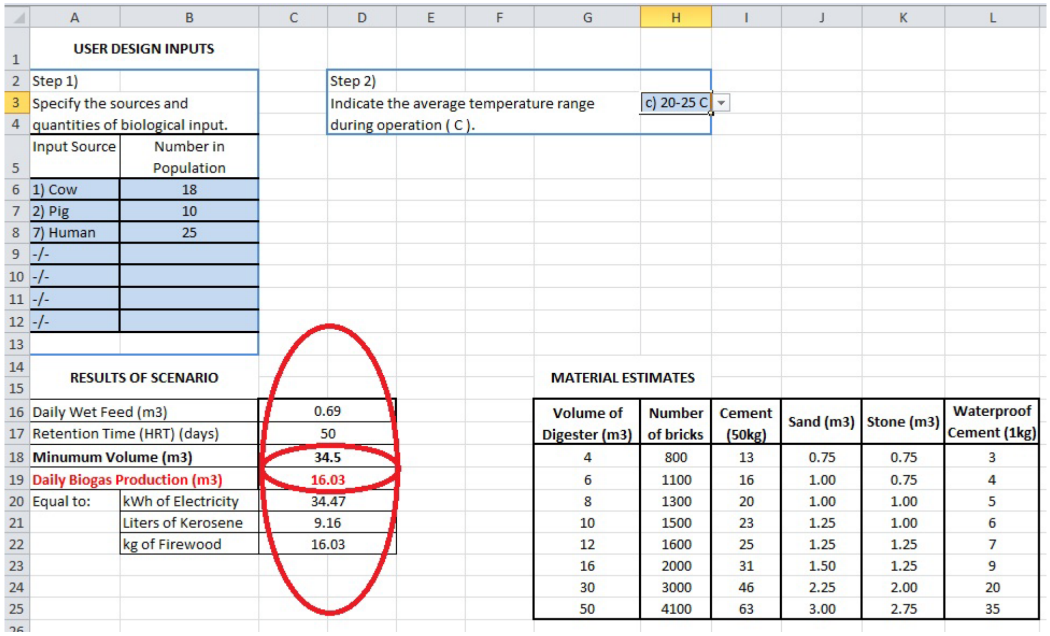
Table 3.2: Temperature and HRT relation (Adapted from Fulford, 1988; Karki, 1984).

| **Temperature Range ($^oC$)** | **Hydraulic Retention Time (Days)** |
|---|---|
| < 15 $^oC$ | 100 |
| 15-20 $^oC$ | 80 |
| 20-25 $^oC$ | 50 |
| 25-30 $^oC$ | 40 |
| 30-40 $^oC$ | 30 |
| >40 $^oC$ | 20 |

Figure 3.1 also shows the UI for selecting the temperature range of the digester site. Users simply select the range from a dropdown list and the model selects the appropriate HRT to insert into the calculations. With the amount of material available for digestion calculated, and the designed HRT selected, the model is capable of generating figures for the digester volume and the amount of biogas produced.

### 3.1.2 Model Outputs

The model calculates and reports the digester volume and the daily biogas production, both in cubic meters. Figure 3.2 displays the output that would be generated with the input indicated. The digester volume and the biogas produced are the primary outputs of interest. The model also reports the equivalent amount of electrical energy, kerosene fuel, and firewood generated by the biogas which is produced. These power sources are common in developing regions. Kerosene and firewood are common fuel sources for heat, light, and cooking sources. The following section will explain the calculations behind the model which generates the output given the user inputs.



**USER DESIGN INPUTS**

Step 1)
Specify the sources and quantities of biological input.

| Input Source | Number in Population |
|---|---|
| 1) Cow | 18 |
| 2) Pig | 10 |
| 7) Human | 25 |
| -/- | |
| -/- | |
| -/- | |
| -/- | |

Step 2)
Indicate the average temperature range during operation ( C ).

c) 20-25 C

**RESULTS OF SCENARIO**

| | | |
|---|---|---|
| Daily Wet Feed (m3) | | 0.69 |
| Retention Time (HRT) (days) | | 50 |
| **Minumum Volume (m3)** | | **34.5** |
| **Daily Biogas Production (m3)** | | **16.03** |
| Equal to: | kWh of Electricity | 34.47 |
| | Liters of Kerosene | 9.16 |
| | kg of Firewood | 16.03 |

**MATERIAL ESTIMATES**

| Volume of Digester (m3) | Number of bricks | Cement (50kg) | Sand (m3) | Stone (m3) | Waterproof Cement (1kg) |
|---|---|---|---|---|---|
| 4 | 800 | 13 | 0.75 | 0.75 | 3 |
| 6 | 1100 | 16 | 1.00 | 0.75 | 4 |
| 8 | 1300 | 20 | 1.00 | 1.00 | 5 |
| 10 | 1500 | 23 | 1.25 | 1.00 | 6 |
| 12 | 1600 | 25 | 1.25 | 1.25 | 7 |
| 16 | 2000 | 31 | 1.50 | 1.25 | 9 |
| 30 | 3000 | 46 | 2.25 | 2.00 | 20 |
| 50 | 4100 | 63 | 3.00 | 2.75 | 35 |

Figure 3.2: Design model outputs.

### 3.1.3 Model Calculations

The first figure calculated is the daily amount of digestible material fed into a digester. This figure is found using a set of equations which analyze the amount of digestible material present in each unit of manure. A single cow with physical characteristics similar to those used by the Urban Energy Unit will be used as an example; waste properties are seen in table 3.1. Using this example, the average 500kg cow produces about 14kg of manure, which is referred to as “wet feed” each day. Of that 14kg 18%, or 2.5kg, of the material is solid. Of that 2.5kg, 77%, or 1.94kg of material is considered to be “volatile solids” (VS) or “digestible feed” which are solids that are available for digestion and biogas production. The size of the digester is based on the figure related to the total amount of wet feed which will be introduced into the digester. The amount of biogas produced is related to the VS amount. In general, these figures will need to be expressed volumetrically (cubic meters) instead of by mass. To calculate this, equation 3.1 is used which calculates the daily wet feed (*v*) in cubic meters.

$$v = \frac{2w}{\rho} \tag{3.1}$$

Where:

*w* = total wet feed (kg/day)

*ρ* = the density of the feed, 1000kg/m3 when the material is properly mixed with water (Fulford, 1988; Steffen et al., 1998).

Retention time also affects the size of the digester. Hydraulic Retention Time (HRT) refers to the period of time that a quantity of digestible material remains inside the digester. HRT is defined as the total volume of a reservoir divided by the inflow rate, as summarized in the equation below where *V* is the total reservoir volume and *Q* is the material inflow rate expressed volumetrically (Rowse, 2011).

$$HRT = \frac{V}{Q} \tag{3.2}$$

One should first designate the HRT based on the ambient temperature of the region in which the digester is going to be built, as this is the largest factor effecting digester performance.

Once the volumetric amount of daily wet feed and the HRT are known, the volume of the digester can be calculated. The volume of the digester (*V*) is the volume of daily wet feed (*v*) multiplied by the retention time (*HRT*) in days (Rowse, 2011).

$$V = HRT * v \tag{3.3}$$

As stated, the amount of biogas produced is based on the amount of volatile solids present in waste material. The formula which will be used to calculate the daily biogas production is as follows:

$$g = \frac{C*V*S*k}{1+k*HRT} \tag{3.4}$$

Where:

*g* = the amount of biogas produced ($m^3$/day)

*C*= a dimensionless mathematical constant = 0.402

*V*= the internal digester volume ($m^3$)

*S*= Initial concentration of digestible material (kg/$m^3$) expressed as: (digestible feed (kg)/daily wet feed ($m^3$)

*k*= a dimensionless mathematical constant= 0.083

*HRT*= the hydraulic retention time measured in days (Karki, 1984; Fulford, 1988; Steffen et al., 1998).

A lower HRT is typically associated with a higher temperature, though in some situations it coincides with an incomplete anaerobic digestion process. In the case of this design for a digester program, it is assumed that the HRT reflects a complete digestion process. From this equation, it should be noted that lowering the HRT would also decrease the volume of the reactor needed and result in a mathematically lower amount of biogas produced given the same amount of input, indicating incomplete digestion. However, if the volume of the digester is held constant in the equation, and the HRT decreased, the amount of biogas produced per day would be higher, reflecting what would be expected in a situation with a higher temperature. So a fixed volume digester will produce more biogas per kg of feedstock and unit of volume in conditions with a higher temperature and shorter retention time. Temperature is the factor which defines the rate of VS decay, and by extension, the HRT.

For example, using the daily waste from 500 people in Kenya with a temperature zone of 20-25˚C, a digester will be 65$m^3$ with an HRT of 50 days and a daily biogas production of about 16$m^3$. Using these same inputs and raising the temperature range to over 40˚C, the resulting digester volume is 13$m^3$ with a 20 day HRT and 13$m^3$ of biogas produced per day, a figure which is not possible. We would expect to see a higher amount of biogas produced with this higher temperature which coincides with a shorter HRT, but since the digester volume is calculated based on the HRT, it also changes. However, if the volume of the digester is held at 65$m^3$ and the temperature is raised to over 40˚C with an HRT of 20 days, still using the waste from 500 humans as input, the daily volume of biogas produced would be over 30$m^3$. It is important to realize that using these equations to determine the volume of the digester relies on the designed HRT. It is therefore prudent to consider setting the volume of the digester and designing the HRT to suit the needs of the situation. Section 4.1 will further explore the outputs of the model using inputs of various operation scales. Additionally, a user manual for the biogas estimation tool is found in the appendix within the fixed-dome biogas digester manual.

## 3.2 Construction Manual Development

While working as an intern with the Urban Energy Unit of UN-Habitat's Nairobi office, the author was responsible for writing a construction and operation manual for fixed dome biogas digesters. The idea was for the manual to be used in-house for development purposes and distributed to interested parties. The UN generally relies on outsourced contractors to do the design, planning, and construction of biogas programs, but it was deemed highly useful for more resources to be developed by the Urban Energy Unit to diversify the knowledge pool. With that in mind, a manual was written to outline and instruct on the steps of sizing, selecting a site for, building, and operating and maintaining a fixed-dome biogas digester. UN-Habitat primarily deals with fixed-dome digesters in Africa and other warm, tropical developing regions because of the relative ease of construction, operation, and material sourcing. Some of the benefits of fixed-dome digesters are as follows:

- There are many variations of design and configuration; the fixed-dome digester construction design can vary to suit specific needs;
- Subterranean: takes up less space on the surface than other types of digesters;
- No moving parts: simple operation and maintenance;
- Relatively low construction costs: makes use of locally available materials; and

- Long operational life spans: when built properly and maintained well, they can last for 20-50 years (Fulford, 1988; Rowse, 2011).

There were four steps of interest that were specified in the construction manual and include:

1. The sizing of the digester;
2. Selecting an appropriate site for the digester;
3. Building the digester;
4. And operating and maintaining the digester.

The methods for developing the content of each of these steps will be outlined and expanded upon in the following sections.

### 3.2.1 Sizing the Digester

The size of the digester should be based on some of the logistics of the specific location. The manual and the model for estimating the size are based on three specific parameters including:

1. **The Feedstock:** including daily measurements of amount, type, physical properties, and mixing rations;
2. **The HRT:** largely affected by the ambient temperature, volume of inflow, type of digester used, and reservoir volume; and
3. **Gas Consumption and Energy Requirements:** proposed uses for the biogas and amounts needed.

Generally, the UN's development partners, such as the Kibera slum based NGO Umande Trust, build digesters of a standard size so as to make construction processed more uniform. Nelson Wamwayi, a representative of Umande Trust, an NGO which builds biogas digesters in community centers around East Africa, described some of the different applications in scale of the digesters they build. The different sizes cater to specific needs based in the parameters previously described and are outlined in table 3.3 (N. Wamwayi, personal communication, 4 March, 2014).

Table 3.3: Common digester sizes and purposes.

| **Digester size ($m^3$)** | **Size of operation** |
|---|---|
| 4 | Small single family |
| 6 | Small family, some animals |
| 8 | Small family, some animals |
| 10 | Family with animals |
| 12 | Family with animals |
| 16 | Family with animals |
| 30 | Many animals/small community |
| 50 | Community/Commercial size building/Many animals |

On occasions when a total volume greater than $50m^3$ is necessary, digesters are sometimes arranged in a series or parallel configuration with several uniform sized digesters accepting the load. Presently, larger digesters are still used, though UN-Habitat seems to be moving away from that trend because of higher rates of failure that have been observed.

The amount of feedstock which is available for use is the main deciding factor in designating the size of the digester. Additionally, the specific types of feedstock used, like cow manure versus human waste versus water hyacinth affect the amount of biogas which can be generated. The UN's main interest was in human waste because UN-Habitat deals primarily with urban settlements; however, the Urban Energy Unit wanted the model to include some common kept animal waste as well.

Retention time also affects the size of the digester. Temperature is a factor which dictates the rate at which feedstocks anaerobically digest; an offset of the HRT. The anaerobic bacteria which facilitate the digestion process are more active in warmer temperatures; specifically, methanogens are active in temperatures above 30˚C (Fulford, 1988). The time can vary greatly depending on the average and consistency of temperature. Table 3.2 outlines recommended HRTs used by the Urban Energy Unit based on the range of ambient temperatures (Fulford, 1988).

The amount of energy, and therefore biogas, that a site uses should also be considered when designing a biogas program. The proposed uses of the biogas, though, can affect how large or small the digester will be. In general, developing regions benefit from biogas in its use as a cooking, heating, and lighting fuel. Therefore, considerations should be made as to the amount of gas needed for these purposes. Table 3.4 can be used to gauge the amount of gas needed by showing the estimated energy equivalents of $1m^3$ of biogas (Marchaim, 1992; Nijaguna, 2002; Banks, 2009).

Table 3.4: Biogas equivalents to other energy sources (Adapted from Marchaim, 1992; Nijaguna, 2002; Banks, 2009).

| **Energy Source** | **Units replaced/generated by 1m$^3$ of biogas** |
|---|---|
| Electricity | 2.15 kWh |
| Gasoline | 0.6 Liters |
| Diesel | 0.55 Liters |
| Kerosene | 0.6 Liters |
| Firewood | 1 kg |

For example, if a family usually uses 1 Liter of kerosene per day, they would need a little over 2 m$^3$ of biogas produced by their digester each day. However, it is more common for sites in DRs to simply use whatever amount of biogas is available at the time. This figure can better serve as an indicator of the amount of energy that can be saved or replaced by an operation to promote economic benefits gained by adopting a biogas program.

### 3.2.2 Selecting a Site

The digester should be located near the waste material source to limit the amount of transportation and handling required. Additionally, it is beneficial to consider the distance from the digester to the point of use to limit the length of the gas pipeline. The site should have adequate soil physical properties and should have a substantial and reliable water source nearby for mixing. Soil at the site should have low clay content and be well-drained to deter water from being trapped in the soil surrounding the digester and limit heaving during weather and temperature events. The digester also has an outflow point, so considerations should be made regarding the location of the outflow relative to what is in the vicinity. For example, one would not want the outflow point to be near a well for drinking water. Several questions need to be asked and addressed when selecting a site and a community in which to install a biogas digester (Koottatep et al., 2003).

- What sort of water resources, including source, quantity, and quality does the community have access to?
- What is the source and amount of waste generated by the community?
- What are the physical and chemical characteristics of the waste material?
- What are the potentials for biogas generation of these materials?
- What are the energy consumption practices of the community that would be accounted for by supplementing biogas? (Koottatep et al., 2003).

One should consider the surrounding terrain and structures such as roads, pipelines, rivers, natural obstacles, and water sources near the proposed build site. It Is prudent to take into account construction locations in relation to where gas will be used and whether the client may look to expand building in the future. In the case of a digester located in a rural setting, proximity to animals and their pens should be considered (Figure 3.3).

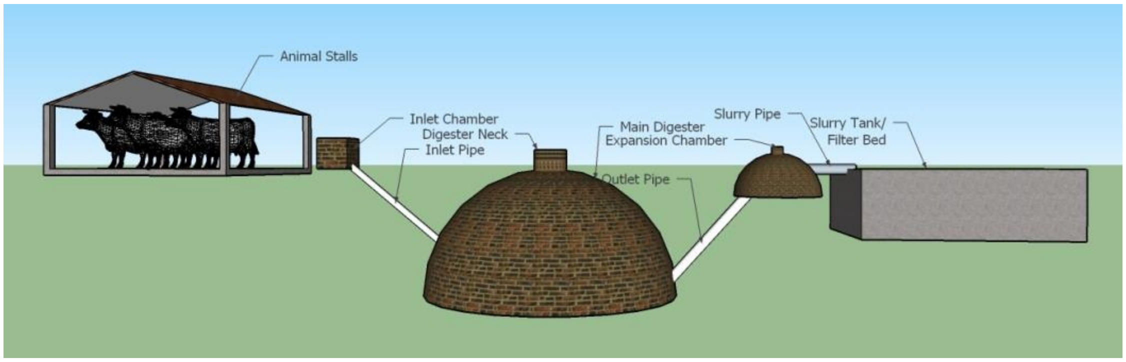



Figure 3.3 Digester proximity to animals and layout.

The digester should be oriented in a position which has some slope in elevation from the inlet point relative to the outlet. Digesters located in urban sites are commonly employed in community centers that provide services like communal toilets, showers, and other facilities. Selecting locations in these settings will require a large amount of community involvement. Ultimately, a site needs to be selected based on the people in the area. How many are close enough to and willing to use the center? Community members are more likely to select the location based on where it is most likely to be implemented. The center should be organized in a manner which utilizes the physical characteristics of the location to maximize the effectiveness of the digester and the convenience of its construction, operation, and maintenance.

### 3.2.3 Building the Digester

For the purpose of the manual, the construction process is broken down into 11 steps to ensure simplicity of instructions. Furthermore, compartmentalizing the construction process makes for an easier time managing and planning the procedure.

These steps summarize the construction of the three main components of the digester system which include the mixing chamber or inlet tank, the main digestion chamber, and the expansion or displacement chamber. The mixing chamber or inlet tank is where the waste material is mixed with water before it flows into the main digestion chamber. The dome-shaped main digestion chamber is where the biological waste materials ferment and gas is produced and digested material is pushed out by system pressure. Longevity and overall plant effectiveness rely heavily on careful and precise construction so it is critical that the main digestion chamber be air-tight to prohibit leakage (Fulford, 1988; KENDBIP, 2009). The expansion chamber, also called the displacement chamber, is where excess and digested material is allowed to flow out. The manual's construction steps are broken down into the following;

1. Layout and survey of site
2. Excavation
3. Digester foundation
4. Beginning construction of the digester
5. Placing the inlet and outlet pipe
6. Finishing the lower section of the dome
7. The weak and strong ring lower and upper dome section connection
8. The upper section of the dome
9. Construction of the expansion chamber
10. Construction of the mixing chamber
11. The main digester neck and lid

The steps and processes involved in construction were a compilation of resources developed and used by UN development partners and other international and domestic organizations (GTZ/GIZ, 1999; Koottatep et al., 2003; Karki et al., 2005; KENDBIP, 2009; SKG, 2013). The detailed construction process for the digester is outlined in the manual which can be found in Appendix A.

Materials and construction personnel are two components that cannot be over looked in any building project. Construction requires specialized personnel for an effective result. The number of people needed will vary based on the desired build speed, the funds and resources available, the people available and their skill level. In general, a mason is needed, as well as a person specializing in concrete. General laborers are also necessary, though they should be experienced in construction and supplemented by specialists. For example, a 10-16$m^3$ digester should have at least one mason, one concrete expert, and perhaps 2-6 laborers (KENDBIP, 2009; SKG, 2013).

In the construction of a fixed-dome biogas digester in a developing region, the materials needed are common and widely available in most places. The amount of materials needed for the construction will vary based on the design of the digester system. The volume of the digester will largely dictate the amount of materials needed. Specifically, the amount of cement, sand, stone aggregate, and bricks are of concern. Pipes and other similar hardware will need to be determined on site when logistics of positioning will be determined. Table 3.5 was used in the manual to describe the different materials needed including their purpose in the construction of the digester and key features to analyze when sourcing them (GTZ/GIZ, 1999; Koottatep et al., 2003; Karki et al., 2005; KENDBIP, 2009; SKG, 2013).

Table 3.5: Construction materials for a fixed-dome digester

| Material | Description |
|---|---|
| **Cement** | Cement will be used for most components in this construction. Fresh cement is best; a supplier should be found with access to supplies. |
| **Sand** | Sand particles of appropriate size should be found (<4mm). It needs to be free of earth, clay, and other components of soil. |
| **Stone aggregates** | Granite stone works best for casting cement in biogas digesters. It may be hard to find and more expensive, but the quality of stone provides a much better construction material. 20-25mm is preferred. |
| **Bricks** | The types of brick appropriate for construction vary. Solid bricks are preferred, if the dome is to be brick. Bricks must be well burnt and compacted with low porosity. Standard dimensions are typically 22x10x7cm. |
| **Pipes** | Typically, PVC pipe is used with great success. PVC is widely available and inexpensive. The uses include inlet pipe (10cm), outlet pipe (15cm) and gas line pipes (1-2cm). |
| **Pipe joints** | The right joints and bonding agents for the PVC pipes should be used. |
| **Flow control valve** | A valve is needed to control the flow of biogas out of the digestion dome |
| **Plaster** | Plaster is used as a sealing agent if brick is used to construct the dome. It seals the pores of the brick to prevent leakage. |
| **Sealant** | Sealants are used to prevent system leakage. This must be expertly applied as failures in fixed-dome digesters are most often due to leaks. |
| **Water** | Water is needed in most stages of construction: mixing cement, sealing the digester, mixing with the substrate, etc. Water availability needs to be seriously considered when choosing a site. |

In regards to the amounts of materials that are used in the standard sized digesters using the described construction processes, table 3.6 was made to estimate the amount of material that would need to be acquired. The development of table 3.6 made the following assumptions:

- Bricks used were standard 22x10x7 cm;
- The number of bricks is rounded up to the nearest 100;
- The number of bags of cement and waterproof cement are rounded up to the nearest whole number;
- The volumes of sand and stone are rounded up to the nearest 1/4$m^3$;
- 1:2:4 and 1:4 ratios are used for foundation building and plaster/mortar, respectively;
- The digester dome is constructed in a hemispherical configuration. The height of the digester is equal to the radius of the circular foundation;
- The expansion chamber is a hemispheric dome with a volume 1/3 that of the main digester;
- The inlet tank is a cube with an open top and volume equal to the daily feed.

Additionally, the amounts of brick and mortar materials are calculated by quantifying the volumes of the structures built (described in the appendix). So the volume of material used in the main digester, the expansion chamber, the mixing chamber, and the foundations was found and a few assumptions were made to give a rough estimate of the materials needed. The material estimates are meant to be seen as a guideline and not a specific figure. For the purposes of the manual, this was deemed adequate to help potential users compile materials.

Table 3.6: Digester construction material estimates

| Volume of Digester ($m^3$) | Number of bricks | 50-kg Cement bag | Sand ($m^3$) | Stone ($m^3$) | Waterproof Cement (kg) |
|---|---|---|---|---|---|
| 4 | 800 | 13 | 0.75 | 0.75 | 3 |
| 6 | 1100 | 16 | 1.00 | 0.75 | 4 |
| 8 | 1300 | 20 | 1.00 | 1.00 | 5 |
| 10 | 1500 | 23 | 1.25 | 1.00 | 6 |
| 12 | 1600 | 25 | 1.25 | 1.25 | 7 |
| 16 | 2000 | 31 | 1.50 | 1.25 | 9 |
| 30 | 3000 | 46 | 2.25 | 2.00 | 20 |
| 50 | 4100 | 63 | 3.00 | 2.75 | 35 |

### 3.2.4 Operating and Maintaining the Digester

The limited long-term success of anaerobic digestion systems is often attributed to poor system design, improper system installation, and inadequate system management (Beddoes et al., 2007). Additionally, capital costs associated with construction and operation, safety and handling issues, and the need for technical operational expertise and management can contribute to the difficulties in maintaining a successful biogas program (Beddoes et al., 2007). Therefore, the proper maintenance and organization of a biogas program is of the utmost importance; many of the failed programs have causes related to improper or inadequate management and maintenance (Fulford, 1988).

The digester will need to be properly seeded to begin working and should only begin after the civil works constructed have cured completely. Large quantities of manure or other waste material, as well as water, will need to be introduced and should be free of unwanted particles like trash, sand, wood, or other impurities. In general, the amount of material introduced for the seeding period should be equal to the amount of material which would be introduced under normal operation during the full retention time. So if the designed HRT is 50 days, then 50 days' worth of waste material and water should be the amount of initial feed. Manure from cattle, or other ruminants, is ideal for initial seeding as the manure already contains the bacteria necessary for anaerobic digestion; the digester start up times will be considerably less if the seed material already has the necessary bacteria (Fulford, 1988). If a different source is to be used, the digester should be catalyzed by adding the necessary bacteria; starter kits are also available in some places.

The digester should be fed via the inlet pipe so as to make sure no bulky substrate is able to enter which may otherwise clog the outlet. The lid should remain off during the initial filling and then sealed once the substrate has reached a point higher than the inlet point and equal to the necessary amount. The lid should be sealed with clay and kept in a water bath to prevent drying of the seal and gas leakage. Clay particles expand when they are wet and they stick to each other. So putting a layer of clay in between the lid and the fitting and then submerging it in a water bath creates an air-tight seal. The lid, which is already heavy, should be chocked with wooden blocks or a similar set-up to resist the building gas pressure and maintain air-tightness, as seen in figure 3.4.

Figure 3.4: Properly sealed digester lid

Fixed-dome biogas digesters require little maintenance in terms of intensity and in comparison to other types of digesters. Routine inspections of the entire civil work should be made periodically to check structural integrity and address any problems that may be found.

- Daily
  - Feed the digester
  - Inspect the inlet pipe and outlet opening and make sure they are clear
- Monthly
  - Wet the clay sealed lid
  - Check the gas lines for leaks
- Yearly
  - Open the main digester and stir the contents well
  - Clean out the expansion chamber and digester

The expansion chamber should be cleaned out periodically to avoid solids crusting in corners and flow pipes. The overflow slurry point should always be kept clear of debris.

A scum layer can form and harden in the main digestion chamber and should be broken up; else it can limit and disrupt gas production and substrate flow. This layer forms as indigestible materials rise to the top of the chamber and harden together.

If the digester is not well maintained or operational practices are not in good standing, it may be necessary to clean out the digester every few years as residue can build up. This can result in a long downtime and the digester would need to be brought offline and totally cleaned. However, if the digester is properly maintained and operation is within the design parameters, the digester could last for up to 50 years. From time to time, a concrete specialist (preferably the same one who helped with construction) should inspect the structure. In the manual, table 3.7 was used to depict possible problems, their causes, and solutions which are common to fixed-dome digesters in developing communities (KENDBIP, 2009).

Table 3.7: Fixed-dome biogas digester troubleshooting guide

| **Problem** | **Possible Cause** | **Possible Solution** |
|---|---|---|
| Insufficient gas pressure | Gas leakage along the line; inadequate feedstock | Check for leaks along the gas line and address accordingly, make sure the plant is fed adequately |
| Decrease in gas production | Underfeeding, leaks, scum formation, improper dung/water mixing, formation of solids in the digester | Ensure proper feeding, check for leaks, check and possibly clean out the digester |
| Offensive smell | Too much feedstock addition, leaks | Ensure proper feeding, check for leaks |
| Appliances not functioning well | Faulty appliance, leaks in gas line, inadequate gas production | Check appliances, check for leaks, check for gas production fixes |
| Thick effluent at overflow point | Incorrect mixing ratios, no movement of substrate inside the digester, water and slurry leakages | Maintain good mixing ratios, check for water leaks in the plant, make sure gas is used regularly to maintain systems pressure, empty the plant and reseal |
| Feedstock not entering the plant | Blocked inlet pipe, pipe position or mixing chamber height is incorrect | Clear out the blockage, check the height dimensions of the mixing chamber relative to the outlet and adjust if needed |
| Liquid entering the gas line | gas outlet pipe is positioned lower than the overflow point | Check the slurry overflow point for blockages, lower the overflow point |

## 3.3 Biogas Use

Biogas which is generated in developing communities is commonly used for simpler energy applications. Most often, the gas is directly burned for applications like cooking, lighting, and heating (Beddoes et al., 2007). Biogas is usually used as an energy source replacement and can also be used to expand operations. For example, biogas contains about 6KWh of calorimetric, or heat based energy, per $1m^3$. Biogas is an effective replacement for wood and kerosene, two common fuel sources in developing communities (Marchaim, 1992; Banks, 2009). Firewood and kerosene are commonly used for cooking and indoor lighting and their use, particularly firewood, contributes to problems with indoor air quality. As discussed previously, biogas burns more cleanly than other fuel sources and can help to mitigate air quality concerns (Rowse, 2011).

### 3.3.1 Small Scale Development Applications of Biogas Resources

Biomethanation, or anaerobic digestion, and biogas technologies have been widely used in developing communities for over 80 years. China, India, and Africa were locations where the development of simple biogas technologies and resources were concentrated, while Latin America has also seen rich research and development periods (Fulford, 1988; Ni et al., 1994; GTZ/GATE, 1998). Fixed-dome biogas digesters, those of interest in the biogas manual developed for UN-Habitat, were pioneered in China while the floating-drum design first surfaced in India; both of these digesters types are commonly used in development projects in places like Africa. GIZ, also called GTZ or GATE, the German Federal Enterprise for International Cooperation, was responsible for a large amount of biogas program development in Africa in the past few decades and pioneered much of the technology and program designs seen there (GTZ/GATE, 1998; GTZ/GIZ, 1999). Most often, the technologies are used specifically for generating biogas to be burned directly.

Biogas can easily be used as a quality fuel source for cooking and heating. In its basic, natural form, biogas is well suited for direct burning. In instances such as these, biogas can function in much the same manner as kerosene.  Biogas can be piped directly from the source within the digester to the burner, where it needs to be mixed with air to burn well. The images below (figures 3.5, 3.6, and 3.7) are of several different biogas cooking burners and were taken in an MCEC, a prison, and a biogas research facility in Kenya, respectively. These particular burners were modified from commercially available kerosene stoves to run on biogas. Biogas stoves are commercially available, however, there are no industry standards for them in Africa and most are imported from China or India. Some biogas cook stoves are locally produced, but the quality and safety, specifically in East Africa, have little to no regulation.

Figure 3.5: MCEC cook stove

Figure 3.6: Prison cook stove

Figure 3.7: Research center cook stove with air mixing

Biogas can also be used much like propane or kerosene as fuel for gas lanterns. These can be small lanterns, like common camping lanterns, or street lights (Fulford, 1988). Figure 3.8 is a picture of a biogas lantern used in a UN sponsored multifunctional clean energy center in the Kibera slum of Nairobi, Kenya. Lanterns like this generate night time lighting in the centers and decrease the amount of electricity consumed. These lanterns function in much the same way as common kerosene or propane lanterns. In fact, kerosene or propane lanterns are often able to run off of biogas in their current state, or simply require a small amount of modification. Small interior lanterns are a common sight in biogas programs in developing regions.

Figure 3.8: Biogas lamp

Simple boilers and heaters can be fueled with biogas for their specific purposes; a practice which is widely seen in American and European agricultural applications where animal waste is digested to produce biogas (Beddoes et al., 2007). Boiler and heater technologies are not widely used in the biogas programs seen in developing countries; though their integration would not be difficult given the appropriate technology. Some of this is because the scale of most programs does not lend itself to these kinds of applications and there is not a notable need for them.

### 3.3.2 Biogas Upgrading

Biogas can be upgraded by means of cleaning and conditioning into a higher quality biomethane. At this time, some methods of upgrading biogas quality are not suitable in developing countries. Biomethane is a term used to refer to methane which was produced by the process of anaerobic digestion. It is essentially biogas which has been further processed to remove impurities and improve its quality to similar levels of pipeline methane gas. Biomethane is a more energy dense gas with benefits over biogas; including increased energy density, pipeline transportability, and the ability to be used in more sensitive systems. Biogas contains 60%-70% $CH_4$ by volume, which is not a suitable composition for use in gas engines or other applications that may require a higher quality gas. The upgrading process is important because it increases the heating value of biogas and increases the quality of it to meet standard requirements for different gas appliance

"Cleaning" and "conditioning" are different terms used to describe the physical processes of upgrading the properties of biogas and converting it into biomethane. The USDA uses the term "cleaning" to refer to removal of $H_2S$ and similar impurities from the gas and "conditioning" to refer to the removal of moisture and $CO_2$ (Beddoes et al., 2007). Treating biogas can be done through many techniques that vary in cost and availability, some of which are described in table 3.9 (Chen et al., 2010). Sometimes only one treatment process needs to be applied, depending on the desired purpose of the fuel. For example, gas engines for generating electricity have internal components that are sensitive to $H_2S$ and moisture, but are largely unaffected by carbon dioxide. Conversely, biogas engines for automobiles and trains require higher density fuels and $CO_2$ needs to be removed. Biogas which has been both cleaned and conditioned (biomethane) can be used to augment the natural gas grid as they have similar physical and combustive properties. Depending on the desired use of the biomethane, different methods can be used to clean the gas including chemical and physical absorption, adsorption, conversion to a different chemical form, and membrane separation. Filters, membranes, absorption mechanisms, and similar processes can be used to remove a wide range of other contaminants from biogas. The most widely used method for upgrading biogas is water washing, a process where biogas under high pressure flows through a column of water which removes contaminants. Other techniques can be used to clean biogas; figures related to their capital investments, operation and maintenance, biomethane production rates, and costs per amount produced can be seen in table 3.8. The original source table, which was compiled by Chen, Overholt, Rutledge, and Tomic, reports on the data and costs associated with upgrading biogas into biomethane. A section of the table is shown in table 3.8 (Chen et al., 2010). Investments for biogas upgrading should be made according to the resources and capital available; a higher cost technology may be more practical to use in a certain location as opposed to a lower cost one because of the differences in the annual operation and maintenance.

Table 3.8: Biogas upgrading options and estimated costs (Chen et al., 2010).

| Upgrade Method | Capital Investment ($) | Operation and Maintenance ($/yr) | Cost of upgrading ($/1000ft3) |
|---|---|---|---|
| $FeCl_3$ | $12,000.00 | $29,300.00 | $23.20 |
| Biological | $22,300.00 | $3,930.00 | $1.86 |
| Iron Oxide | $8,000.00 | $13,500.00 | $0.80 |
| Membrane (Separex™) | $970,000.00 | $29,100.00 | $2.13 |
| Water Scrubber | $2,130,000.00 | $5,500.00 | $0.38 |
| Glycol Dehydration | $43,000.00 | $6,440.00 | $0.02 |
| KOH-activated-carbon bed | $50,000.00 | $5,440.00 | $0.46 |
| Selexol ® Physical Absorbent | $1,200,000.00 | $491,000.00 | $5.08 |

# CHAPTER 4. SITE ASSESSMENTS AND RESULTS

## 4.1 Site Observations from UN Biogas Development Projects

The United Nations Office of Nairobi (UNON), one of the world's four United Nations headquarters, serves as the headquarters for the Human Settlements Program. The Urban Energy Unit, which is part of the Urban Basic Services Branch (UBSB), has a great interest in furthering the development of biogas resources as a means to address growing problems in access to modern clean energy sources. The unit was in need of a better model for estimating the biogas that could potentially be produced by the digestion of various biological materials. The unit did have a tool for estimating those figures, designed by Fred Ochieng, the UEU biogas specialist, but it was neither very easy to use nor very effective. Mr. Ochieng suggested that using the equations in the model which already existed would suffice in developing a spreadsheet which had a better user interface and a more concise and easily understandable set of outputs. The UEU had also been working on acquiring a construction manual for biogas digesters; at that point the unit had been working on getting a manual from one of the firms they consult with, but chief of the unit Dr. Vincent Kitio expressed that some firms are reluctant to divulge their process. The responsibilities and objectives of the internship and the research to be done with the UN-Habitat Urban Energy Unit are described by the following:

a) To design a program which can be used to assess the energy potentials of biogas systems of various scales based on a continuous process.
b) To develop a manual for the design, construction, operation, and maintenance of fixed-dome biogas digester programs.
c) To report methods for advancing biogas technology in developing regions past basic levels and improve the biogas output of digester programs.
d) To travel to and observe existing biogas digesters and provide comments and insight on their functionality and effectiveness.

The biogas manual took time to develop because of the assembly of several different resources for the construction process. There are very few resources which actually give an in-depth, step-by-step process for planning and construction; most resources describe the different components and give a rough overview of their construction. The manual also included a basic rundown of biogas applications which could be considered by users, and methods by which biogas technology in developing regions can be improved to generate more biogas. The manual was the key task of the internship with the UN as it serves as a resource that can be used to disseminate information to the public about biogas digesters. The UN has many resources which are focused on biogas, but it would seem that many of them are not easily or readily accessible by civilians. It was the hope of the staff in the UEU that this manual can be used to dispel some of the negative views on biogas programs by explaining the planning, construction, and operation processes more in addition to expanding on the biochemical processes involved.

### 4.1.1 Site Visit Summaries

Several different site visits to locations and centers which used anaerobic digesters for treating wastewater and generating biogas for fuel were made. The sites visited were located in Kibera and were bio-centers built by Umande Trust with UN funding. They are similar in design to the Multifunctional Clean Energy Centers briefly discussed in chapter 2. These centers were visited in an effort to improve the understanding of the place that anaerobic digesters have in development endeavors. The prisons which were visited at Homa Bay and Kisii were designed and built in conjunction with the Prisoner's Care Program (PCP) and the UN. The prison digesters do not function properly, so the site visits had the purpose of diagnosing the problems associated with them and planning for future follow up. These visits helped to improve the understanding of the roles that development and sustainability play in biogas programs. Additionally visiting both successful and unsuccessful project sites allowed for analysis of what factors influence the quality and long term viability of a biogas project. Original site visit reports are found in appendix B.

Kibera Bio-centers

Umande Trust is a non-governmental organization (NGO) that collaborates with the UN and a few other organizations in building and managing bio-centers in several different parts of East Africa, particularly in the Kibera Slum of Nairobi, where there are some 18 centers. Two different bio-centers were observed in Kibera;

the Muvi and Katwekera Tosha centers. The bio-centers are community centers with toilets, showers, and similar facilities whose wastewater feeds into biogas digesters. The services at the center including toilets, showers, water, cooking facilities, laundry rooms, and rental rooms are all pay as you use; rates are agreed upon between the NGO and the recipient communities to ensure fairness and feasibility. The Muvi and Katwekera centers serve 200-300 and 600-700 people daily, respectively. The trust designs centers and plans their organization with members of the recipient communities to ensure general acceptance, effectiveness, and design feasibility of the programs (N. Wamwayi, personal communication, March 4, 2014). These centers are practical examples of the MCECs described in chapter 2. There were a few lessons learned from this visit, chief of which was the importance of community inclusion in project development. Furthermore, Umande Trust displayed success at following up and providing a support structure for existing centers in a long term and sustainable manner. It is evident that these factors, community collaboration and long term support, contribute to a successful and sustainable project.

During one of the site visits, the opportunity arose to talk with some of the Kibera residents who used Umande Trust's bio-centers as well as a representative of the NGO about what life is like there and how bio-center projects are carried out. The NGO coordinates with recipient communities for the project (N. Wamwayi, personal communication, March 4, 2014). Expectations can be radically different from the reality of things and how preparation by research and remote communication is very different from actualities. Development engineers need to do as much on-the-ground development and communication as possible to better understand the realities of a project environment. The bio-centers in conjunction with Umande Trust are an example of a successful and sustainable biogas project. These projects have been successful to the point where communities will approach the aid organizations with the interest of receiving a center (N. Wamwayi, personal communication, March 4, 2014). These centers serve as an example of how technology and management can be combined to solve problems regarding the availability of urban basic services; expanded benefits were described in chapter 2. The bio-center programs show aspects of transdisciplinarity in that multiple parties and their perspectives are involved in the project processes.

The projects are successful because of the observed factors:

- Umande Trust includes community leaders and members in the planning stages of the bio-center: they agree on location, size, services provided and their prices, maintenance schedules, and what each party is responsible for
- Community members are trained on the operation and maintenance of the biogas digesters and the other facilities of the bio-centers
- The UN and Umande Trust maintain communication and a mutually beneficial relationship with each other
- Community members are hired as operators and managers of the centers during hours of business
- Capitol generation allows the center to become self-supporting

- The UN and Umande Trust meet with the operators and check up on the facilities periodically to ensure their condition and effectiveness
- Projects are publicized; attention, visibility, and transparency encourages the program to remain in good standing

UN and PCP Prison Programs

The UN and the Prisoner's Care Program (PCP) partnered to build and install digester programs at prisons in Kenya. Two of these centers were visited; the prison at Homa Bay and the prison at Kisii. The digesters were built to serve the prisoners and the officials at the prisons by treating their biological waste and producing biogas to be used for cooking. However, neither of the digesters at the prisons was functioning properly. The reasons for this can primarily be attributed to breakdowns in communication, improper training, and unfinished and flawed construction and design.

The Homa Bay prison is home to 410 prisoners and intended to be serviced by a $124m^3$ digester. The toilets and sanitation systems used by the prison are flush toilets which are supposed to be connected to the digester; however, the prison is frequently plagued by problems related to water shortage, meaning that toilets do not always have flushing capabilities. Furthermore, there was a noted lack of training programs set in place which resulted in a lack of knowledge related to the maintenance and operation of the digester. The importance of providing the recipients of aid with the appropriate resources and support knowledge related to the proper management and running of a program is evident.

The digester has not operated properly in its entire 15 month lifetime. Construction of the digester was completed in 2012; at which time, it was theoretically operational, pending proper seeding and subsequent management. At this point, the sewage generated by the prison does not flow into the digester at all. It is probable that the sewage does not flow into the digester because of problems associated with the elevations of the different works of the digester system. The waste collection point is not high enough relative to the input point of the digester. Because of this, there is not a substantial enough gradient to allow proper hydraulic flow of material through the transport lines.

The Homa Bay project did not perform as expected for the following factors:

- The prison officials were not properly involved with the project design process and did not receive training in operation and maintenance
- The design implemented was not sound in quality or design principle: the digester is much too big and was not specifically designed for the site, the sewage lines leading to the digester are clogged and disconnected, and the elevation levels do not enable hydraulic flow
- The stakeholder groups did not maintain communication or enact follow up procedures upon the completion of the primary construction stage

In general, the digester program at Kisii is performing better than the one in Homa Bay. Notably, the Kisii prison digester does function to some degree. The prison houses 1497 inmates, both male and female, as well as several staff members who are connected to the digester system. All of the prisoners use flush toilets but the sewage from the toilets is not presently connected to the digester. The digester is fed only about three times a week with the waste generated by just 3 cattle. At $124m^3$, the digester volume is very large relative to the current amount of waste which is being deposited; it is an appropriate size for the prison if all of the prisoner's waste was included. In this prison, the warden and many staff members were present at the time of construction and have at least some level of understanding with regards to the operational configuration of the digester program.

A channel for the waste to be brought to the inlet of the digester needs to be built. Furthermore, a method and system needs to be introduced which separates wastewater and water used for cleaning and disinfecting, as these chemicals are harmful to the fermentation process. The gas produced by the digester is an inadequate amount for beneficial use in the cooking locations. While there is, in fact, biogas being produced, it is of a quantity and at system pressure inadequate for sustained burning and cooking times. The system pressure is often too low for the gas to effectively reach the kitchens in the women's cell block of the prison. For the most part, the situation at Kisii would be improved by attaching the toilets to the digester; a task that should have been performed before the PCP and UN ended their construction. The Kisii project did not perform as expected for reasons similar to the Homa Bay project:

- The stakeholders did not maintain communication or enact follow up procedures upon the completion of the primary construction stage
- Prison officials were involved in the construction and received some operation training, but they did not receive adequate maintenance training
- Construction was not completed and the sewage lines were not connected

#### 4.1.2 Aspects of Successful and Unsuccessful Projects

Successful projects convey the following aspects:

- High levels of stakeholder collaboration during all stages of project development and the maintaining of long-term professional relationships;
- The use of sound engineering design principles;
- Appropriate levels of training and education imparted to recipient party;
- A method for being self-sufficient in operation of technology.

The two observed bio-center projects featured these aspects and can serve as a visible example of what techniques and project models are effective for long term function and sustainability. High levels of community involvement and collaboration with the aid agency during all stages of project development and continuing long-term relationships and observation of projects helps maintain long term success. Sound engineering in the design of the biogas program promotes an effective solution while methods of becoming self-sufficient allow for long project life-spans. The successes of the bio-centers support the claim that involving recipient stakeholders in development programs fosters a sense of ownership and responsibility for a project and the distributed technology.

Projects which do not succeed or meet the desired expectations may do so because of the following:

- Inadequate stakeholder collaboration during the different stages of the project;
- Difficulties in post-project follow up;
- Improper engineering design in the project planning;
- Lack of training and education procedures imparted to the recipient group.

The two prison projects displayed these factors to some degree. These projects featured some level of deterioration in communication among stakeholders. This can often happen because aid groups often have a set of procedures and funding schedules which can be difficult to coordinate with aid recipient groups. Those operating the digesters need to have the support and background necessary to do so, yet inopportune schedules and limited resources can detract from the provision of these. It is beneficial for the aid agency to have some ground level involvement in the project, yet limited resources can contribute to lower levels of that. To some degree, development projects sometimes rely on using past designs and technologies and do not tailor projects to the situation at hand. For example, the Kisii and Homa Bay prison biogas projects employed a very similar design with a $124m^3$ digester; the Kisii prison had a high enough population and input amount to warrant this, but the Homa Bay prison did not, giving credit to the idea of using engineering design principles specific to the task. These projects serve as an example of the importance of a multifaceted design process; one that includes all stakeholder parties in its development and allows for projects to be analyzed from multiple perspectives. It supports the claim that involving recipient stakeholders and training them in the operation and maintenance of a technological solution fosters a sense of ownership and responsibility of a project and the distributed technology.

## 4.2 Model Output Results Based on Theoretical Inputs

The spreadsheet designed for the Urban Energy Unit reports the estimated volume of a digester, the amount of biogas produced, the equivalent amounts of energy, and the materials needed for construction. All of these estimates are calculated by having a user quantify the amounts of material input and the HRT of the digester. This section will present the set of outputs which are found based on a set of theoretical inputs as described below (Figure 4.1). The inputs are created on a theoretical small rural village in Kenya based on averages observed by the author. The temperature range is set to 20-25$^{o}$C, a typical temperature range in highland Kenya. The temperature denotes the designed HRT for the biogas reactor.

**USER DESIGN INPUTS**

| Step 1) | |
|---|---|
| Specify the sources and quantities of biological input. | |
| Input Source | Number in Population |
| 7) Human | 30 |
| 1) Cow | 15 |
| 4) Goat | 30 |
| 2) Pig | 15 |
| 6) Chicken | 50 |
| -/- | |
| -/- | |

| Step 2) | |
|---|---|
| Indicate the average temperature range during operation ( C ). | c) 20-25 C |

Figure 4.1: Theoretical User Inputs

Based on these inputs, the resulting outputs are as follows (Figure 4.2). As can be seen, using the model, the total volume of the digester based on the previously described inputs should be at least 46.4m$^3$. It may be worth recommending that a larger digester volume be used. Using a volume larger than what is necessary could prove beneficial should the digester malfunction in some way or if the operation or animal populations feeding the digester expands.

**RESULTS OF SCENARIO**

| | | |
|---|---|---|
| Daily Wet Feed (m3) | | 0.93 |
| Retention Time (HRT) (days) | | 50 |
| **Minumum Volume (m3)** | | **46.4** |
| **Daily Biogas Production (m3)** | | **21.00** |
| Equal to: | kWh of Electricity | 45.14 |
| | Liters of Kerosene | 12.00 |
| | kg of Firewood | 21.00 |

Figure 4.2: Theoretical model results

In this instance, it is estimated that approximately 21m$^3$ of biogas would be generated daily, assuming the digester is fed accordingly each day.

In the chapter 3 section outlining the equations behind the model, it was referenced that the biogas production rates of the model are based on the HRT designated by the temperature and not the temperature itself. A higher temperature results in a shorter HRT and should also signify a greater amount of biogas production. However in this model, that is not the case. With this particular example, if the temperature range during operation is changed from 20-25$^o$C to 30-40$^o$C, the results are as follows in figure 4.3. Figure 4.3 compared to figure 4.2 shows that the digester volume is 27.8m$^3$ in place of 46.4m$^3$, since a higher temperature and thus a shorter HRT means a lesser volume of material is stored in the digester. The figure comparisons also report a smaller volume of biogas produced, 18.59m$^3$ compared to 21m$^3$; not what would be expected given the higher amount of biological activity resulting from the increased temperature.

| | A | B | C | D | E |
|---|---|---|---|---|---|
| 15 | | **RESULTS OF SCENARIO** | | | |
| 16 | | | | | |
| 17 | | Daily Wet Feed (m3) | | 0.93 | |
| 18 | | Retention Time (HRT) (days) | | 30 | |
| 19 | | **Minumum Volume (m3)** | | **27.8** | |
| 20 | | **Daily Biogas Production (m3)** | | **18.59** | |
| 21 | | Equal to: | kWh of Electricity | 39.97 | |
| 22 | | | Liters of Kerosene | 10.62 | |
| 23 | | | kg of Firewood | 18.59 | |

Figure 4.3: Results with higher temperature range

However, if the volume of the digester is held constant, as suggested in development programs, the amount of biogas produced increases as the temperature rises and HRT decreases. Figure 4.4 displays the results if the user locks the digester volume resulting from the previous scenario.

| | A | B | C | D | E |
|---|---|---|---|---|---|
| 15 | | **RESULTS OF SCENARIO** | | | |
| 16 | | | | | |
| 17 | | Daily Wet Feed (m3) | | 0.93 | |
| 18 | | Retention Time (HRT) (days) | | 30 | |
| 19 | | **Minumum Volume (m3)** | | **46.4** | |
| 20 | | **Daily Biogas Production (m3)** | | **30.98** | |
| 21 | | Equal to: | kWh of Electricity | 66.62 | |
| 22 | | | Liters of Kerosene | 17.71 | |
| 23 | | | kg of Firewood | 30.98 | |

Figure 4.4: Results from higher temperature and locked digester volume

The resulting output shows a notable increase in the amount of biogas produced; from $21m^3$ of biogas produced daily by a $46.4m^3$ fixed-dome digester to nearly $31m^3$ of biogas produced daily by a digester with the same volume but an HRT of 30 days instead of 50. It is assumed that the digesters are operated in a continuous feed configuration with feedstock added and biogas used on a daily basis. Therefore, it is recommended that users take this into account and consider setting the volume of the digester and optimizing the retention time accordingly.

The energy sources commonly used in domestic settings are also reported in the model output. Kerosene, firewood, and electricity are often used for cooking, heating, and lighting in developing regions like Africa. The model calculates the equivalent amounts of energy that are found in the amount of biogas generated by the digester by referencing the appropriate ratios seen in table 3.4 (Marchaim, 1992; Nijaguna, 2002; Banks, 2009). Gasoline and Diesel amounts are also reported to give another set of reference points but they are not used in the model because they are not commonly used in developing countries. A table like this is used to display the potential energy that can be produced by a digester and the sources it can replace, reducing the amount of capital that is spent for energy generation.

The output section of the model shows the amount of materials that the construction of the digester will require. These figures are to be seen as an estimate and the development of it was previously discussed in the third chapter. The assumptions behind the generation of table 3.6 were also discussed in this chapter so as to help ensure a beneficial estimate is provided. These figures are given so those interested in building a digester can estimate the costs associated with procuring the needed construction materials.

## 4.3 Discussions

Biogas programs in developing regions can greatly benefit communities by providing a clean source of energy and an effective method for treating waste water and biological waste. However, these programs would benefit from expanded involvement of stakeholder parties and the adoption of more transdisciplinary design models and processes. Both successful and unsuccessful digester programs, the Kibera bio-centers and the prison programs, were discussed and showcased the importance of community and stakeholder involvement. Projects benefit from having personnel who can provide different perspectives and professionals of varying disciplines. The benefits of including the groups discussed have been previously explored but the reasoning for their lack of inclusion should be noted. Consulting and including the recipient stakeholders in the development of a biogas digester program, and any other form of development, helps ensure long term acceptance and success of a program. Consulting with and including professionals and persons with varying disciplines and perspectives helps to make sure a solution can address a problem from multiple angles in a manner which can be deemed both robust and resilient. Addressing a problem and neglecting the community does not show respect for the community or allow them to have a sense of ownership and responsibility for the digester program while ignoring those with different backgrounds and perspectives can produce a one dimensional and weak solution. These practices are not always adopted because of the complications that they can introduce to a project's development.

It is common within the sustainable development community for larger organizations to contract project development out to smaller organizations, like NGOs. In cases like this, the large organization provides funding and management while it is often up to the contracted organization to explore an inclusive and transdisciplinary model for development. Future endeavors would benefit from the development of a program which includes more of the personnel and resources form the larger organization to increase involvement and opportunities to include a variety of perspectives. Simply providing funds and some oversight can neglect the other resources, in the form of personnel or experience, which a larger body can offer.

Biogas programs in developing regions suffer for a few reasons including inadequate training and education, ineffective maintenance methods, and poor support systems. In an effective biogas program, the community and stakeholders building and receiving a digester need to be trained and educated in the ways to operate a digester effectively. Again, as with the problems regarding a transdisciplinary and inclusive model, this sort of activity takes time and money and can seem to detract from the resources available. This is often the reason for the lack of doing. Furthermore, standards for training and educating do not exist so there is no set method for properly doing so. It is paramount that those receiving aid in the form of technology be trained and educated on how to operate, maintain, and repair it effectively. Currently, many larger aid based organizations do include training programs in their aid endeavors, and are generally successful; but occasionally, they do not have the level of effectiveness which is desired. On some level, this can be attributed to the fact that programs are sometimes contracted and not developed in-house with a standard method and process.

Many digester programs are started successfully but soon fail due to improper management and maintenance. This goes along with training and education again. Too often, the recipients of biogas technology are not given the tools which enable them to properly maintain and keep the operation of their digesters. The observations at the prisons in Kisii and Homa Bay support this claim. Without good maintenance, digesters can quickly loose function and be rendered useless. For example, if the contents of the main digestion chamber are not stirred periodically, a hard film will form on the surface of the substrate which does not allow for the generated biogas to be released into the storage chamber. Pipes clog, concrete cracks, and slurry outflow chambers eventually fill up. While generally low maintenance, biogas digesters need to be maintained properly, just like any tool or piece of technology. Yet if communities and recipients of aid are not instructed how to or enabled to maintain biogas resources and technology, these programs will eventually fail. Additionally the proper tools for construction, maintenance, and repair are needed on top of the skills and training that is needed. At present, there is little support infrastructure for biogas resources in programs in developing regions; there is little state or broad range private support for these projects.

With the list of factors detracting from the effectiveness of biogas programs, the question arises as to what practices can be enacted to circumvent these problems. It is easy to answer that question by saying, "train and educate the people, make sure they know how to maintain the digester, and build up infrastructure", but the reality is more difficult than just saying that. Biogas programs in developing countries would greatly benefit from the introduction of standards for development programs. Standards should be initiated that include education and training programs, construction methods, and maintenance and operational standards. Programs have to start somewhere, and the development of guidelines which standardize the enactment and operation of programs is a good place to start. Standards help to streamline development processions and help ensure a level of safety and effectiveness. They can help by easing the tasks that NGOs and development organizations currently have by making it so they do not have to organize and develop training and education programs on their own. Standards in African regions are typically developed by private organizations in conjunction with the state. With pressure taken off of development organizations to design training programs, their resources can be freed up for the actual design and construction. Furthermore, standardizing construction and operation ensures safe and effective digester programs. The state and local authorities are more likely to enact measures to improve biogas infrastructure if there are standards. A resource that has been standardized has a greater image of being more “official”; credence is given to the technology as being a worthwhile and effective endeavor.

The manual which was written for the Urban Energy Unit is an example of a resource which serves as a tool for the improvement and development of biogas programs. It is meant to help improve the access that people have to literature on biogas and awareness can be spread. It is hardly sustainable if the only communities that have access to biogas resources are those selected by governmental and nongovernmental organizations and communities lack the resources to pursue such endeavors themselves. Likewise, the model was designed to be improved and made available to the public so they can estimate the potential that their family, farm, or community has for energy production.

Ultimately it comes down to taking steps which improve the access that citizens have to biogas resources which enable them to pursue the development of biogas programs on their own. It is necessary to reduce, and eventually eliminate, the dependence that developing communities have on government and no government international and local aid agencies. It is the basic idea of ensuring that recipients are able to take ownership of and responsibility for the technologies that are made available. Without this, programs can never be sustainable. Development cannot be considered truly sustainable if those people whose resources and communities are being improved are reliant on the resources and expertise of another. True, a community can receive supplies or personnel from another place, but that can turn into a mutually and equally beneficial arrangement which is organized in a sustainable fashion. Development programs need a model of transdisciplinarity and community involvement to maintain and promote long term sustainability. The UN bio-center and MCEC program, in conjunction with Umande Trust and other organizations, is an example of the successful integration of a transdisciplinary model which involves stakeholders and design personnel from different background and specialties as well as the host communities in the development process. Successful transdisciplinary design models exist and are gaining ground in public visibility; it is time this practice reaches a critical mass and becomes a standard operational procedure in sustainable biogas development.

# CHAPTER 5. CONCLUSIONS AND RECOMMENDATIONS

## 5.1 Conclusions

The literature reviewed revealed that there are gaps linking transdisciplinary projects models to sustainable development. Similarly there are limited resources for small scale anaerobic digester operations and their design; including sizing equations and biogas production rates. Some of the gaps were addressed which were related to sizing equations and gas production rates for small scale operations in development situations. Contributions were made to the UN's literature and resources for biogas design, construction, and technology. Common designs and parameters seen in urban energy programs in developing nations were identified and explored while appropriate methods for enacting biogas technologies were discussed for their inclusion in program solutions.

The Excel spreadsheet design tool developed for the UN needs verification of its accuracy. This could be done by measuring the productivity of an actual digester in a developing region and comparing it against the output from the design tool. The only verification if received was that the biogas volume and the digester volumes estimated for 400 people was in the right range estimated by the UEU and the programs it is involved with. The assumptions made based on the waste produced by each type of animal and the gas which they produce are based on those made by the UEU from the Karki (1984), Fulford (1988), and Steffen et al. (1998) resources and need to be better verified against measured values and a variety of literature. The manual developed by the author for the UN needs to be published and distributed to those needing resources for biogas programs and technology.

Transdisciplinarity design models intersected with the biogas resources development by including persons with different perspectives in its development and by giving considerations to holistic approaches and project enactment. Biogas projects that the UN is involved in integrate the technical content by collaborating with community members receiving aid yet would be improved by increasing involvement from people of differing educations and perspectives. Model verification of the biogas tool, the manual, and the techniques of integrating biogas technology and transdisciplinarity is the best step for improving the sustainability of these resources.

## 5.2 Future Development

The gaps in the literature addressing the linking transdisciplinary projects models to sustainable development were explored, as were gaps regarding the literature for biogas resources in developing regions. There was no opportunity for the collection of a significant enough number of field data points regarding the functioning biogas digesters in terms of their performance, material input, biogas produced, and slurry output. It would be beneficial for the UEU to invest in monitoring systems for the biogas programs which they support. This would quantify the productivity of the digesters and help provide a benchmark for assessing drops in performance which could be attributed to malfunctions. Installing monitoring systems and programs would help to validate and improve the biogas production estimation model. The exact number of people, and therefore substrate input, was not clearly observed at the time of development. The model is based on theoretical values and has not been properly tested and validated. Simple pressure and flow gauges and sensors can be used to quantify inflow and outflow which indicate performance; failures or problems with the digester can be found much sooner. The design tool could be adjusted based on real-world waste quantities and gas production rates. The model was based on theoretical amounts for waste figures, which vary to some degree based in the source, and equations based off of UN figures and standards. As referenced in Chapter 4.1, regarding the model and the effect of the HRT on the output, the model does not report an increase in biogas production as the temperature in the region increases; a factor could be found, quantitatively, and insert into the equation, or a modified version of it, to adjust the biogas production based on the temperature effects. Another step could be to make the worksheet into a tool that could be used online or an application for mobile devices.

The fixed-dome biogas digester manual was designed to be used by the UN to aid in the development of biogas resources and distributed to improve public awareness of biogas technologies and options. Currently, the manual has been approved by the UEU and submitted for publishing to the UN's in-house publishers. Further work on the manual would include pursuing publication. The manual could be improved by field testing its effectiveness through surveys and discussions with NGOs doing biogas work and citizens with an interest in biogas technologies. The material lists could be better compared against the amounts of materials that are used. Additionally, improvements could be made by acquiring more photographic documentation to aid in visualizing certain steps and instructions in the construction process. Finally, the manual could be translated into other languages which are commonly spoken, such as the six official languages of the UN: Arabic, Chinese, English, French, Russian, and Spanish. Some manuals in these languages already exist, but a standardized manual would help bring more consistency.

The expansion of biogas programs into more prisons, schools, universities, and hospitals means that the physical properties of the inputs will vary. For example, the use of antibiotics and medicines in hospitals affects the waste properties and can prove harmful to the anaerobic bacteria. Future work in the design of anaerobic digesters in developing countries should include investigating the effects that contaminants can have on biogas yields. Furthermore, the methods by which biogas yields can be increased using existing small scale systems could be expanded upon. Additionally, industry standards for biogas technology and resources should be pursued to increase effectiveness, visibility, project transparency, and operational safety. The Association of Biogas Contractors in Kenya (ABC-K) are working on federally supported standards; a step in the right direction. In general, the support structure for biogas projects and the overall success of biogas programs can be improved with the addition of development resources and technological understanding.

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APPENDIX

# Appendix A Fixed-dome Biogas Digester Manual

Fixed-dome digesters first appeared in 1800s China, and are often referred to as Chinese dome digesters. Based on a simple design, dome digesters are essentially an underground masonry chamber with a dome fixed atop it. The chamber is typically constructed using brick or concrete, depending on the availability of material, personnel, and equipment. Gas is stored above the digesting substrate and is sealed by a cover on top of the dome. Commonly, the digester pit is constructed as a dome. The dome design is used because when under compression, domes are self-supporting; little extra reinforcement is needed. Feedstock is mixed in a mixing pit and fed into the digester through an inlet point. The inlet point should be in the actively digesting layer of the reactor. An expansion chamber sets adjacent to the main reactor where digested material is flows out of the digestion chamber. As pressure from the newly produced biogas builds up, it forces digested material into the overflow slurry reservoir via the displacement principle.

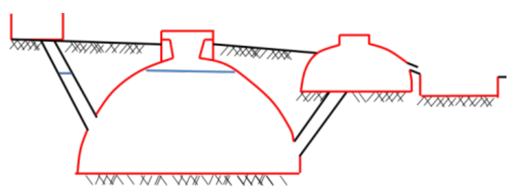

Figure A.1: No Gas Displaced

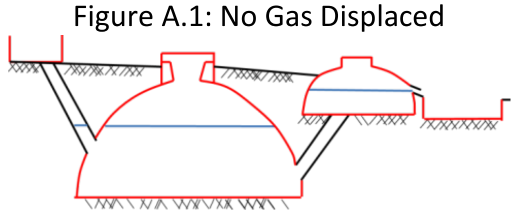

Figure A.2: Gas Displaced

Benefits of Fixed-dome Digesters

- There are many variations of design and configuration; the fixed-dome digester construction design can vary to suit specific needs. Digester configurations can vary dramatically by size, or installed in series or parallel.
- Subterranean: takes up less space on the surface than other types of digesters;

- No moving parts: simple operation and maintenance;
- Relatively low construction costs: makes use of locally available materials, requires precision and expertise to ensure structural integrity and adequate sealing; and

  Long operational life spans when maintained properly: when built properly and maintained, fixed-dome digesters can be used effectively for 20-50 years.

Figure A.3: Digesters in series

Size Selection

Sizing the reactor is based on three specific parameters:

- **The Feedstock**: including daily measurements of amount, type, physical properties, mixing ratios;
- **The Hydraulic Retention Time**: largely affected by temperature, volume of inflow, and reservoir volume; and
- **Gas Consumption and Energy Requirements**: proposed uses for the biogas and amounts needed

In general, digesters are built to a set standard size to make construction processes more uniform. Size options cater to specific needs based on input amounts and biogas usage.

Table A.1: Common Digester Sizes

| Digester size (m3) | Size of operation |
|---|---|
| 4 | Small single family |
| 6 | Small family, some animals |
| 8 | Small family, some animals |
| 10 | Family with animals |
| 12 | Family with animals |
| 16 | Family with animals |
| 30 | Many animals/small community |
| 50 | Community/Commercial size building/Many animals |

The Feedstock

Different animal manures have different physical properties which contribute to the amount of biogas which can be produced. Different animals also produce different amounts of manure each day.

Table A.2: The number of animals whose manure will generate $1m^3$ of biogas

| Type of Organism | Number of organisms requiring 1m3 of total digester volume |
|---|---|
| Human | 8 |
| Cow | 1 |
| Pig | 2 |
| Chicken | 100 |
| Horse | 1 |
| Sheep | 3 |
| Goat | 3 |

The table shows an estimate of the number of animals accounting for $1m^3$ of digester volume based on average daily waste. For instance, the waste from 8 humans calls for at least $1m^3$ of digester volume. A $50m^3$ digester could potentially handle the waste from up to 400 people.

Hydraulic Retention Time

Hydraulic Retention Time (HRT) refers to the period of time that a quantity of digestible material remains inside the digester. HRT is defined as the total volume of a reservoir divided by the inflow rate, as summarized in the equation below (where *V* is the total reservoir volume and *Q* is the material inflow rate expressed volumetrically.)

$$HRT = \frac{V}{Q}$$

The designed HRT is based on the ambient temperature of the digester's and this is the most critical factor in digester performance. The time can vary depending on the average temperature and consistency. In general, anaerobic digesters which are not heated or otherwise improved are better used in warmer, tropical climates. This table outlines recommended HRTs based on the range of ambient temperatures.

Table A.3: The relation between temperature and HRT

| Temperature ( C ) | HRT (Days) |
|---|---|
| < 15 | 100 |
| 15-20 | 80 |
| 20-25 | 50 |
| 25-30 | 40 |
| 30-40 | 20 |
| >40 | 10 |

As an example, if a region is best suited for an HRT of 50 days, the volume of the digester should be equal to 50 times the average daily load. Multiply the HRT by the daily inflow (*Q*) to get the minimum recommended digester volume (*V*).

$$HRT * Q = V$$

Gas Consumption and Energy Requirements

This factor is somewhat limited by the first two. The amount of biogas that can be generated per day is based on the amount of waste material available. The proposed uses of the biogas, though, can affect how large or small the digester will be. In general, developing regions benefit from biogas in its use as a cooking, heating, and lighting fuel. Therefore, considerations should be made as to the amount of gas needed for these purposes. This table can be used to gauge the amount of gas needed.

Table A.4: Biogas equivalent to common fuel sources

| Energy Source | Units replaced/generated by 1m3 of biogas |
|---|---|
| Kerosene | 0.6 Liters |
| Firewood | 1 kg |
| Electricity | 2.15 kWh |

For example, if a family usually uses 1 Liter of kerosene per day, they would need a little over 2 $m^3$ of biogas produced by their digester each day.

Site Selection

The digester should be located near the source of the waste material to limit the amount of transportation and handling required. As an added benefit, this helps limit the length of the gas pipeline from the digester to the burner (or whatever mechanism is consuming the biogas.) The site should have adequate soil physical properties and should have a substantial and reliable water source nearby for mixing. The soil in the site should have low clay content and be well-drained. The digester also has an outflow point, so considerations should be made as to the location of the outflow relative to what is in the vicinity. For example, you would not want the outflow point to be near a well for drinking water.

Several questions need to be asked and addressed when selecting a site and a community in which to install a biogas digester.

- What sort of water resources, including source, quantity, and quality does the community have access to?
- What is the source of waste generated by the community?
- How much biological waste material available for use in biogas digesters is produced by the community?
- What are the physical and chemical characteristics of the waste material?
- What are the potentials for biogas generation of these materials?
- What are the energy consumption practices of the community that would be accounted for by supplementing biogas?

Consider the surrounding terrain and structures: Roads, pipelines, rivers, natural obstacles, and water sources? Consider locations in relation to where gas will be used. Consider whether the client may look to expand building in the future.

Rural Sites

In the case of a digester located in a rural setting, proximity to animals and their pens should be considered.

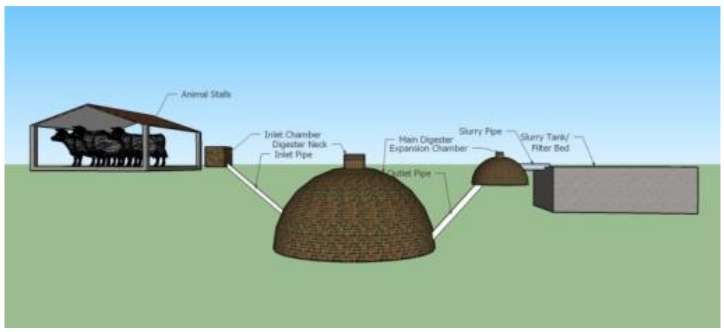


Figure A.4: Digester proximity to feedstock source

It is ideal that the digester be oriented in a position which has some slope in elevation from the inlet point relative to the outlet.

Urban Sites

Digesters located in urban sites are commonly employed in community centers that provide services like communal toilets, showers, and other facilities. Selecting locations in these settings will require a large amount of community involvement. Ultimately, a site needs to be selected based on the people in the area. How many are close enough to and willing to use the center? Community members are more likely to select the location based on where it is most likely to be implemented. The center should be organized in a manner which utilizes the physical characteristics of the location to maximize the effectiveness of the digester and the convenience of its construction, operation, and maintenance.

Constructing the Fixed-dome Biogas Digester

Construction Components

There are three main component sections of a fixed-dome biogas digester. The **mixing chamber/inlet tank** is where the waste material is mixed with water before it flows into the main digestion chamber. The dome-shaped **main digestion chamber** is where the biological waste materials ferment. Gas is produced in the main chamber and digested material is pushed out by system pressure. The **expansion/displacement chamber** is where excess and digested material is allowed to flow out. Longevity and overall plant effectiveness relies heavily on careful and precise construction. It is critical that the main digestion chamber be air-tight to prohibit leakage.

Figure A.5: Main digester and expansion chamber

Construction Materials

The materials needed to construct a fixed-dome biogas digester are common and widely available in most places. The amount of materials needed for the construction will vary based on the design of the digester system. The volume of the digester will largely dictate the amount of materials needed. Specifically, the amount of cement, sand, stone aggregate, and bricks are of concern. Pipes and other similar hardware will need to be determined on site when logistics of positioning will be determined. The following table summarizes the materials needed and describes what they will be used for and key features to analyze when sourcing them.

Table A.5: Construction materials

| Material | Description |
|---|---|
| **Cement** | Cement will be used for most components in this construction. Fresh cement is best; a supplier should be found with ready access to fresh supplies. M20 Portland grade is recommended. |
| **Sand** | Sand particles of appropriate size should be found (<4mm). It needs to be free of earth, clay, and other components of soil. |
| **Stone aggregates** | Granite stone works best for casting cement in biogas digesters. It may be hard to find and more expensive, but the quality of stone provides a much better construction material. 20-25mm is preferred. |
| **Bricks** | The types of brick appropriate for construction vary. Solid bricks are preferred, if the dome is to be brick. Bricks must be well burnt and compacted with low porosity. Standard dimensions are typically 22x10x7cm. |
| **Pipes** | Typically, PVC pipe is used with great success. PVC is widely available and inexpensive. The uses include inlet pipe (10cm), outlet pipe (15cm) and gas line pipes (1-2cm). |
| **Pipe joints** | The right joints and bonding agents for the PVC pipes should be used. |
| **Flow control valve** | A valve is needed to control the flow of biogas out of the digestion dome |
| **Plaster** | Plaster is used as a sealing agent if brick is used to construct the dome. It seals the pores of the brick to prevent leakage. |
| **Sealant** | Sealants are used to prevent system leakage. This must be expertly applied as failures in fixed-dome digesters are most often due to leaks. |
| **Water** | Water is needed in most stages of construction: mixing cement, sealing the digester, mixing with the substrate, etc. Water availability needs to be seriously considered. |

Cement should be mixed according to the preferences of the specialist, based on the conditions of the area. Make sure to soak bricks before they are used; wet bricks adhere to mortar and plaster much better than dry bricks. The next table estimates the amounts of brick, cement, sand, and stone needed based on standard digester volumes. The table makes the following assumptions:

- Bricks used were standard 22x10x7 cm

- The number of bricks is rounded up to the nearest 100
- The number of bags of cement and waterproof cement are rounded up to the nearest whole number
- The volumes of sand and stone are rounded up to the nearest 1/4m$^3$
- 1:2:4 and 1:4 ratios are used for foundation building and plaster/mortar, respectively
- The digester dome is constructed in a hemispherical configuration. The height of the digester is equal to the radius of the circular foundation.
- The expansion chamber is a hemispheric dome with a volume 1/3 that of the main digester
- The inlet tank is a cube with an open top and volume equal to the daily feed

The table should be seen as a guideline only and not an exact measure of supplies.

Table A.6: Material estimates based on digester volume

| Volume of Digester (m3) | Number of bricks | Cement (50kg) | Sand (m3) | Stone (m3) | Waterproof Cement (1kg) |
|---|---|---|---|---|---|
| 4 | 800 | 13 | 0.75 | 0.75 | 3 |
| 6 | 1100 | 16 | 1.00 | 0.75 | 4 |
| 8 | 1300 | 20 | 1.00 | 1.00 | 5 |
| 10 | 1500 | 23 | 1.25 | 1.00 | 6 |
| 12 | 1600 | 25 | 1.25 | 1.25 | 7 |
| 16 | 2000 | 31 | 1.50 | 1.25 | 9 |
| 30 | 3000 | 46 | 2.25 | 2.00 | 20 |
| 50 | 4100 | 63 | 3.00 | 2.75 | 35 |

Construction Personnel

Construction requires specialized personnel for an effective result. The number of people needed will vary based on the desired build speed, the funds and resources available, the people available and their skill level. In general, a mason is needed, as well as a person specializing in concrete. General laborers are also necessary, though they should be experienced in construction and supplemented by specialists. An average sized digester (10-16$m^3$) should have at least one mason, one concrete expert, and perhaps 2-6 laborers. Furthermore, if excavation is mechanized, it is assumed that the operators be skilled and competent.

Setting up the guide stick

The guide stick, or radius stick, is used to maintain the proper radius when building the main digester dome and the expansion chamber. The method for assembling this tool can vary. Essentially, the stick needs to be able to mark the proper radius and have one end fixed in the center of the digester while being able to pivot. It can simply be a stick which is cut to the needed length and attached to a pivot point. It can also be a telescoping stick with an adjustable length.

Figure A.6: Using the guide stick

Mixing mortar/plaster and concrete

In this construction, the mortar and plaster are generally mixed using the same ratio of 1:4. The first number refers to the ratio of cement in the mixture while the second indicates sand. For every volume unit of cement, there should be 4 volume units of sand. The flowing describes the preparation of mortar.

1. Mix 1 part of cement with 4 parts of sand until it is well blended

2. Slowly stir in clean water to the mixture; water should be added and the mixture stirred until the plaster is a thick, creamy substance with no lumps
3. Do not mix more than what will be used in about 1 hour

Concrete and cement are often used interchangeably. Cement is actually a component of concrete. In this manual, cement will refer to the bags of powder which are mixed to form mortar, plaster, and concrete, while concrete will refer to the mixed material used for foundation building. Concrete is mixed in 1:2:4 ratios; 1 part cement, 2 parts sand, and 4 parts stone aggregates. The preparation of concrete is similar to mortar. However, the concrete should have water added and be mixed until it has a consistency that allows it to stick together but still form clumps.

Step 1: Layout and Survey of Site

The site needs to be planned out and the layout of the digester arranged. The site will need to be surveyed and include elevation and dimension data. The completed digester system shown in this construction manual will have a side profile similar to the figure below.

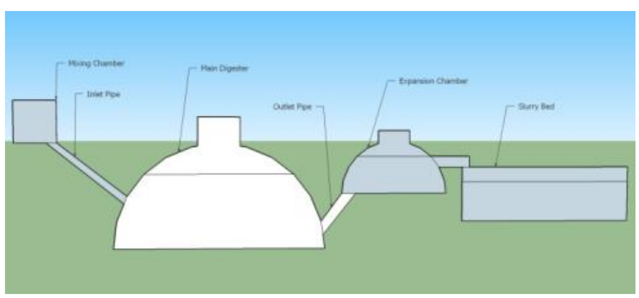


Figure A.7: Digester Profile

A simple layout has to be made for the excavation of the pit which designates the position of the main digester. The locations of the mixing chamber and displacement need to be addressed relative to the best location for the main digester. The layout must be done carefully and precisely. A peg can be placed at the center location for the digestion chamber attached to a rope with the same length as the outer radius of the chamber.

Set the reference line

A reference line needs to be set and is used in construction to keep levels. The line is a string connecting two leveled points passing through the center of the plant and is the elevation point of reference during construction. The line is set at 1 meter above the overflow point of the expansion chamber. See the following instructions and diagram.

1. After outlining the plant, erect a 1.5m post (1)at the inlet mixing chamber
2. Place a peg (2) at the slurry overflow point with the top 10cm above the ground
3. Place a 1.5m post (3) 1m away from peg 2, in line with post 1 and peg 2
4. Measure 1m from the base of post 1 and tie a string from that point to the top of peg 2
5. Use a level to tie a string 1m high on post 1 to post 3. The string should be level so the height from the ground at post 2 will not be 1m
6. Note the center of the digester chamber and mixing chamber along the line

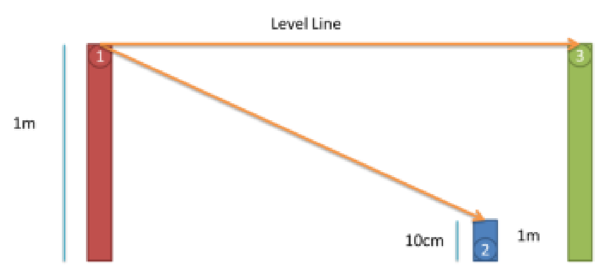


Figure A.8: Level line side view

Step 2: Excavation

Ideally, a backhoe or similar excavation machine should be used for digging the pit; manual methods can be used if that is what is available. A large square pit should be dug to allow enough room for the hemispheric chamber. Keep the excavated soil at the site as it will be needed for backfill.

The depths are set according to the design. The bottom of the pit must be excavated precisely according to the designed size. The bottom portion will need to be curved and compacted according to the plant size. Likewise, the section for the displacement chamber needs to be excavated according to the design. The pit below is trimmed and ready for its foundation. The pit should be dug with at least 0.5m of clearance beyond the radius of the digester to allow room for maneuvering.

Figure A.9: Excavated pit

Table A.7: Digester volume and radius

| Volume of Digester (m3) | Radius and Depth (m) |
|---|---|
| 4 | 1.2 |
| 6 | 1.4 |
| 8 | 1.6 |
| 10 | 1.7 |
| 12 | 1.8 |
| 16 | 2.0 |
| 30 | 2.4 |
| 50 | 2.9 |

This table shows the dimensions that need to be excavated for the main digestion chamber; assume a depth about 50cm deeper than the one specified. Use a radius stick to mark the radius of the digester's foundation.

Main Digester Overview

The following outlines the different components of the main digestion chamber.

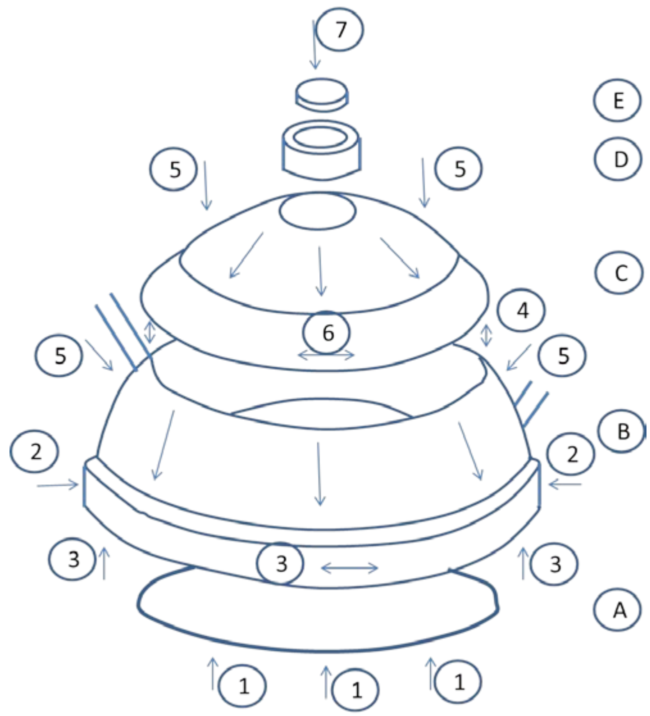


Figure A.10: Main digester components

A. The foundation of the digester
B. The lower slurry section of the digester
C. The upper gas storage section
D. The neck
E. The gas-tight lid

1. Foundation
2. Lower layer of bricks on foundation
3. Foundation Ring
4. The Weak Ring
5. Backfilled soil
6. The String Ring
7. Digester Lid

Step 3: Digester Foundation

1. Make sure the base is highly compacted, use pile drivers if necessary. Digesters of this kind are not well suited in climates with freeze and thaw cycles, but if one were to be built there, the foundation would need footings and extra support.
2. Use a radius stick to establish the ring
3. Make sure the depth of the pit is appropriate; at least 8cm
4. Make a mix of cement for the foundation; bed concrete should be a mix of cement, sand, and stone aggregates. The ratio can vary but should be in the range of 1:2:4 to 1:1:3.
5. Cast the foundation; it can be layers with wire mesh or rebar reinforcement if desired, this is component 4 of the main digester and part A
6. Use a radius stick to put a layer of brick along the outer edge of the foundation; do this while the cement is still wet (see picture). This is component 1 of the main digester

Figure A.11: Reinforcement ring

7. Mix mortar (1:4 cement to sand ratio)
8. There should be a 1cm gap between the bricks in the foundation reinforcement layer; fill in the gaps with mortar and make sure the bricks are fixed to the foundation
9. Allow the construct to cure at this point; periodically wet it down, concrete should not be allowed to totally dry out

Step 4: Beginning construction of the digester

Building the wall

1. Wait for the concrete of the foundation to cure; this may take a few days
2. Set up the guide stick which is fixed in the absolute center of the digester
3. Begin building up a cylindrical wall using the guide stick to check the radius
4. Bricks should be laid perpendicular to the bricks in the reinforcement layer
5. Use a 1cm bead of mortar on the contact faces of the bricks
6. Buildup 4 layers, or at least 15cm of bricks, this is component 2 or the digester
7. Use the guide stick to maintain proper radius

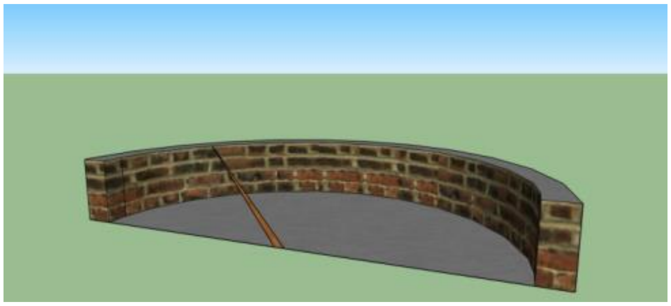

Figure A.12: The lower wall

Starting to build the dome

Use a guide stick which is fixed at the center of the digester floor and begin building the dome.

1. Lay mortar on the top of the wall to prepare for the next layer of brick
2. Each brick needs to be laid against the guide stick and the dome allowed to take shape (This is easier done than explained)
3. Build up the dome
4. Insert the inlet and outlet pipes at the correct height while building

Figure A.13: Building up the lower dome

Step 5: Placing the inlet and outlet pipe

Outlet pipe

The outlet pipe should be positioned close to the bottom of the digester to allow fully digested waste material to flow out. It is a good idea to shape the end of the pipe according to the contact profile with the brick. Mortar does not adhere particularly well to PVC; roughen the surface of the pipe with a file to improve bonding.

Figure A.14: Pipe positioning

1. Pipe length will vary according to the size of the digester (see the appropriate table)
2. The outlet pipe should be at least 15cm in diameter
3. The pipe should be positioned about 2-3 brick layers from the foundation
4. The outlet pie should be positioned at about a $45^0$ angle, relative to the ground
5. Set the pipe in place and trim the end to fit against the bricks
6. Apply mortar to connect the pipe and the brick layers
7. Continue building the brick wall around the pipe
8. Backfill around the pipe

Inlet pipe

The inlet pipe needs to be situated at the appropriate height so that the material flowing into the digester is introduced to the zone of active digestion. The pipe should also be located higher than the outlet pipe. The length of the pipe itself will vary, and it should be an appropriate length based on the planned position of the mixing tank.

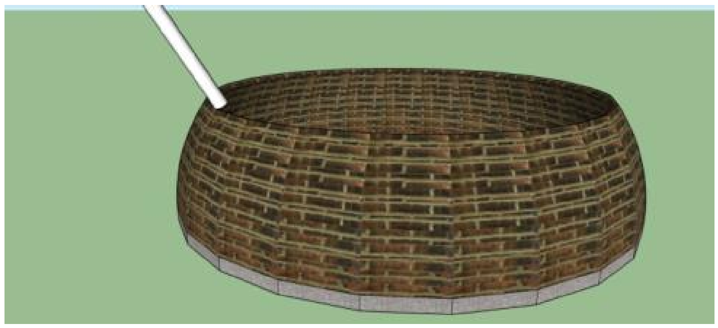

Figure A.15: Inlet Height

1. The inlet pipe should be PVC and at least 10cm in diameter
2. Installing the inlet pipe is the same process as the outlet
3. The pipe should be positioned at least 30cm above the bottom of the digester
4. Make sure the inlet point is higher than the outlet pipe position

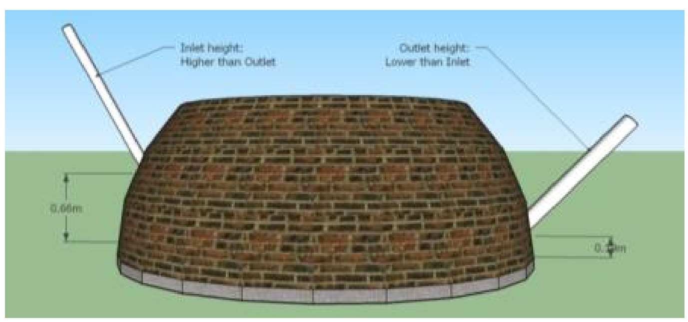


Figure A.16: Inlet pipe higher than the outlet pipe

Step 6: Finishing the lower dome section

Finishing the lower brickwork

At this point, both the inlet and outlet pipes should be in place.

1. Continue building up the brick layers

2. Once the radius stick is at a 45˚ angle, relative to the floor of the digester, stop building layers

Plastering the lower section

Once brickwork has reached the level of the weak ring, plaster should be applied to the entire outside surface of the digester. Plaster should also be applied to the interior of the digester. The interior is plastered to insure water-tightness.

Figure A.17: Interior plastering

1. Wash the brick construct with cement water prior to plastering
2. Plaster should be about a 1:4 ratio; the same as the brick mortar
3. Plaster should be applied carefully and at least 1-2cm thick on both the interior and exterior
4. Make sure the plastering is smoothed and applied uniformly
5. Allow the plaster to harden for at least 4 days, sprinkling with water several times a day

Backfilling

Backfilling is a vital component of digester construction. When the digester is active, internal pressures from slurry and gas can be quite high, so an equal and opposite force must be generated. This comes from backfilling, which provides structural integrity and stability. Backfilling is essentially burying the construct with compacted soil. At this point, the digester has been built up to section B.

1. Wait for the plaster to harden and cure at least 4 days before backfilling
2. The first two layers of brickwork should be backfilled using a light concrete mix of about 1:3:9

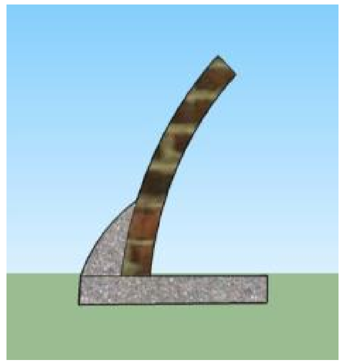

Figure A.18: Lower layer concrete backfill

3. The rest can be backfilled with soil; soil should be non-binding, so soils used should be low in clay content and moisture. They should have a high bulk density.
4. Fill in slowly, a little soil at a time covering two layers of brickwork, compressing the layers after each application; do not just fill in the soil all at once and compress once
5. Backfill all the way up to the current brick layer, water can be used to help compress soil

Step 7: The weak and strong ring lower and upper dome section connection

Figure A.19: Strong and weak ring construction

The lower slurry-tight and upper gas-tight sections of the digester dome are connected by a series of “weak” and “strong” rings. These rings are special layers of brick, concrete, and mortar which function as a connective piece and a buffer zone between the two parts of the dome. The two rings and absorb and dissipate gravitational forces resulting from the weight of the upper dome. It also prevents any cracks from spreading from one section to another.

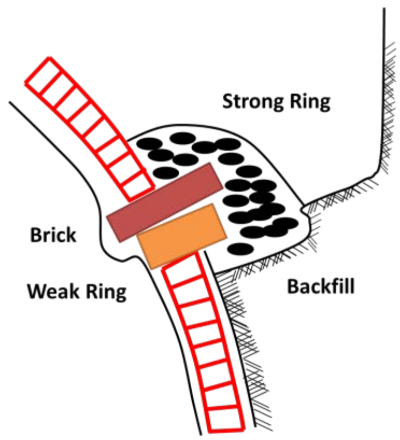


Figure A.20: Weak and strong ring layout cross section

The weak ring

The weak ring separates the lower slurry storage part of the dome from the upper gas storage section. The weak ring serves as a cushion and protects the upper part of the dome from cracks which may occur in the lower part. It is called the *weak* ring because the material is meant to be malleable and deform under stress. It should be noted that the inlet pipe should be placed no higher than the weak-ring, depending on the designed size. The ring is a loose mixture of mortar in 1:15 ratios which sits between the lower dome section and the upper section and is held in place by a layer of brick.

1. Make sure backfill is level with the current height of brickwork and compressed well
2. Extend the length of the radius stick by 20cm or the length of one brick

3. Using the extended radius stick, place a ring of bricks around the digester, on the soil (form brick)
4. Create a mix of mortar in a 1:15 cement to sand ratio
5. Apply the concrete on top of the last brick layer of the digester, extending out to the form brick ring (weak ring)

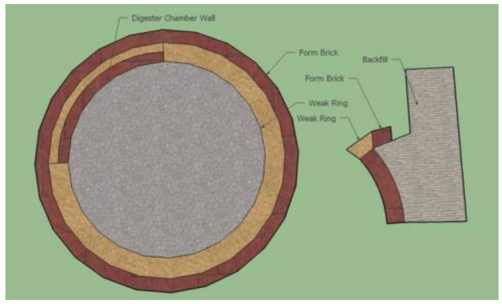


Figure A.21: Weak ring profile

6. The concrete thickness should not exceed 7cm thickness, or the thickness of a brick
7. Take care when applying the weak ring, make sure it is done uniformly and evenly, use a mortar trowel and smoother block

The strong ring

The strong ring is a layer of brick reinforced by concrete that sits on top of the weak ring. This ring receives tension forces from the upper dome and can be thought of as a foundation for the upper dome. It is called the *strong* ring because it is not meant to deform under stress like the weak ring; it should absorb and dissipate stresses.

1. Change the radius stick back to its original length, then reduce the length by 4cm or about 1/4 the length of a brick
2. Install a ring of bricks on top of the mortar of the weak ring using the radius stick; the bricks should be placed long ways, like the brick used in the digester foundation
3. The bricks should be centered over the bricks of the lower dome section

4. The bricks, which are perpendicular to the bricks of the lower dome, should have a 1cm spacing and be mortared appropriately

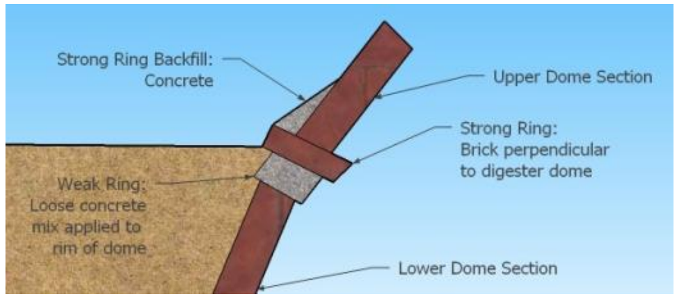


Figure A.22: Strong ring profile

5. Return the radius stick to its original length
6. Install three layers of brick on top of the strong ring foundation brick in the same orientation in which they were applied in the lower dome section, mortar and space the bricks appropriately
7. Backfill around the weak ring, strong ring foundation, and the three layers of brick with 1:2:4 concrete

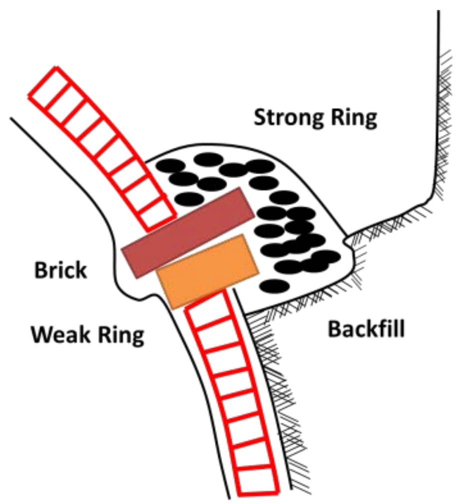


Figure A.23: Backfill and concrete

8. Allow the concrete and rings to cure for at least 4 days, sprinkle with water several times each day
9. Step 9: Construction of the expansion chamber and Step 10: The mixing chamber can begin while the rings cure

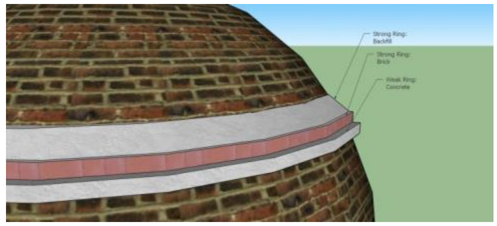


Figure A.24: Ring Locations

Step 8: The upper dome section

Step 9: Construction of the expansion chamber and Step 10: The mixing chamber can happen at the same time as this step 8. This upper section is the gas tight dome section of the digester; most of this section will contain the biogas produced by the digester. It is absolutely critical that this section of construction be precise and gas tight. Because bricks in this section will be slanting, it will be necessary to use counterweights or a similar mechanism to support the brickwork as the mortar sets.

Brickwork

1. Use the radius stick, which should be set at the original length, to maintain proper brick placement
2. Brickwork continues in the same manner as the first three layers of brick in the strong ring
3. Because bricks will be slanting, layers will need to be applied slowly and counterweights will need to be used, the best method is to use rope or metal hooks and attaching bricks to provide weight

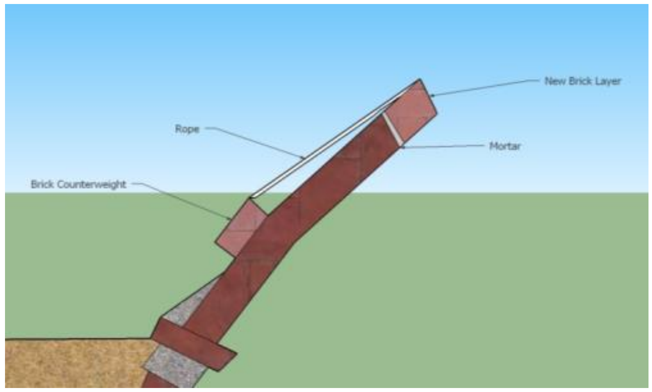


Figure A.25: Counterweights

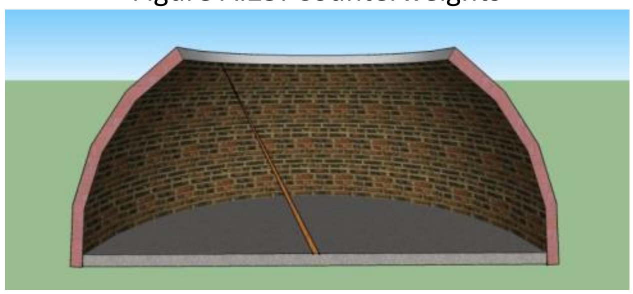

Figure A.26: Brick support system

4. Mortar will need to cure and the bricks will need to be secured before the next brick layer can begin
5. Continue slowly building the upper dome section until an opening of approximately 60-100cm in diameter remains. Keep in mind, a person will need to be able to easily climb down into the digester through this hole.

Figure A.27: Upper dome top opening

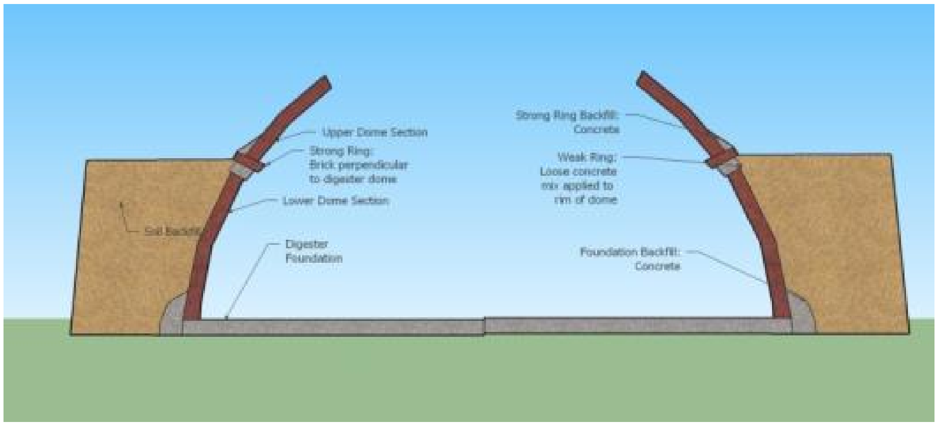


Figure A.28: Upper dome side profile

Plaster

The upper section needs to be plastered on both the interior and exterior. Sealing the interior of the digester is the most critical part of the construction process. Most often, failures in fixed-dome digesters can be attributed to leakages resulting from inadequate sealing. Workers will need to be able to access the interior. Be very careful in this process, not just in the construction but more critically, in worker safety. Airflow is limited and workers can overheat and have trouble getting fresh air. It is recommended that work on the interior sealing be reserved for cooler parts of the day. The workers will need adequate lighting and easy access to the exit if needed. Different set ups can be used to provide lighting to the interior. Overall, make sure the workers are safe during this critical step.

1. Wash the interior and exterior in a cement water mixture
2. Once the appropriately sized opening remains, plaster the outside of the digester with a 1:4 mix 1-2cm thick. The interior can be plastered at the same time.
3. Scrape clean the interior of any excess mortar
4. Apply a 1cm thick 1:4 plaster coat on the interior
5. Smooth the plaster layer and allow it to set

Figure A.29: Interior plastering

6. Apply a layer of cement paste in a 1:1 cement: water ratio, be sure the mixture is smooth and consistent, the layer should be 1-2mm thick and carefully cover the entire upper section interior
7. Once this layer has set, mix a waterproofing agent with a 1:1 cement paste mix and apply a third coat of 1-2mm to the interior
8. Polish the final layer of sealer and ensure there are no cracks
9. Allow the plaster to cure for 4 days, sprinkling with water several times a day
10. Once the plaster has cured, backfill the upper dome section with soil and compress, in the same manner as in Step 6

Figure A.30: Exterior plastering

Step 9: Construction of the expansion chamber

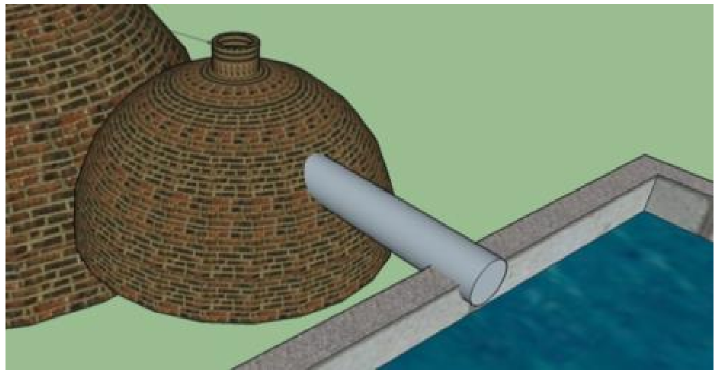

Figure A.31: Expansion Chamber

This step can occur while the concrete and components of the strong and weak ring cure in-between steps 7 and 8; work can be done during step 8, if there are enough workers.

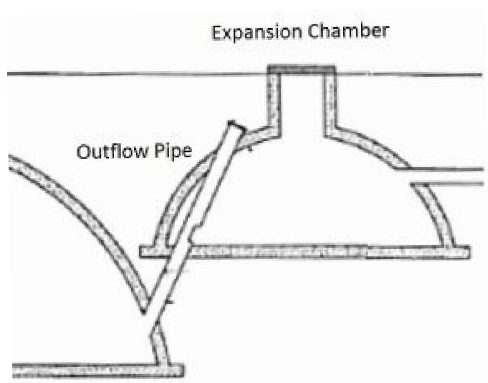


Figure A.32: Expansion chamber position

The expansion chamber is the storage chamber for digested material as the pressure from the biogas forces is up and out of the main digestion chamber. The shape and configuration of the expansion chamber can vary greatly; however, this manual will instruct on how to build a spherical expansion chamber. The construction will differ from the main digestion chamber in that the dome is roughly 1/3 the volume and the weak and strong support rings are absent; otherwise the construction is quite similar. The expansion chamber should also have an integrated slurry bed and filtration unit where liquid can flow out and be collected from the chamber.

Excavation

The location of the expansion chamber should have been outlined already. The area will need to be excavated. The depth will vary based on the design and should be measured relative to the level line.

1. Compress the soil in the area firmly
2. Demark the radius of the chamber
3. Indicate the location for the slurry drainage point
4. The table below can be seen as a guide for the radius of the expansion chamber based on the volume of the main digester

Table A.8: Expansion chamber radius

| **Volume of Digester (m3)** | **Radius and Depth (m)** |
|---|---|
| 4 | 0.9 |
| 6 | 1.0 |
| 8 | 1.1 |
| 10 | 1.2 |
| 12 | 1.2 |
| 16 | 1.4 |
| 30 | 1.7 |
| 50 | 2.0 |

Foundation

Use the same principles as those used in building the main digester foundation when constructing the foundation for the expansion chamber.

1. Mix a 1:2:4 cement
2. The foundation should be around the outflow pipe; the outflow pipe can either end inside the chamber or extend beyond it and be capped
3. The base of the foundation should be at roughly the same height as the weak and strong rings on the main digester
4. Build the foundation 5-8cm thick

5. Use a radius stick equal to the radius of the expansion chamber
6. Cast the first layer of brickwork around the outer radius of the foundation
7. Allow the foundation and the first brick layer to cure, sprinkle with water as needed

Expansion chamber dome

Building the dome for the expansion chamber follows the same basic process as the main digestion chamber, except there is no weak or strong ring.

1. Make sure bricks have been soaked
2. Mix a 1:4 mortar mix
3. Assemble a small radius stick set to the interior radius of the expansion chamber
4. Build up the brickwork dome of the expansion chamber; maintain appropriate brick spacing and mortar thickness; use counterweights when necessary
5. About halfway up the height of the expansion chamber, a 10-15cm pipe for outflow slurry needs to be installed, this pipe flows to a designated liquid outflow point of either a slurry tank or channel. This will need to connect to a filtration bed in municipal settings.

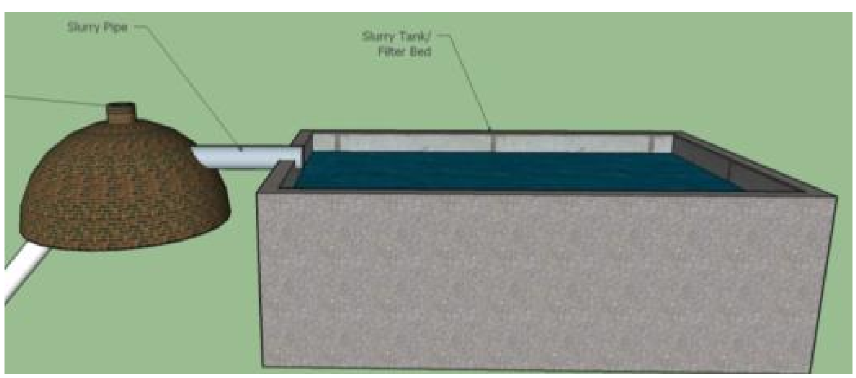


Figure A.33: Expansion chamber outflow point

6. Build up the dome until the opening of the top is about 50-70cm in diameter
7. Allow the brick and mortar to set for at least 1 day

Plaster

Once the desired opening diameter is reached, plastering of the interior and exterior can begin. Like plaster on the main digestion chamber, use a 1:4 mortar mixture and apply plaster to the interior and exterior at a 1-2cm thickness.

1. Wash the expansion chamber with cement water
2. Apply a 1-2cm thick coat of plaster to the interior and exterior
3. Smooth the plaster
4. Allow the plaster to set for at least 4 days; sprinkling with water

Neck construction

Once the plaster has dried, build the neck up from the top of the dome to ground level. This can be a square or cylindrical shape and is simply brick built up from the expansion chamber dome to ground level. Cast an appropriately sized lid for the opening of the neck out of 1:2:4 concrete. Do this by making a frame in the shape of the lid that is needed and in which concrete can be poured.

Figure A.34: Neck construction

Backfill

Backfill around the completed and cured expansion chamber using the same techniques previously employed. Do small layers at a time and compact the soil well.

Filtration bed

In urban settings, it is important to have a slurry filtration bed for the flow coming out of the expansion chamber. This manual will not go over the construction of this bed, but it is important to note its necessity. Filters are often a series of stratified materials like sand and gravel which screen out particulate matter.

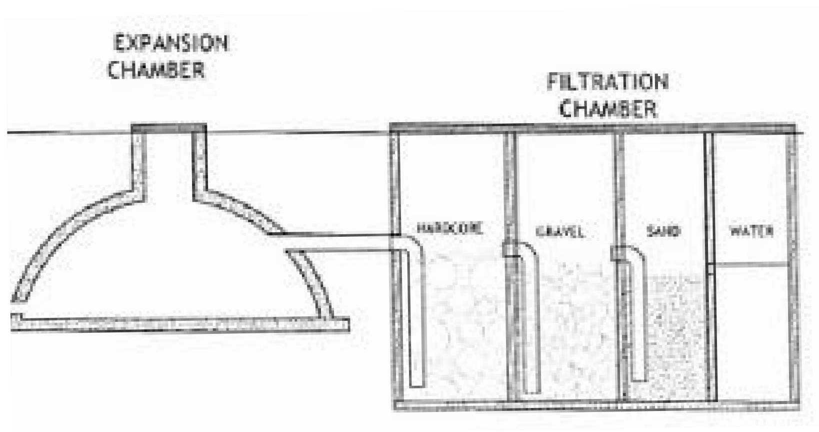


Figure A.35: Filtration bed

Step 10: Construction of the mixing chamber

While constructing the displacement tank, work can also be done on the inlet tank. This tank needs to be set at the appropriate height and position based on the location of the inlet pipe. The height should be at least 10cm higher than the outlet tank base. Raise the ground level accordingly while remembering to properly compact the soil. The mixing tank will be cubic in shape and have a volume equal to at least 1 days' worth of input.

Foundation

Cast a square foundation of 6-8cm thick using the same concrete casting techniques as before. Build the first layer of brickwork while the concrete is still wet; be sure to bind the brick and concrete well. The inlet pipe should be flush with the floor of the foundation and mixed material should be able to flow freely into the pipe.

Brickwork

Build the tank based on the dimensions designated by the design. Depending on user preference, the volume of the inlet tank could be equal to the volume of the daily input. This assumes that the operator collects and mixes the input only once daily. If utilities are directly connected to the digester inlet pipes, they may bypass the inlet tank. Configurations will vary, but when estimating the size of the inlet tank, a volume equal to one days' worth of feed is adequate.

The mixing tank will be square and should be built up to the appropriate volume and configured accordingly. The mixing tank is essentially an open-topped box. The interior and exterior should be plastered, as before.

Table A.9: Mixing chamber side dimensions

| Volume of Digester (m3) | Side Length (m) |
|---|---|
| 4 | 0.60 |
| 6 | 0.70 |
| 8 | 0.75 |
| 10 | 0.80 |
| 12 | 0.85 |
| 16 | 0.95 |
| 30 | 1.15 |
| 50 | 1.40 |

Step 11: Main digester neck and lid

The main digester is closed with a removable cover and is supported by a frame, or "neck", which comes up from the top of the digester dome to ground level. The gas outlet passes through the lid and can be piped to whatever location is desired. This line should be fitted with the appropriate hardware like flow control valves and pressure relief valves. It is important that this section be gas-tight and properly protected.

Figure A.36: Neck construction process

The neck

The neck is a cylindrical chimney like structure which leads from the top of the digester dome to the surface.

1. Wet the needed bricks
2. Prepare a 1:4 mortar mixture
3. Prepare a measuring stick which has the same length as the diameter of the opening in the digester. This will be used to position the bricks of the neck and maintain adequate spacing.
4. Build up the neck from the hole in the top of the digester; keep the wall vertical and rotate the measuring stick to maintain proper distances
5. Build the neck up to at least ground level; it can go higher depending on the preferences of the client and the gas outlet configuration

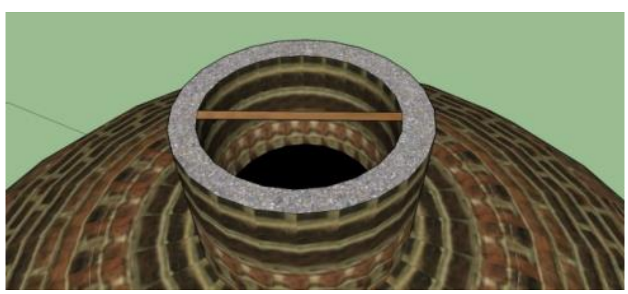

Figure A.37: Neck diameter spacing

6. The neck will need to be fitted with a collar to hold the lid and remain gas-tight

The molded lid and conical interior support

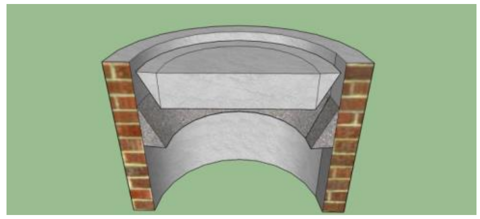

Figure A.38: Neck and support

A mold needs to be made to cast both the lid and the fitting for the lid ensure that the two components will match and fit together as tightly as possible. The mold can be a metal tapered pan shape which can be filled with cement to create the lid. The pan needs to be at least 20cm deep and its smaller diameter must be at least 50cm across (man-sized).The mold can be pressed into a bedding of mortar to form the lid support.

1. Mix a 1:3 cement: sand ratio concrete
2. Add a water-proofing solution to the concrete mixture
3. The gas pipe will go through the lid; set the pipe into the mold and be sure it is positioned correctly. Make sure there is enough clearance to install fittings to the rest of the pipe.
4. Using the mold, cast the cement for the lid; make sure the cast for the lid is at least 20cm thick
5. Install handles into the lid as the cement hardens; these can simply be curved metal hand holds which make moving the lid easier

1. When the lid has set, remove it from the mold
2. In a cylindrical container which has a diameter less than that of the neck, pour cement
3. Press the mold into the mortar bedding to form the conic fitting for the lid
4. The fitting should essentially be a ring which is tapered inwards and allows the lid to fit in it
5. Once the fitting has set and hardened, install it into the neck of the digester
6. This should be done using mortar and steel fittings

Figure A.39: Lids

7. The fitting should drop into the neck, steel hooks can be set in place which anchor the fitting to the sides of the neck; fill in with plaster that has water-proofing to ensure a good seal and good support

The gas line

The piping system of a fixed-dome digester is highly variable based on the position of the digester in relation to the location in which the biogas will be used. In general, the line should follow the shortest distance possible. Pipes are typically made of PVC, which will resist corrosion. Generally the pipes are 1.5-2cm in diameter for outdoor lines and 1cm in indoor lines. Piping should be buried in a trench about 10-15cm deep and the line should be clearly marked. The line should have the proper fittings and connective pieces and be installed properly. The proper flow control valves, pressure relief valves and gauges should be included if available. Hook up the gas line to the outlet on the lid of the digester using the appropriate fittings.

Biogas sites will vary from one location to another just as the piping systems will vary. This part of the construction should be tailored to the specific design and location. Be sure to check for leaks in the line and repair them accordingly. The gas line can be split to address the different appliances which will need the gas. Biogas contains some water, so the pipes need to be arranged at a slope to gather condensation and keep it clear of the lines; water traps can also be used.

## Starting, Operating, and Maintaining the Digester

### Starting the digester

The digester will need to be properly seeded to begin working. Seeding should only begin after the civil works have cured completely; up to 20 days after the completion of construction. Large quantities of manure or other waste material, as well as water, will need to be introduced. Make sure materials used are free of unwanted particles like trash, sand, wood, or other impurities. In general, the amount of material introduced for the seeding period will need to be equal to the amount of material which would be introduced under normal operation during the full retention time. So if the designed HRT is 50 days, then 50 days' worth of waste material and water should be the amount of initial feed. Manure from cattle, or other ruminants, is the best for initial seeding as the manure already contains the bacteria necessary for anaerobic digestion; the digester start up times will be considerably less if the seed material already has the necessary bacteria. If a different source is to be used, the digester should be catalyzed by adding the necessary bacteria. The easiest way is to add manure from a ruminant but starter kits are also available in some places.

The digester should be fed via the inlet pipe so as to make sure no bulky substrate is able to enter which may otherwise clog the outlet. The lid should remain off during the initial filling and then sealed once the substrate has reached a point higher than the inlet point and equal to the amount of material which would be introduced during a full HRT cycle.

Figure A.40: Inlet Mixing Chamber

The lid should be sealed with clay and kept in a water bath to prevent drying of the seal and gas leakage. Clay particles expand when they are wet and they stick to each other. So putting a layer of clay in between the lid and the fitting and then submerging it in a water bath creates an air-tight seal. The lid, which is already heavy, should be chocked with wooden blocks or a similar set-up to resist the building gas pressure and maintain air-tightness.

Figure A.41: Properly applied water bath

Maintaining the digester

Fixed-dome biogas digesters require little maintenance in comparison to other types of digesters. That being said, routine inspections of the entire civil work should be made periodically to check structural integrity. Pipes and flow points should be monitored and maintained in good stature. Check for cracks or other fissures in the structure and repair them as needed. The concrete works should never totally dry out, so keep in mind that it may be appropriate to maintain moisture in the structures. This can be done by simply applying water. The clay sealed lid must always be wetted, so make sure to check and wet that accordingly.

- Inspect the inlet pipe and make sure it is clear daily
- Inspect the outlet opening and make sure it is clear daily
- Wet the clay sealed lid weekly
- Check the gas lines for leaks monthly
- Open the main digester and stir the contents well every year
- Clean out the expansion chamber yearly

The expansion chamber should be cleaned out periodically to avoid solids crusting in corners and flow pipes. The overflow slurry point should always be kept clear of debris. A scum layer can form and harden in the main digestion chamber which can limit and disrupt gas production and substrate flow; it may be necessary to break this up from time to time.

If the digester is not well maintained or operational practices are not in good standing, it may be necessary to clean out the digester every years as residue can build up. This can result in a long downtime and the digester would need to be brought offline and totally cleaned. However, if the digester is properly maintained and operation is within the design parameters, it is probable that the digester need not be fully cleaned out. These digesters can have a life span up to 50 years if properly maintained and operated. From time to time, a concrete specialist (preferably the same one who helped with construction) should inspect the structure.

Troubleshooting

Table A.10: Troubleshooting table

| **Problem** | **Possible Cause** | **Possible Solution** |
|---|---|---|
| Insufficient gas pressure | Gas leakage along the line; inadequate plant feeding | Check for leaks along the gas line and address accordingly, make sure the plant is fed adequately |
| Decrease in gas production | Underfeeding, leaks, scum formation, improper dung/water mixing, formation of solids in the digester | Ensure proper feeding, check for leaks, check and possibly clean out the digester |
| Smell | Over-feeding, leaks | Ensure proper feeding, check for leaks |
| Appliances not functioning well | Faulty appliance, leaks in gas line, inadequate gas production | Check appliances, check for leaks, check for gas production fixes |
| Thick effluent at overflow point | Incorrect mixing ratios, no movement of substrate inside the digester, water and slurry leakages | Maintain good mixing ratios, check for water leaks in the plant, make sure gas is used regularly to maintain systems pressure, empty the plant and reseal |
| Materials not entering the plant | Blocked inlet pipe, pipe position or mixing chamber height is incorrect | Clear out the blockage, check the height dimensions of the mixing chamber relative to the outlet and adjust if needed |
| Slurry entering the gas line | gas outlet pipe is positioned lower than the overflow point | Check the slurry overflow point for blockages, lower the overflow point |

Using the “Biogas Plant Table”

The *“Biogas Plant Table”* is a tool which is designed to help estimate the size of digester which should be used in a particular instance. It requires the user to indicate the type and number of organisms whose manure will be used to feed a digester. It also requires the user to indicate the average temperature range in a region.

Using these inputs, the spreadsheet runs through an array of equations to report the amount of daily wet feed which a plant will receive in $m^3$, the best HRT under the conditions, the minimum digester volume, and the estimated amount of biogas produced daily. Using these outputs, the client can get an idea of what size digester is best suited for their situation.

Example

User Inputs:

Table A.11: Example user input

| | |
|---|---|
| Step 1) | |
| Specify the sources and quantities of biological input. | |
| Input Source | Number in Population |
| 1) Cow | 6 |
| 2) Pig | 2 |
| 7) Human | 8 |

| | |
|---|---|
| Step 2) | |
| Indicate the average temperature range during operation ( C ). | c) 20-25 C |

Output:

Table A.12: Example program output

| | | |
|---|---|---|
| **RESULTS OF SCENARIO** | | |
| Daily Wet Feed (m3) | | 0.21 |
| Retention Time (HRT) (days) | | 50 |
| **Minumum Volume (m3)** | | **10.6** |
| **Daily Biogas Production (m3)** | | **4.82** |
| Equal to: | kWh of Electricity | 10.35 |
| | Liters of Kerosene | 2.75 |
| | kg of Firewood | 4.82 |

Analysis:

Based on the user's input, the results show that the digester for this location needs to be at least $10.6m^3$. Referring to the list of standard sized digesters, it can be seen that the best sized digester for this scenario is a $12m^3$ digester. Furthermore, any digester larger than $10.6m^3$ could be used and would provide a greater safety factor and cushion.

Table A.13: Digester construction material estimates

| Volume of Digester (m3) | Number of bricks | Cement (50kg) | Sand (m3) | Stone (m3) | Waterproof Cement (1kg) |
|---|---|---|---|---|---|
| 4 | 800 | 13 | 0.75 | 0.75 | 3 |
| 6 | 1100 | 16 | 1.00 | 0.75 | 4 |
| 8 | 1300 | 20 | 1.00 | 1.00 | 5 |
| 10 | 1500 | 23 | 1.25 | 1.00 | 6 |
| 12 | 1600 | 25 | 1.25 | 1.25 | 7 |
| 16 | 2000 | 31 | 1.50 | 1.25 | 9 |
| 30 | 3000 | 46 | 2.25 | 2.00 | 20 |
| 50 | 4100 | 63 | 3.00 | 2.75 | 35 |

What if the reported minimum volume is greater than $50m^3$? This is one of the great advantages of using fixed-dome digesters. They can be easily installed in series, where multiple digesters can be set up together to increase the volume and still function in the same manner.

Appendix B Site Visit Reports

Kibera Bio-center site visit

March 4, 2014

Uweza Foundation:

The first meeting was with the Uweza Foundation and the representatives there. The progress and status of the Solar Light Bulbs project was discussed. The technicians who install the bulbs expressed some of the issues that the users are seeing. Some are commenting on the fact that some of the bulbs eventually start to leak; some of the bottles themselves break and leak, while the sealant around some shrinks and expands with the temperature fluctuations and the sun's radiation. However, even with the leaks, people typically leave the bulbs in place, seeing the light as a benefit that outweighs the problems of leakage. In general, the solar light bulb project is well regarded by the households which have had them installed.

The next step is to find an appropriate way to commercialize the project. The community is resistant to the idea of the Foundation adding a cost to the solar light bulbs because thus far, they have been provided for free. However, for the project to become sustainable, it must be able to generate enough capital to account for construction, operation, maintenance, installation, and labor costs for the technicians responsible for them. A few ideas were discussed including adding a small "maintenance fee" where technicians will periodically check up on the bulbs and repair or refit them as necessary, at cost to the user.

- Solar light bulbs
    - Constructed from recycled clear plastic bottles filled with water, sealed with silicone around a sheet metal plate and put into the roof of a house. Sunlight comes in and reflects off of the water and shines light.
        - Each cost about $3 to construct and install

        - Some problems with leaks
        - House may or may not be heated a bit
        - Floodlights near houses using the light bulbs increase light at night
    - Foundation has installed 4000 bulbs for free
        - UN-Habitat funds and oversees the projects
        - Next step is to commercialize the product. People are resistant to this since the service had previously been provided for free.
    - Lighting is a huge issue in slum upgrading projects
- Most people in Kibera have access to electricity
    - Illegally acquired: not through Kenya Power
        - Tapped into other lines and take the power
    - Generally pay about 300-500KSh set fee a month
        - This will likely increase if users switch to legal outlets

Umande Trust:

The next meeting was with representatives of Umande Trust. The Trust deals with building and maintaining many bio-centers around East Africa, particularly in Nairobi and Kibera. The Trust operates 18 bio-centers in Kibera. We observed two different bio-centers in Kibera. The first one observed was the Muvi Bio-center followed by the Katwekera Tosha Bio-center. Observations and impressions from each of the sites are as follows:

- Bio-center projects
    - Community centers with toilets, showers, and similar facilities with biogas digesters.
    - About 60 centers built in East Africa
        - 18 or so in Kibera alone
    - Umande Trust funded by UN-Habitat and other organizations and is in charge of the design, planning, construction, and operation of the centers
    - Umande Trust fully involves the community in the design of the project

        - Designating a location
        - Finding out what services to provide
        - Deciding a reasonable cost for citizen use
        - Providing training in operation and administration
        - Discussing the acceptance/effectiveness/feasibility of the centers
- Muvi Bio-center
    - Built April 2010 for 1.8 million KSH construction
    - Estimated annual profit of 500,000KSH
    - About 200-300 regular daily users
    - TV and conference room upstairs
    - Latrines/bathrooms
        - 3 women's latrines, 1 women's shower, 3 men's latrines, 2 men's showers, 1 stall.
        - 5KSH for toilet use, 10KSH for bathroom/shower use
    - Local people can cook using the burners at the center which are fueled by the produced biogas
        - 10KSH to use the 2 small burners on site
    - People can pay using a "beba" card. Essentially a loadable credit card to pay digitally and eliminate cash exchange.
    - Water distribution point, water is collected from the city and made available to the community
    - Digester is about $50m^3$ in total volume and generates an estimated $8m^3$ of biogas daily, though this is not monitored as whatever is being produced is certainly adequate for the cooking needs
    - Center also has electricity from the Kenya Power company to run lights and TV
        - Partnership with a bank which has invested and located services in the center

- Katwekera Tosha Center
    - First center built by Umande in Kibera
    - Originally designed for about 300 users
        - Digester had to be expanded as the center soon saw up to 1000 users
        - Now has stabilized at about 600-700 daily users
    - Several toilets and showers
        - 5KSH for toilet, 10KSH for shower
        - 10KSH for cooking
    - Features several rooms upstairs
        - Kitchen
        - Computer room
        - Conference room
        - TV room
    - A nearby school is one of the primary beneficiaries of the center
        - Meals for the children are cooked at the center for the standard fee
        - More economic
    - Features a “bio-centre card” digital payment system
- Most bio-centers see a surplus in biogas production and could benefit from expansion
    - Recommended the following:
        - Install more cooking burners
        - Put in biogas lanterns
            - They had not heard of these working before so I explained a bit
        - Look at western models of biogas resources
            - Boilers

    - Heaters

- Umande Trust representatives expressed interest in ways to improve efficiency and effectiveness
- Would benefit from biogas technology upgrades


Figure B.1: Muvi Bio-Center Images

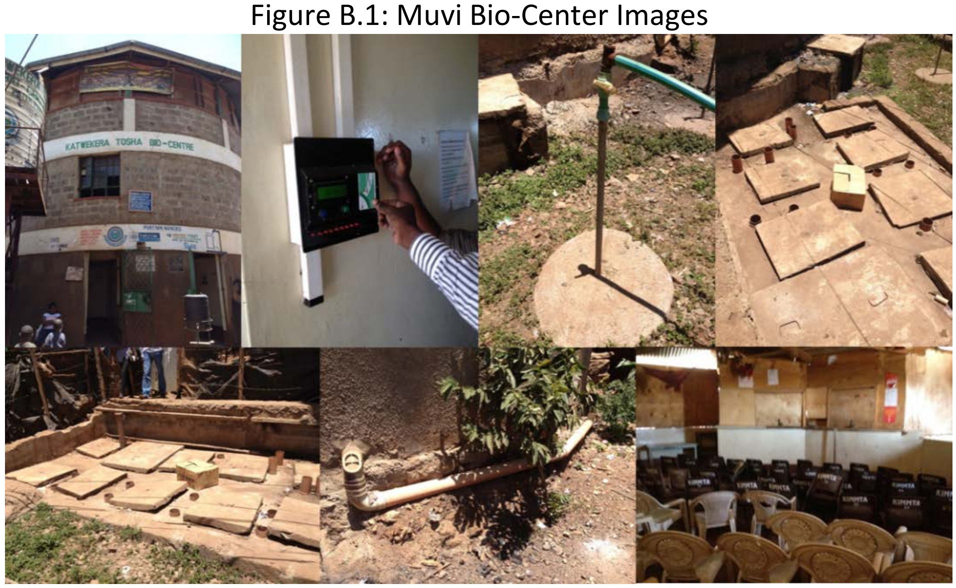


Figure B.2: Katwekera Tosha Bio-center Images

## Homa Bay and Kisii Prison Biogas Projects

### Introduction

In 2012, UN-Habitat provided support for the development and implementation of biogas plants in prisons located in both Homa Bay and Kisii. This project, operated under the Prisoners Care Program (PCP), features the installation of 124m$^3$ biogas digesters. These digesters, which are meant to both treat generated biological waste and produce energy, operate under the principles of anaerobic digestion; a biological process in which biological waste materials are broken down by digestive bacteria. Anaerobic digestion, as a process, addresses problems related to both energy production and sanitation. In both situations, it appears that the projects were completed as far as construction was concerned. However, problems seem to have arisen in regards to training related to operation and maintenance of the digesters. In short, the digesters are not operating in the manner in which they were intended to and are not properly treating waste generated by the prison and producing biogas; this can be attributed to inadequate operational procedures in the program.

### Mission Parameters

UN-Habitat sent a team to assess the current status of the prison digesters. The aim of the mission was to discuss the situation with the prison officials and stakeholders while observing the digesters themselves so as to deduce the reasoning behind their apparent inoperability. Upon completion of the assessment, recommendations are to be made as far as solving the observed problems and improving operational procedures. The mission team consisted of a Senior Consultant, Program Officer, Biogas Technician, and two interns associated with UN-Habitat.

- James Murage: Senior Consultant (Water and Sanitation).
- Joseph Gikonyo: Program Officer.
- Patrick Mwangi: Biogas Technician.

- Patrick Bakke: Habitat Intern (Water and Sanitation).
- Chris Limiac: Habitat Intern (Urban Energy).

The mission took place from March 26th to March 28th and featured the following schedule:

March 26th,

Departure at 12pm, travel from Nairobi to Kisii, arrival at lodgings

March 27th

Mission to Homa Bay (morning)

Mission to Kisii (afternoon)

March 28th

Travel from Kisii to Nairobi

The missions to both prisons involved preliminary discussions with the prison wardens as well as key personnel pertinent to the operation of the respective digester programs. Furthermore, visual inspections were made of the biogas civil works as well as the sewer lines, kitchen and cooking areas, and sanitation facilities on site.

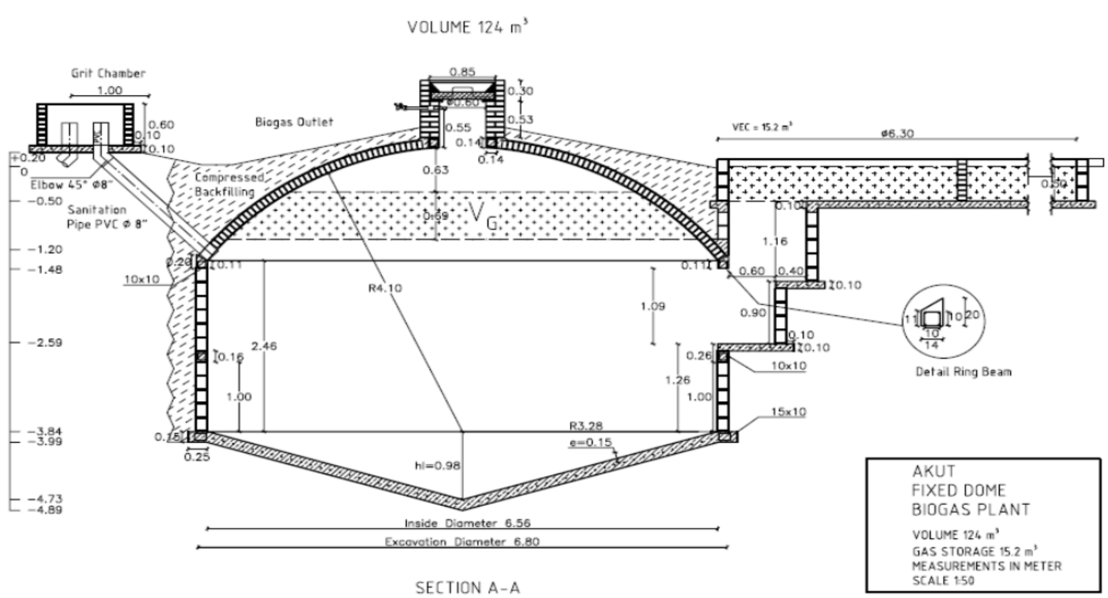


Figure B.3: Digester Schematic

Homa Bay Prison Digester

Homa Bay prison is home to 410 prisoners who are connected to the sewage system which are supposed to be linked directly to the digester. The toilets and sanitation systems employed by the prison are flush toilets; however, the prison is frequently plagued by problems related to water shortage, meaning that toilets do not always have flushing capabilities. The prison has attempted to combat this problem by employing the use of a few $50m^3$ water reservoirs. Furthermore, of the guards and administrators currently stationed at the prison, only one was around during the construction phase of the digester. This has resulted in a lack of knowledge related to the maintenance and operation of the digester. Additionally, it would seem that PCP did not provide the prison officials with the appropriate resources and support knowledge related to the proper management and running of the plant itself.

Problems Observed

The digester has not operated properly in its entire 15 month lifetime. Construction of the digester was completed in 2012; at which time, it was theoretically operational, pending proper seeding and subsequent management. For its seeding, the prison imported several truckloads of cow manure from slaughterhouses, farms, and other nearby locations. After two weeks of manure collection, the digester was filled and digestion began. In the meantime, the works officers attempted to connect the prison sewage system to the digester inlet. It was reported by the officer that upon attempted connection, sewage began to backflow into the sewage line chamber. Since that time, no further attempts (either successful of unsuccessful) have been made in connecting the sewage line to the digester chamber. At this point, the sewage generated by the prison does not flow into the digester at all.

It is estimated that the sewage does not flow into the digester because of problems associated with the elevations of the different works of the digester system. The waste collection point is not high enough relative to the input point of the digester.

Because of this, there is not a substantial enough gradient to allow proper hydraulic flow of material through the transport lines.

In addition to problems regarding waste transport into the digester, it is hypothesized that the gas lines leading from the digester to the cook stoves may have leaks. An attempt was made to assess the integrity of the lines; however, more intensive investigation must be done to further, and more effectively, analyze this. Also, the expansion chamber has some cracks in the walls which will need to be addressed, pending repair of the other issues.

Solution Procedures

To reiterate, the digester needs to be properly attached to the sewage input points. In addition, the height of the sewage input point needs to be raised, relative to the digester's input point. This can be done by simply disconnecting and bypassing the current line and constructing a new on of appropriate configuration. The cracks in the wall of the expansion chamber can simply be repaired by means of patching with mortar. The gas lines can be checked by pressurizing the system and observing where leaks would occur and then patching them accordingly. The **most** important step which should be taken in regards to the Homa Bay digester is to improve the operational understanding of the stakeholders. A program or system must be set in place which educates and instructs key personnel in the fundamental operation and maintenance of the digester. Persons should work with the biogas technical specialists so as to ensure that the prison is able to operate the digester on its own. Failure to do this will most likely result in another breakdown of operation.


Figure B.4: Homa Bay Images

Kisii Prison Digester

In general, the digester program at Kisii is performing better than the one in Homa Bay. Notably, the Kisii prison digester does, in fact, function to some degree. The prison houses 1497 inmates, both male and female, as well as several staff members which are connected to the digester system. All of the prisoners use flush toilets and there has been no report of water shortage which alters the flushing configuration. The sewage from the toilets is not presently connected to the digester. The digester is bed about three times a week by the waste generated by 3 cattle. At $124m^3$, the digester volume is very large relative to the current amount of waste which is being deposited. In this prison, the warden and many staff members were present at the time of construction and have at least some level of understanding with regards to the operational configuration of the digester program.

## Problems Observed

The first observed problem was a substantial gas leak which is present in the lid of the digester. This is evidenced by the bubbling and gas seen escaping from the water bath sitting atop the lid. The digester runs exclusively on cow manure and waste from the toilets and prison is not deposited into the digester. A channel for the waste to be brought to the inlet of the digester needs to be built. Furthermore, a method and system needs to be introduced which separated wastewater and water used for cleaning and disinfecting, as these chemicals are harmful to the fermentation process.

The gas produced by the digester is an inadequate amount for beneficial use in the cooking locations. While there is, in fact, biogas being produced, it is of a quantity and at system pressure inadequate for sustained burns and cooking times. The system pressure is often too low for the gas to effectively reach the kitchens in the women's cell block of the prison.in addition, prison officials expressed an interest in modifying the jikos used for cooking in a way so that they would enable the use of biogas. The stoves are currently open flame, uninsulated burners.

To summarize, the Kisii prison digester has a lid with a leaky seal, the digester is not connected to the sewage lines, the sewage lines do not separate wastewater from disinfecting water, the digester doesn't produce enough gas, the pressure is too low to consistently reach parts of the prison, and the current cookers are not modified for biogas use.

## Solution Procedures

Sealing the lid of the digester is as simple as removing it, ensuring proper fitting, and resealing with a clay barrier while submerging it in a water bath. To address the issue of inadequate gas production, more waste must be input into the digester. This should be done by attaching the sewage lines to the digester and reconfiguring the system to separate actual waste from disinfectant water. To address the pressure problem in the women's block, a separate gas line could be installed dipped directly from the digester to the women's kitchen, by passing the men's kitchen. A prototype design should be made which modifies a jiko to use biogas. This could be done by opening up the sides of the bottom of the jiko to allow for better airflow while still insulating the cooking area.

Observations and Conclusions

In general, prison officials were not properly educated and instructed by the sponsoring parties as to the proper operational procedures of the digesters. This cannot be faulted to one group, but is a fundamental problem that must be resolved for the success of this project. Furthermore, it would appear that there was inadequate supervision and insubstantial involvement by the technical specialists from UN-Habitat and the PCP. A more integrated and involved approach must be taken to ensure quality of design and effectiveness of operation.

In both prisons, neither of the digesters is connected to the sewage lines, which largely defeats the purpose of installing them. This must be rectified. In the Kisii prison, it is imperative to install a system which allows for water used for cleaning to be diverted away from the sewage line which leads to the digester.

The digesters are of a generic size which was not tailored to the prison. The Homa Bay prison and Kisii prison digesters are both 124m$^3$ despite the fact that Kisii has nearly 4 times as many inmates. Having an improperly sized digester can result in increased an unideal Hydraulic Retention Times and wasted space and materials.

Figure B.5: Kisii Images

Recommendations for Future Development

The sites must be revisited for more intensive analysis and testing. This can include further testing and pressurizing of the system to observe any gas or civil works leakage.

- The elevation of the civil works at Homa Bay must be adjusted
- Separate wastewater and cleaning water lines must be established at both sites, primarily at Kisii
- Cooking jikos can be modified for biogas use and could include an air baffle system along the line to improve air mixing
- Gas line integrity should be assessed and rectified where necessary
- Pressure valves and meters should be installed at various points along the gas line

Most importantly, the prison officials need to be properly educated in the operation of all of the processes involved in the configuration of the biogas digesters. These projects failed to live up to the expectations because there was some sort of breakdown in communication and involvement from both parties deteriorated in a manner unconducive to productive development. Manuals can be made for operation, scheduled inspections can be made by the sponsoring organizations, regular meetings and lines of communication can be established to express and analyze the effectiveness of the program’s operation. In short, those operating the digesters need to have the support and background necessary to do so.