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Biogas in Nepal: Limitations for the Expansion of Community Plants

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Miljøfysikk og fornybar energi

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Abstract

A large amount of the world population still rely on the use of solid biomass for cooking. The implementation of the biogas support program (BSP) in 1992 has successfully contributed to the popularization of biogas in Nepal and helped reduce the dependency on traditional fuels by introducing a sustainable alternative. Even though the extended use of biogas has had a positive impact on the environment and health of thousands of Nepalese families, the technology has yet to benefit the poorest portion of the population due to the relatively high construction costs. Promoting the use of community biogas plants over private household digesters can reduce the economic cost per volume of gas produced and opens the opportunity to run commercial applications, making the biogas plant a potential source of income. However, based on paper reviews and an inspection of two community plants in the Southern region of Nepal, there seems to be a strong tendency for community plants to fail. This failure is often related to social conflict that arises within the community and results in mismanagement and in many cases the abandonment of the plant. The GGC biogas plant design that is standardized in Nepal is used for both single household and community plants, but is not properly optimized for community use. Modifying the plant design to ease cooperation and management i.e. by separating the gas storage for each household within the community, could help mitigate social conflict. More research and development in this regard is necessary to determine the present state and functionality of existing community plants, and to create a more appropriate design for community biogas in Nepal.

Abbreviations

ADB/N – Agricultural Development Bank

AECP – Alternative Energy Promotion Center

BSP – Biogas support program

BSP-N – Biogas Sector Partnership – Nepal

CGN – Clean and Green Nepal

GGC – Gobar Gas Company

IEA - International Energy Agency

LHV- Lower heating value

NGO – Nongovernmental organization

RW – Renewable World

SNV – Netherlands Development Organization

WHO – World Health Organization

CONTENTS

1 OVERVIEW

1.1 Introduction

The world's energy demand is increasing rapidly. This has been especially true for industrialized countries and transition countries since the onset of industrialization (Graßl, et al., 2004). The present stress on the global energy system is concerning as greenhouse-gas emissions are continuing to rise and conflict between countries, such as Ukraine and Russia or in the Middle East, is threatening a stable energy supply. At the same time, an estimated 1,2 billion people still live without access to electricity and many countries are still catching up on development. As a result, it was predicted in 2014 that the energy demand would increase by 37 percent by 2040 with India and China being the biggest consumers (IEA, 2015).

An adequate energy supply is a precondition to economic growth, making energy central in the process of relieving poverty and increasing living standards. However, a large portion of today's energy supply is based on fossil fuels and has become a threat to our planet's eco system and thus ourselves. A shift is necessary, where renewable energy gains ground and replaces fossil fuels as the leading energy supply. The goal with renewable energy is good health, high living standards, a sustainable economy and a clean environment. No form of energy is good or bad in itself, but is only as valuable as far as it can deliver this goal. Wood is the main source for fuel in developing countries with about 38 percent of the world's population depending on traditional use of biomass (IEA, 2015). The demand for wood is increasing with the need for fuel, construction materials and a growing population. As a result, Earth's total forest areas are diminishing with consequences for global warming, but also for the local population: their income and traditional source of fuel is being depleted; the risk of draught and flood is increased; and they are forced to invest in expensive fuels. It has become obvious that traditional fuels are unsustainable in many areas.

A conflict of interest has emerged for developing countries as the conventional and most affordable sources of energy often are the least sustainable. A political decision must be made within each country as to what degree they are willing to sacrifice environment and health to keep up with commercial development. From a scientific standpoint, the challenge revolves how to promote sustainable technologies and make them affordable. This conflict is present in Nepal, a country where 80 percent of the population still relied on traditional use of biomass and 7 million people had no access to electricity in 2013 (IEA, 2015). However, Nepal has a significant potential for developing both hydropower and biogas. Political and economic investment in these fields has encouraged sustainable development, but has not reached its full potential.

In Nepal, the development of biogas technology has had a positive economic and health impact on rural households and has blossomed into an industry with more than 100 registered private companies (BSP-N, 2012). Unfortunately, the traditional plant design has its limitations and require a relatively high initial economic investment. For this reason, the biogas technology has yet to benefit the poorest portion of Nepal's population (Bajgain & Shakya, 2005; BSP-Nepal, 2005). Promoting community biogas plants can reduce the "entrance fee" on the technology, but experience show that social challenges often rise within the community and is limiting the benefits of community plants (Finlay, et al., 2013; Lichtman, 1982). Dedication and proper training of the users is imperative to make community plants functional. In addition, the plant has to be designed specifically for each community to satisfy the users' needs and capabilities in an effort to mitigate social conflict.

1.2 Aim of thesis

The aim of this thesis is to review the present limitations on the expansion of community biogas plants in Nepal. This thesis does not include any information on the current health of community plants in general, but only presents challenges that have risen in specific cases.

This thesis defines community plants as a centralized biogas plant with two key characteristics: (I) it is supplied by feedstock from all connected households, either manually or through pipes and (II) managed and owned by the community, usually though an organization. Community plants are different from single household plants because more than one household is connected and is different from institutional plants in the way it is managed and owned by a group of people, rather than a single individual or institution.

1.3 Problem description

Single household biogas plants have successfully contributed to improve the health and economic situation for thousands of Nepalese families and is continuing to do so at an increased rate (Sidgel, 2007; Bajgain & Shakya, 2005). Several users' survey confirm that the development has been a success and 97 percent of the digesters were estimated to be operational in 2013 (MEG, 2013; NESS, 2011). However, two key parameters are limiting the beneficial outcome of biogas:

1. **Technical limitations.** Temperature is by far the most important parameter in terms of plant performance. Seasonal variances can reduce biogas production by 50 percent (Finlay, et al., 2013), and is the reason for why almost one third of the users receive sufficient gas in the summer months only (MEG, 2013). Climate is also limiting expansion of biogas to the mountain regions of Nepal, concentrating the technology to the southern districts (Bajgain & Shakya, 2005).

2. **It is expensive to build and maintain a digester.** The wealth requirement to build and properly maintain a digester is relatively high. The farmer needs sufficient cattle, water and economic strength to apply for a subsidy and build a digester. This is preventing biogas from benefiting the poorer families and has been a point of critique of the technology (BSP-Nepal, 2005).

Point 1 is general for all biogas plants, but can be improved by design and is covered in more detail in section 4.4. Point 2 is primarily mitigated with economic aid from governmental subsidies and NGO's (BSP-Nepal, 2005). However, these solutions make the farmers and the development of biogas dependent on a third party. The alternative is to introduce technology that lowers the wealth barrier and makes it possible for poorer farmers to enjoy the benefits of biogas. Constructing community plants can be a solution in terms of economic effectiveness, as it reduces the capital cost per volume of gas produced in addition to several other benefits such increased gas production for alternative applications and the possibility to connect community toilets (Sarkar & Uddin, 213). Unfortunately, community plants present a new challenge:

3. **Community biogas plants have high failure rates.** The failure rate on single household digesters is suggested to be as low as 3 percent in Nepal. An equivalent study has not been completed for community plants, but it is generally understood that the failure rate on community plants is much higher (Finlay, et al., 2013; Lichtman, 1982). This is often related to social problems and failure to cooperate within the community. Note that all the community plants investigated in this thesis have been financed by NGO's, which could have an impact on the failure rate due to reduced sense of ownership of the plant.

The reasons for the high failure rates are complex and not well documented, but the standard approach to negate this problem involves social solutions such as better training and more rigorously conducted feasibility studies (BSP-Nepal, 2005). Some reports also recommend "community testing" by requiring the community to start digging or build a road before the plant construction can begin (Finlay, et al., 2013). These solutions are viable, but they are beyond the scope of this thesis. Instead, the focus lies in mitigating social problems through technical solutions. Ideally, a combined effort of social and technical improvements must be implemented to make community plants viable. The complexity of the community also makes it so that different solutions fit better for different communities. The plant needs to be appropriate to the needs and capabilities of its users. Only then, will it be correctly operated and maintained.

1.4 Methodology and disposition

Most of the information presented in this thesis is based on paper reviews. This includes contextual background, a technical introduction to biogas technology, its most relevant applications, its development in Nepal and examples from existing community plants. *Section 5.1* also includes firsthand experience from the recently constructed Jamuni and Jahirpur community plants in southern Nepal and information from studies and interviews by/with Biogas Sector Partnership – Nepal (BSP-Nepal), Alternative Energy Promotion Center (AECP), Renewable World (RW) and Clean and Green Nepal (CGN).

There is limited information available on the status of existing plants. Many reports are written shortly after construction and do not give enough time for social problems to develop. For this reason, the failure rate of community plants in Nepal remain unknown and the conclusions reached in this thesis cannot be used to generalize the status quo of existing community plants.

2 CONTEXTUAL BACKGROUND

A biogas plant needs to be designed specifically to accommodate its users. Social, economic and geographical parameters are important considerations. Generally, the plants in Nepal need to be cheap, easy to build and somewhat insulated.

2.1 Geography

Nepal is located in Southern Asia and is land locked between India and China. The landscape is diverse and the elevation goes from less than 100 meters in the south to the Himalayan heights in the north. This has a great impact on Nepal's climate. The southern areas experience subtropical, wet summers and mild winters. The north is dominated by cool summers and severe winters in a tundra-like environment. Precipitation also varies greatly with the annual average ranging from 250 to 4500 mm (WECS, 2010).

2.2 Economy and demography

Nepal's population was estimated to be 28 million in 2014 (World Bank, 2014). About 7% of people live in the Mountain region, which occupies 35% of the land area. Hilly region occupies about 42% of the area and supports about 44% of the population. The Terai occupies only 23% Nepal's land mass, but is the most fertile region and supports almost half the population (WECS, 2010). Nepal is among the poorest countries in South Asia, with about one-quarter of its population living below the poverty line. Agriculture provides livelihood to about 70% of the population and accounts for almost one third of GDP (Sijapati, et al., 2015).

2.3 Energy demand

Failure in developing alternative energy has resulted in a growing energy crisis despite the high potential for hydroelectric power (Ministry of Finance, 2015). Total energy consumption in 2013/2014 was about 130,6 TWh and a summary of energy development can be seen in *table 1*. The energy sources can be split in three main categories: traditional fuels, commercial energy and alternative energy.

Table 1: Energy consumption status in Nepal [TWh].

Energy Source	2008/09	2009/10	2010/11	2011/12*	2012/13	2013/14
Traditional:						
Cattle Manure	6,3	6,4	6,5	5,2	5,9	5,0
Firewood	84,9	86,8	88,5	73,0	83,2	94,8
Agricultural residues	2,8	3,8	3,8	3,6	4,1	4,7
Sum Traditional	95,2	97,0	98,9	81,8	93,2	104,5
Commercial:						
Hydropower	2,1	2,5	2,7	2,9	3,0	4,3
Coal	2,1	3,3	3,4	4,0	4,8	3,7
Petroleum products	9,0	11,2	12,3	12,6	13,7	14,7
Sum Commercial	13,2	17,0	18,4	19,5	21,6	22,8
Sum Alternative	0,7	0,8	0,9	1,3	1,9	3,4
Total	**109,2**	**114,9**	**118,1**	**102,6**	**116,7**	**130,6**

* Based on Survey Statistics.

Source: (Ministry of Finance, 2015)

2.3.1 Traditional Fuels

This energy sector dominates the demand and consumption in Nepal and contributes to about 80% of total consumption. Firewood is by far the single most important source of fuel for the rural population, where wood alone supplies 80% of fuel needs compared to 36% in urban areas (WHO, 2010). This fraction has been somewhat reduced in the last 10 years, but the overall consumption is still increasing, meaning alternative energy sources are developing too slow compared to the demand. It is crucial to keep firewood available, but the excessive lumbering is threatening Nepal's forests and contributed to a reduction of 24,5% in the forest cover between 1990 and 2005 (FAO, 2005). Policies have been introduced in an effort to reduce consumption, but they are often hard to implement, as the dependency is too great. Commercially viable alternatives must be introduced before these policies can be effective.

2.3.2 Commercial Energy

Commercial energy includes hydropower and fossil fuels. Nepal's energy supply has been described as insufficient, unreliable and expensive (Bergner, 2012). About 30% of the rural population has no access to electricity (IEA, 2015) and some areas bear with load shedding (planned blackouts) of up to 16 hours during dry season (Bergner, 2012). Additionally, Nepal being a land locked country makes import of fossil fuels expensive and limited. The Himalayas block trade with China and the border with India was closed several times in 2015/16 (Pattisson, 2015; Kathmandu Post, 2016). However, Nepal has the possibility to satisfy its national energy demand with a hydroelectric potential of about 42.000 MW. This sector is still much underdeveloped and less than 2% of the potential hydropower was installed in 2010 (WECS, 2010).

2.3.3 Alternative energy

Alternative energy includes solar, biogas, wind and small-scale hydropower and is the fastest developing energy sector in Nepal, but still only contributes to less than 3% of the total energy consumption. The need to speed up the expansion of this sector to replace traditional and unsustainable conventional fuels is crucial for the development of improved health, economy and environment. Biogas has been especially attractive since a large amount of the populations are farmers or relate their work to agriculture. An estimated biogas potential of 1,5 - 2 billion cubic meters per year was made in 2008/09, based on the number of cattle available to the population (WECS, 2010). In theory, this could produce 9 to 12 TWh and considering biogas' superior thermic efficiency over wood, it could reduce Nepal's firewood consumption by about ¾ (Finlay, et al., 2013). This is an unrealistic estimate, but it shows that the economic, health and environmental impact of biogas are important even if only a portion of the potential is installed.

3 REVIEW ON BIOGAS TECHNOLOGY

3.1 Biogas in Nepal

The use of biogas has been expanding rapidly in Nepal since the biogas support program (BSP) was initiated in 1992 by the Netherlands Development Organization (SNV) with the financial support from the Netherlands Directorate-General for International Cooperation (DGIS). At the time there was only one company, the Gobar Gas Company (GGC), building and managing biogas plants and only one bank, the Agricultural Development Bank (formerly ADB/N), providing loans to biogas farmers (SNV, 2009). The purpose of BSP was to promote and popularize the use of biogas. It was a success in terms of sustainable development with more than 200.000 units installed by 2010. Today, biogas has become its own industry with more than 350.000 constructed plants total (Amatya, 2016) and over 100 registered private construction companies (BSP-N, 2012). The development of the number of biogas plants that were installed by BSP from 1992 to 2012 is shown in *figure 1*, showing that biogas has been successfully popularized in Nepal. The technical biogas potential was estimated to be over one million plants based on the number of households with cattle in 2001, which of 57 percent were located in the Terai region (BSP-N, 2012). Assuming 350.000 units in 2016 and a construction rate of 20.000 new plants per year, it would take about 33 years to reach the maximum potential that was estimated in 2001. However, this calculation does not take into account an increased buffalo and cow population or the introduction of agricultural residues or other substrates in the biogas production.

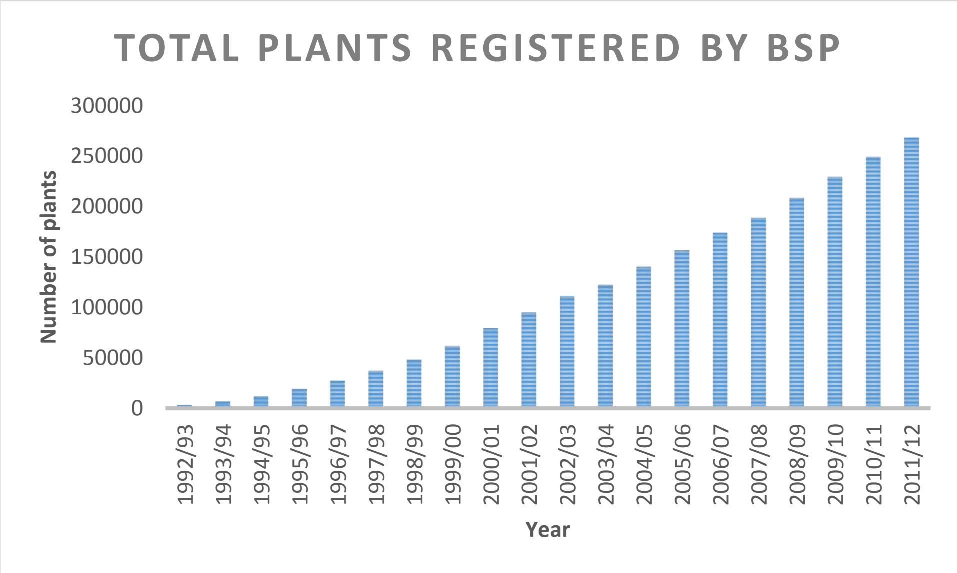

Figure 1. Cumulative number of biogas plants installed by BSP in the period 1992 to 2012. Adapted from BSP-N, 2012.

3.2 Characteristics

Biogas is produced by the breakdown of organic matter in the absence of oxygen (anaerobic digestion), given the right conditions. This process is called the biogas process and heavily depends on the presence of methane-producing bacteria (methanogens). To ensure the function and continued growth of the bacteria, certain requirements have to be met: an energy source such as hydrogen, fats or sugars (Karlsson, et al., 2014); electron acceptors for anaerobic respiration (Ruiz-Aguilar, et al., 2015); building blocks to increase the biomass of the microorganism, mostly carbon and oxygen (Madigan, et al., 2015); and the presence of specific trace elements and vitamins, depending on type of bacteria (Scherer & Sahm, 1913). Additionally, various environmental conditions such as temperature, pH and the concentrations of oxygen and salts have an impact on the characteristics of the gas produced (Schnürer & Jarvis, 2009).

Biogas is used as a fuel, making its energy content an important characteristic. The heat of combustion, which is the total energy released as heat from complete combustion, is related to its methane content and can be estimated by *equation 1* (Smith, et al., 2005).

$$H^{o}_{c,biogas} = H_{c}{}^{o}_{CH4} \cdot p_{CH4} \qquad (1)$$

Where $H^{o}_{c,biogas}$ is the heat of combustion of the biogas [kJ/mol]

$H^{o}_{c,CH4}$ is the heat of combustion of methane [kJ/mol]

p_{CH4} is the portion of methane present in the biogas, %

Methane usually makes up 50-75% of the biogas. Other components include carbon dioxide (25-45%), water vapor (2-7%), oxygen (< 2%), nitrogen (< 2%), ammonia (< 1%), hydrogen (< 1%) and hydrogen sulfide (< 1%) (Al Seadi, et al., 2008). The exact composition of the biogas depends on various operational conditions mentioned above. The properties of biogas when assumed to consist of 58% methane, 42% carbon dioxide, saturated with water vapor at 30 °C and standard pressure is given in *table 2*.

Table 2. Properties of biogas assuming 58% methane, 42% carbon dioxide, saturated with water vapor at 30 °C and standard pressure.

Heat of combustion	516,78 kJ/mol
Effective molecular weight	27,351 (24 to 29)
Density	1,0994 kg/m^3 (0,96 to 1,17)
Specific gravity (air 30 °C)	0,94 (0,82 to 1,00)
Viscosity	1,297 × 10^{-5} kg s^{-1} m^{-1}
Air to fuel ratio	5,5 : 1 (15% biogas) Stoichiometric
Flammability limits	9% to 17% biogas in air
Wobbe Number	27,7 kJ/L

Adapted from Finlay et al., 2013.

3.3 Applications

Biogas is a high-grade fuel and burns at about 1.900 °C in air, making it appropriate for many applications (Caine, 2000). It has been used to run small commercial operations, such as in processing animal products, distilling alcohol and drying crops (Finlay, et al., 2013). Biogas can also be used to run refrigerators and irrigation systems, which could have positive implications for an agricultural economy (Simgas, 2016; Abdel-Galil, et al., 2008). However, biogas is mainly used for cooking, as this is the simplest application and with great benefits.

3.3.1 Cooking

Cooking is by far the most important application of biogas and most household plants in Nepal are connected directly to the kitchen through pipes. Biogas is superior to firewood in many ways, as it has a considerably less negative health impact and does not require physically intensive labor to produce. Additionally, biogas is more energy effective compared to firewood, meaning that a larger portion of the heat is transferred from the fuel to the food when cooking. The thermal efficiency can be estimated as the product of the combustion efficiency, which is the percentage of the chemical energy in the fuel that is actually released, and heat transfer efficiency, which is the percentage of released heat that has successfully been transferred to the receiving material, that is:

$$\eta = \eta c \cdot \eta r \quad (2)$$

Where η is the overall thermal efficiency, %

ηc is the combustion efficiency, %

ηr is the heat transfer efficiency, %

A study by National Risk Management Research Laboratory in 2000 found the combustion efficiency for biogas to be slightly superior to all tested firewood types (ηc for biogas > 0,98 compared to 0,77-0,96 for firewood depending on species). However, the study found the overall thermal efficiency of biogas to be about twice as efficient compared to the best performing wood (NRMRL, 2000). This implies that the heat transfer efficiency is an important advantage for biogas and the performance relies on specialized stoves. One cubic meter of biogas is often estimated to replace 5,5 kg of wood (Mang & Li, 2010), but this greatly depends on environmental conditions. A comparison between the heat transfer efficiencies of different types of fuel stoves is summarized in *table* 3. Electric stoves are the most energy effective stoves, but converting electricity to heat is not desirable when electricity is scarce.

Table 3. Typical values for efficiency comparison between various types of stoves (Conter for Energy Studies, Tribhuvan University, 2001)

Type of stove	**Stove efficiency, η_s [%]***
Biogas stove	45-55
LPG stove	60
Kerosene Stove	43
Wood stove	10
Improved wood stove	20
Electric stove	70

* Depends on environmental conditions, type of vessel, burner size compared to vessel size, burner type and fuel quality.

3.3.2 Lighting

Biogas can be used in specialized lamps to produce light. The lamps consume 0,07 to 0,14 m^3 of gas per hour and emit a clear light equivalent of 40 to 100 candles. The opportunity for extended lighting is a basic need and a status symbol that can be used to promote biogas. About 12 percent of Nepal's single household digesters have been reported to light at least one lamp (BSP-Nepal, 2005). However, the lamps are expensive, ineffective and require service. Additionally, the lamps are calibrated to pressure and may break if the pressure increases, which is problematic with the traditional digester designs (Finlay, et al., 2013). Biogas lamps are a good addition if there is gas surplus of biogas, but they perform worse than both electric and kerosene lamps (Kossmann, et al., 1999).

3.3.3 Commercial use

Biogas can be used in internal combustion engines to run income-generating activities such as small-scale cottage industries, grain mills or irrigation pumps. This offers a decentralized power supply generated by the villagers, using their own resources, close to where animals and crops grow and could increase living standards in rural areas, in addition to reduce urbanization by attracting the young.

The high methane content in biogas makes it an attractive fuel for internal combustion engines (Sanks, et al., 1998). Biogas can be used in both petrol (spark ignition) and diesel (spontaneous ignition) engines. Petrol engines normally run on gasoline, but some are designed to use kerosene, natural gas or alcohol. Biogas can be used directly in petrol engines, but runs inefficiently and produces less power compared to when the engine runs on gasoline (Mihic, 2004). To use biogas in diesel engines, some engine modifications are required due to biogas' high ignition temperature. These modified engines are called dual fuel engines and run on a mixture of air and gaseous fuel as its primary fuel, but still require small amounts of diesel (10-20%) to promote ignition (Ray, et al., 2013). The advantages of dual fuel engines are: operation on diesel is still possible without biogas; any concentration of 0 to 85 percent biogas can substitute a corresponding part of diesel fuel while keeping performance close to 100% diesel fuel operation (M.Duc & Wattanavichien, 2007); and the speed and power of the engine can be easily controlled by changing the amount of diesel injected. However, the use of dual fuel engines cannot operate without a diesel supply and it is recommended to check the injector nozzle regularly due to possible overheating (Ray, et al., 2013).

Generally, biogas is treated to some degree before it is used in internal combustion engines. Biogas consists of varying concentrations of carbon dioxide, hydrogen sulfite and water vapor. It is desirable to remove these gases to increase the portion of methane and thus increase the power output of the engine. Additionally, the presence of hydrogen sulfide can cause severe corrosion damage to the engine and high moisture can cause starting problems (von Mitzlaff, 1988). Carbon dioxide and hydrogen sulfide is removable by water scrubbing since both carbon dioxide and hydrogen sulfide are more soluble in water than in methane. The degree of purification achieved depends on factors such as gas flow pressure, composition of biogas, water purity, and dimension of scrubbing tower (Kapdi, et al., 2003). The solution produced by water scrubbing is acidic and needs careful disposal. Reducing the humidity of the gas is much easier and can be done by cooling the gas and trapping the condensate (von Mitzlaff, 1988).

It is possible to operate an internal combustion engine with low quality gas (Ga, et al., 2014). However, this technology has not been popularized in Nepal, as it would require relatively big plants to produce enough gas for both cooking and commercial use. In addition, the need of a modified engine and possible treatment increases the economic constructing and operational costs.

3.3.4 Bio Manure

A biogas plant treats the feed material used, resulting in biogas and a digested residual product called digestate. Bio-fertilizer is produced whenever the feed material consists of “pure” substances such as manure, food waste or plant materials. The mineral nutrition available in the organic material is released and concentrated in the bio-manure and can be used as high-grade fertilizer for food production. The quality of the bio-manure is determined by the type of substrate, pre-treatment method, process conditions and storage. According to some reports, the bio-manure has the potential to give similar or even better crop yields than mineral fertilizers and has positive effects on the soil chemical status, soil structure and microorganisms (Avfall Sverige, 2005; Odlare, et al., 2008).

In Nepal, it is common practice to collect cow dung to use as fertilizer or fuel after drying. However, the anaerobic digestion of manure has three important benefits compared to using raw manure:

- Generally, nutrients in raw manure cannot be directly absorbed by the roots of the plants, increasing the risk of groundwater contamination and can cause eutrophication (Schnürer & Jarvis, 2009).
- Anaerobic digestion reduces risk of emissions of methane and nitrous oxide as most of the methane has already been produced and stored. Compared to carbon dioxide, these gases are about 20 and 300 times more potent in terms of the greenhouse effect (Börjesson & Mattiasson, 2008; Blasing, 2016).
- Anaerobic digestion of manure reduces both the number of pathogenic microorganisms and the concentration of malodorous components in the manure (BSP-Nepal, 2005).

The benefits of using bio-manure as fertilizer are many, but some farmers in Nepal do not seem to realize the importance of the bio manure and leave it mismanaged. Proper storage is important to prevent sedimentation of organic material and to prevent gaseous emissions of ammonia, nitrous oxide and methane. BSP-N recommends mixing the fertilizer with various organic materials and kitchen waste to produce compost (BSP-Nepal, 2005). This results in a dry fertilizer that is easier to apply to the fields in addition to counteract the drawbacks of long storage periods. The compost may also be used for mushroom production and fish breeding (Hennekens, 2015).

3.4 Benefits

Biogas is a special technology in the sense that it uses a free and readily available resource to produce both fuel and fertilizer. Families that replace their consumption of firewood with biogas are often satisfied with the outcome (BSP-N, 2010). The most important advantages are not always directly related to the use of biogas, but rather to the replacement of firewood. Many of the suggested benefits are therefore not limited to biogas, but could be attached to other sustainable fuel replacements. The main reason to use biogas over other renewable energy sources is because the technology is cheap, reliable and the resources to build and run a biogas plant are readily available for a large portion of the population.

3.4.1 Health

According to the World Health Organization, almost 23.000 people died from diseases related to household air pollution in 2012 in Nepal alone (WHO, 2012). The flame produced by burning biogas is smokeless and does not expose the user to toxic fumes. Replacing firewood with biogas reduces indoor air pollution and noticeable improvements in respiratory health and reductions in eye problems have been reported as a result (Berkeley Air Monitoring Group, 2015). Additionally, a biogas plant partly works as a wastewater treatment plant and increases hygiene. Farmers using night soil or liquid manure to fertilize their fields are exposed to gastrointestinal diseases, such as ancylostomiasis and dysentery, by the transmission of pathogens from the fecal matter. The biogas process greatly reduces the pathogenic capacity of the feeding material and reduces unpleasant odor. Health improvements following biogas implementation have been reported in rural China, with reductions in schistosomiasis and tapeworm of 90–99 percent and 13 percent respectively (ISTAT/GTZ, 1999).

3.4.2 Reduction in workload

SNV estimates a 3 hours reduction in workload by switching to biogas from firewood (SNV, 2009). Wood is related to time-consuming activities, such as gathering and attending the fire, and become even more work intensive as firewood becomes scarcer. The biogas plant can be connected directly to a burner in the kitchen and the flame comes on instantly. The smokeless flame also reduces the need for cleaning cooking pots. This makes women the main benefiter of biogas technology since they are responsible for both wood collecting and cooking in many cases.

3.4.3 Environment

Biogas has a positive impact on the environment both globally and locally. Globally, the use of renewable energy reduces the carbon dioxide emissions by lowering demand of fossil- and traditional fuels. Solid biomass fuels typically undergo incomplete combustion and have low thermal effectiveness compared to liquid and gaseous fuels. As a result, the use of firewood releases increased amounts of carbon dioxide and particles of incomplete combustion compared to biogas (NRMRL, 2000). The biogas plants also capture uncontrolled methane emissions from the cattle manure (ISTAT/GTZ, 1999). On a local level, the use of biogas mitigates deforestation by reducing the dependency on firewood and producing fertilizer, which in turn restores nutrients to the soil and reduces the need to clear new areas for cultivation. Preventing deforestation is especially important in Nepal as the tree cover stabilizes the steep slopes and mitigates the impact of the raining season. A reduced tree cover increases the chance of floods and landslides, as the top soil is washed away and the water absorbing capabilities of the earth is reduced (DPNet-Nepal, 2013).

3.4.4 Economy

For the user, the economic benefits are mostly related to the financial costs in purchasing fuel and fertilizer. The economic benefits become more apparent in community biogas plants, where the capital cost per volume of gas produced is reduced. Theoretically, an increased quantity of gas production opens the possibility to run an engine for commercial purposes and can directly increase the income of the entire community. It is also possible to sell any excess gas or fertilizer provided there is a means of transportation and a local demand. Biogas also increases employment with the construction for new plants and manufacture of building materials (BSP-Nepal, 2005).

3.5 Disadvantages

Biogas has several notable disadvantages: it usually does not generate a direct income, making the economic benefits less visible for the user; requires daily feeding of manure and more water to be collected; and in some cases has been reported to increase the mosquito population. Additionally, the reduced use of firewood and indoor soot pollution make insects, such as ants and termites, more likely to damage the wooden roofs of traditional rural household (BSP-Nepal, 2005).

3.6 The biogas process

The digestion of organic materials is complex. Chemical, physical and biological processes take place to break down proteins, sugars and fats. A mixture of gases emerges as a byproduct, but the nutritional and environmental requirements must be satisfied to produce biogas. The decomposition is a multi-staged process where several microbial communities cooperate through the following four main steps (depicted in *figure 2*):

1. **Hydrolysis.** A large number of different types of specialized enzymes produced by bacteria react with water and break down carbohydrates, proteins and fats into simple sugars, amino acids, fatty acids and alcohol. These constituents are essential nutrients for the microorganisms responsible for the following steps. Hydrolysis can be accelerated by pretreating the substrate i.e. by heating or reducing particle size (mixing or shredding).
2. **Acidogenesis (Fermentation).** Most of the products from the hydrolysis stage are further broken down by various types of bacteria, producing alcohols, ammonia, carbon dioxide, hydrogen and organic acids (butyric acid, succinic acid, lactic acid etc.).
3. **Acetogenesis (Anaerobic oxidation).** This step is regulated by the concentration of hydrogen gas. The bacteria involved with the oxidation of the byproducts from the fermentation step require low concentrations of hydrogen, which is only possible if the hydrogen gas is being consumed as it is produced. The products from the fermentation process are further broken down into acetate, hydrogen and carbon dioxide. The microorganisms involved in this and the previous step consume nitrogen, carbon and oxygen and set the anaerobic conditions that are essential for the methanogens.
4. **Methanogenesis.** Biogas is formed in this last stage by various methanogens. The substrates used are hydrogen gas, carbon dioxide, acetate, methylamines, alcohols and formates. Acetate is the source to about 70 percent of the biogas produced in a digestion tank, making acetotrophic methanogens the dominant methane-producing bacteria (Zinder, 1993 in

Schnürer & Jarvis, 2009). Another important group of methanogens, called hydrogenotrophs, uses hydrogen gas and carbon dioxide as their primary substrate. The methanogenesis is often the rate-limiting factor in a biogas plant because they grow very slowly, with a doubling time of up to 12 days. They are also easily affected by changes in the environment such as pH or concentration of toxins.

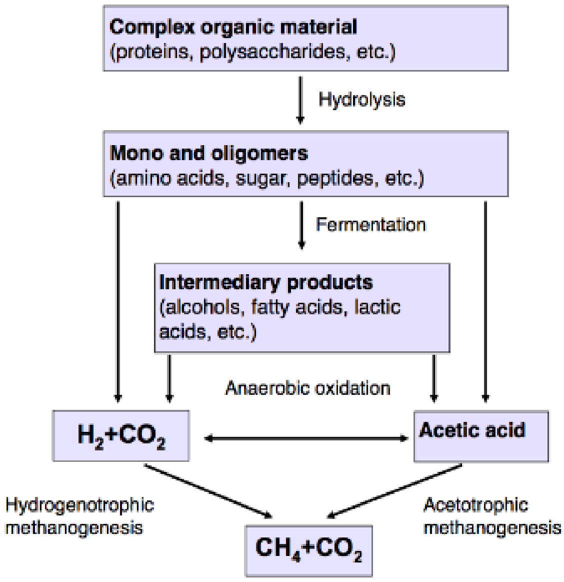

Figure 2. A simplified diagram of the production of biogas (Schnürer & Jarvis, 2009).

3.7 Important parameters

Since methane is the energy carrier in biogas, it is often interesting to consider how to maximize its production. This section reviews some of the many parameters that decide the rate of methane production, including temperature, retention time and substrate characteristics.

3.7.1 Temperature

The types of bacteria involved in the biogas process are classified depending on the temperature range in which they operate: psychrophilic (4-25 °C), mesophilic (25-40 °C) and thermophilic (50-60 °C). It is desirable to have a system operating in the mesophilic or thermophilic range and most conventional biogas plants operate in these temperatures (Schnürer & Jarvis, 2009). An external heat supply is often necessary to reach this requirement, as most of the energy released during anaerobic digestion is utilized to produce methane and releases very little heat.

Rising the temperature of the system has many potential advantages: it increases solubility of organic compounds; chemical and biological reaction rates; diffusivity of soluble substrate; death rate of pathogenic bacteria; and degradation of long chain fatty acids, volatile fatty acids and other intermediates (Bouallagui, et al., 2003). One downside with higher temperature is the increased fraction of free-ammonia, which is inhibitory to microorganisms. However, as long as the temperature is within a range that can be tolerated by the biological system, the temperature dependence of the specific reaction rate, k, can be described by the Arrhenius equation:

$$k(T) = A\ exp(-\frac{E}{RT}) \tag{3}$$

Where A is the preexponential factor or frequency factor, a constant for the reaction

E is the activation energy [J/mol]

R is the ideal gas constant [= 8,314 J/mol K]

T is the absolute temperature [K]

The constants A and E in equation (1) take into consideration all other parameters including substrate characteristics and operational conditions. Thus, A and E must be found experimentally for each biogas system, but a common rule of thumb is that an increase of 10 °C doubles reaction rate (Batista, et al., 2013). One study from Nepal using various types of biogas plants running on manure over a period of two years, found A = $7,5\times10^9$ and (E/R) = 7780, resulting in the graph in *figure 3*. The results portray the impact of seasonal temperature changes on the system and suggest that the production rate could be reduced by 50 percent or more, depending on the severity of the winter.

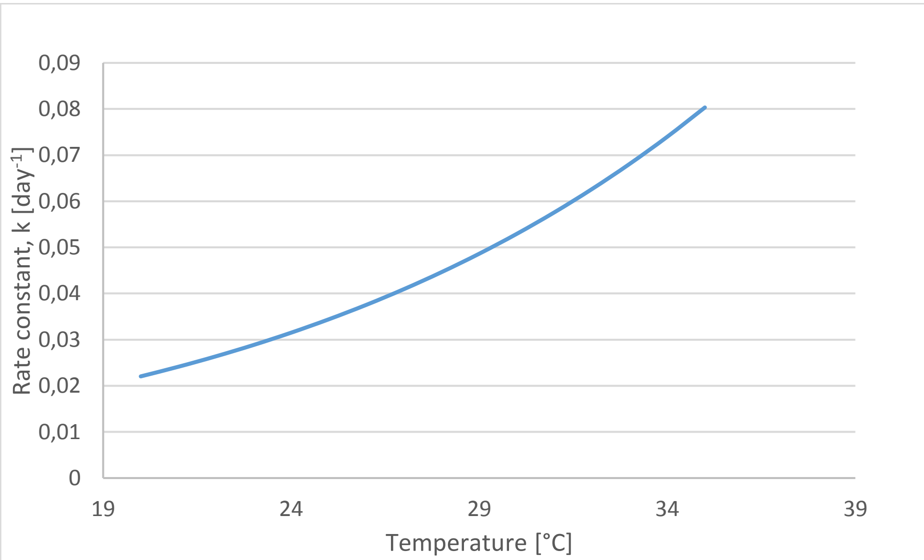

Figure 3. Graphic representation of temperature dependency of reaction rate using the Arrhenius equation with A = $7,5\times10^9$ and E/R = 7780. Adapted from Biogas – Challenges And Experience From Nepal Vol. II (Finlay, et al., 2013).

3.7.2 Retention time

Retention time (RT) is the average time the feed material spends inside the digester. RT normally ranges between 40 to 60 days for simple cow-manure plants, depending mostly on substrate characteristics and temperature (BSP-Nepal, 2005). RT also depends on the desired degree of digestion, defined as the percentage of the organic material broken down and converted into biogas during a specific period. More time inside the digester leads to more methane being produced, but as the nutrients are consumed, the process slows down until no more substrate can be converted. The maximum degree of digestion depends on substrate and common values for different substrates are shown in *table 4*.

Table 4. Approximate degree of digestion for some substrates (Edström & Nordberg, 2004).

Raw material	Degradation ratio (% of VS)
Cattle manure	35
Pig manure	46
Forage crops	64
Sugar beets	93
Fruit and vegetable waste	91

Optimizing RT to reaction rate is convenient to maximize gas production whenever the feed material is abundant. *Figure 4* shows how this has been done experimentally in Nepal by plotting gas production rate against retention time. Increasing temperature affects the reaction rate and thus reduces the optimal retention time (RT_{opt}). The sharp slope before RT_{opt}, signifies wash out of the microorganisms. Operating the plant too close to RT_{opt} is not advisable, as a decrease in temperature can shift R_{opt} to the right, resulting in a washout. For this reason, all the plants studied in *figure 4* are operating in the gentle slope after RT_{opt}.

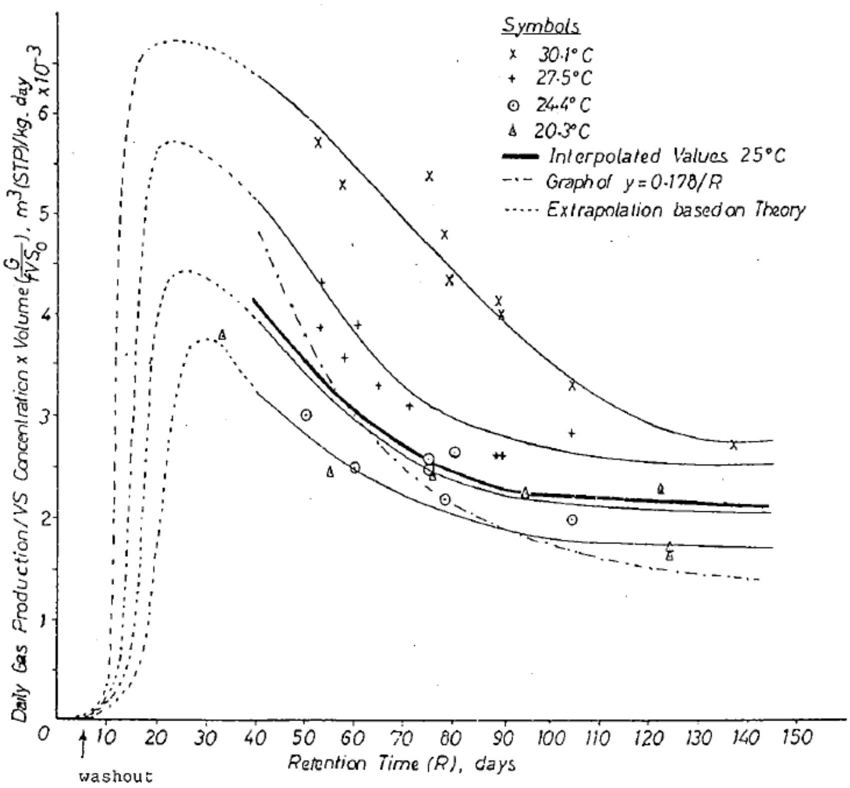

Figure 4. Graphic representation of optimal retention time based on maximum reaction rate. For this specific study, RT_{opt} is between 20 to 30 days, depending on temperature (Finlay, et al., 2013).

3.7.3 Substrate characteristics

The substrate is the material added to the digester then is used in the biogas process. Substrate properties greatly affect the amount and quality of the both gas and digestion residue. The substrate must meet the nutritional requirements for the microorganisms and their enzyme systems to function and reproduce, including trace elements and vitamins. The ratio of carbon to nitrogen (C/N ratio) is also important for the digestion process (Dioha, et al., 2013). Ammonia can accumulate and inhibit the process if the C/N ratio is too low. On the other hand, the bacteria may experience nitrogen deficiency if the ratio is too high. The C/N ratio often varies between 10 and 30, but the optimal range depends on substrate and may be hard to predict (Procházka, et al., 2012).

The protein, fat and carbohydrate content of the substrate can be used to make an estimate to the amount of biogas produced and the methane to carbon dioxide ratio, as shown in *table 5*. Substrates rich on proteins and fats are preferred for their high energy content, but they can cause imbalance in the system and inhibit the digestion. Materials rich on carbohydrates (plant-derived materials) are not optimal for the biogas process. They often contain large amounts of cellulose, which is slow to break down, and lignin, which does not break down at all in the biogas process (Schnürer & Jarvis, 2009).

However, carbohydrate rich materials can still be used beneficially to produce biogas with proper pretreatment, mainly shredding or milling, and by mixing it with other substrates.

Table 5. Theoretical quantity of biogas formed from carbohydrate, fat and protein (Berglund & Börjesson, 2003 in Schnürer & Jarvis, 2009)

Component	Biogas formed [m^3/kg VS]	Biogas composition, CH_4:CO_2
Carbohydrates	0,38	50:50
Fat	1,0	70:30
Protein	0,53	60:40

Mixing substrates is generally beneficial since it promotes a more varied microbial culture, making it more capable to digest the material and more resistant to environmental changes in the digester. Pretreatment of the substrate i.e. shredding or preheating, can also increase performance. The pretreatment method and benefits depends on substrate, but can improve sanitation, yield and rate of the process.

Manure is often used as substrate for the biogas process. The characteristics of the manure depends on the animal, meaning some type of manure may be more suitable as substrate than others. For example, manure from cattle yields less gas than that from pigs or poultry as shown in *table 6*. This is in part because some of the organic material has already been converted into methane during cattle's digestion. Manure can also stabilize the process by introducing more microorganisms and nutrients to the system. Dry manure can be diluted to help the substrate pass through a continuous flow reactor and reduce the concentrations of inhibitory components such as ammonia or volatile fatty acids. Digestion of manure also provides many environmental benefits, including reduced emissions of methane from manure storage facilities (Börjesson & Mattiasson, 2008).

Table 6. Methane yields of different feedstock materials (Al Seadi, et al., 2008).

Feedstock	Percentage methane	Biogas yield, m^3/t FF*
Liquid cattle manure	60	25
Liquid pig manure	65	28
Cattle manure	60	45
Pig manure	60	60
Poultry manure	60	80
Organic waste	60	100

* FF = fresh feedstock

Another important characteristic is the total amount of solid particles in the feed material. For the traditional biogas plants used in Nepal, it is desirable to maintain the total solids (TS) from 5 to 10 percent. This is done by diluting the manure with water at about a 1:1 ratio in a mixing tank before adding the feed material into the digester. The amount of water depends on how much the manure has been allowed to dry, but too much water can cause the solid particles to precipitate at the bottom of the digester and too little water prevents the flow of substrate through the digester (BSP-Nepal, 2005).

3.7.4 Other parameters

Several other parameters affect the biogas process such as pH and the presence of toxic compounds. They are not covered in this thesis, as few reports from Nepal list them as a limiting factor for the functionality of simple biogas plants.

4 PLANT DESIGN

Anaerobic digestion happens naturally in cows' digestion, where grass is broken down into simpler chemicals with the help of various types of bacteria. The process can be continued outside the cow by collecting the manure in a tank (digester) and meeting all the requirements of the biogas process. That is, the digester needs to be airtight and kept at a certain temperature. Once the digester has been built and the digestion process initiated, other organic substrates such as agricultural residues, human excreta or other animal manure, can be fed into the digester. However, mostly cow and buffalo manure are used in Nepal since the manure is easy to gather compared to other animals. Plant material and agricultural residue is avoided because it requires to be shredded before it can be properly broken down by the bacteria and could clog up the digester.

The core of a biogas plant consist of an airproof space where the decomposition of the substrate can take place in the absence of oxygen. In addition, the plant must have some system to insert feed material, remove digestate and store gas. There are various types of digesters and they can be divided in batch- or continuous flow-type digesters. Batch digesters are operated in three steps: (I) loaded with fresh feedstock, (II) left to digest and (III) completely emptied. The process is then repeated. They are easy to build and mostly used for dry digestion (20-40 percent dry matter). Continuous flow-type digesters are regularly fed and the material flows through the digester. This allows operation to continue without interruption and gives a continuous and predictable gas production. The digesters used in Nepalese villages are of the continuous flow type and are a version of the *fixed concrete dome* design, depicted in *figure 5*.

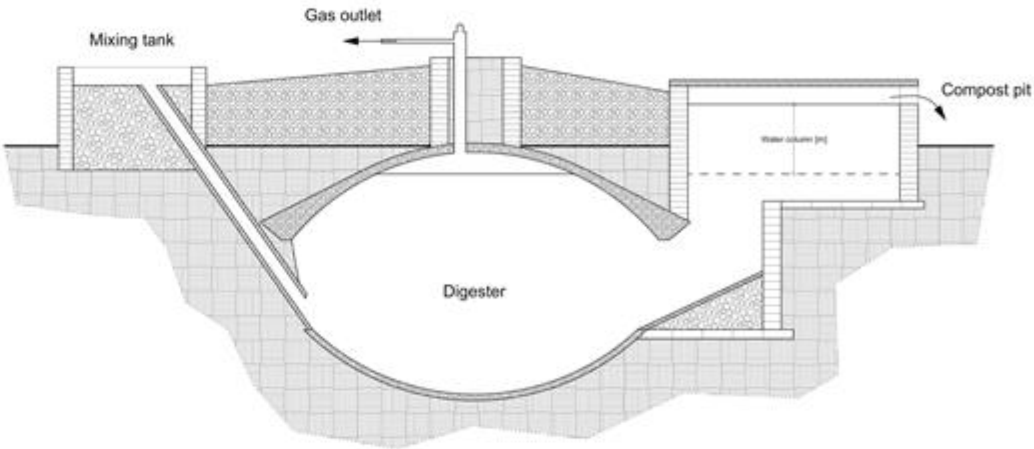

Figure 5. Schematic drawing of a fixed dome plant.

4.1 Fixed concrete dome design

The fixed concrete dome design used in Nepal was developed by the Gobar Gas and Agricultural Equipment Development Company (GGC) and is commonly known as the GGC model (BSP-Nepal, 2005). The GGC-model is very similar to the Chinese fixed dome model and is used for both private and community biogas plants. The GGC model is depicted in *figure 6* and consists of three main compartments:

Mixing tank with inlet pipe. The feed material is mixed with a tool to reduce particle size and blend the substrate before it is allowed to continue into the inlet pipe. The flow of the feed material is often controlled by clogging the pipe with a round stone.

Digestion chamber (digester). Once inside the digester, the biogas process commences. Some of the substrate is converted into biogas and stored in the upper part of the digester, thus increasing the pressure. The material and shape of the digestion chamber is important. It is meant to sustain both external and internal pressure changes and must be gastight. The external forces on the digester can be mitigated by favorable shaping digester and is the reason for the dome shape (Sasse, 1988). The pressure inside the digester increases with the amount of gas stored. The gauge pressure is given by the equation:

$$P_g = \rho g h \tag{4}$$

Where P_g = gauge pressure [Pa]

ρ = density of material [kg/m^3]

g = gravitational acceleration [m/s^2]

h = water column [m]

Building the digester underground has three important benefits: it reduces surface area taken up by the plant; increases the digesters insulation capability; and reduces the material requirements to withstand high pressure, as the internal and external forces on the digester counteract each other. The whole dome should be covered by at least 0,8 m of soil assuming a gauge pressure of 1,2 m when the digester is full (Finlay, et al., 2013). The bottom of the digester in the Chinese model is conical or spherical to distribute the edge loads over the entire surface. It also traps impurities from the feedstock, making it important to clean out the digester regularly. However, the GGC model uses a more horizontal foundation to make construction easier.

Storage/compost pit. As gas volume increases, the digestate is pushed out of the digester and into the compost pit. Two compost pits is beneficial for larger plants. Once one pit is filled up, the flow can be directed to the second pit while the bio-manure is being treated or applied to the fields.

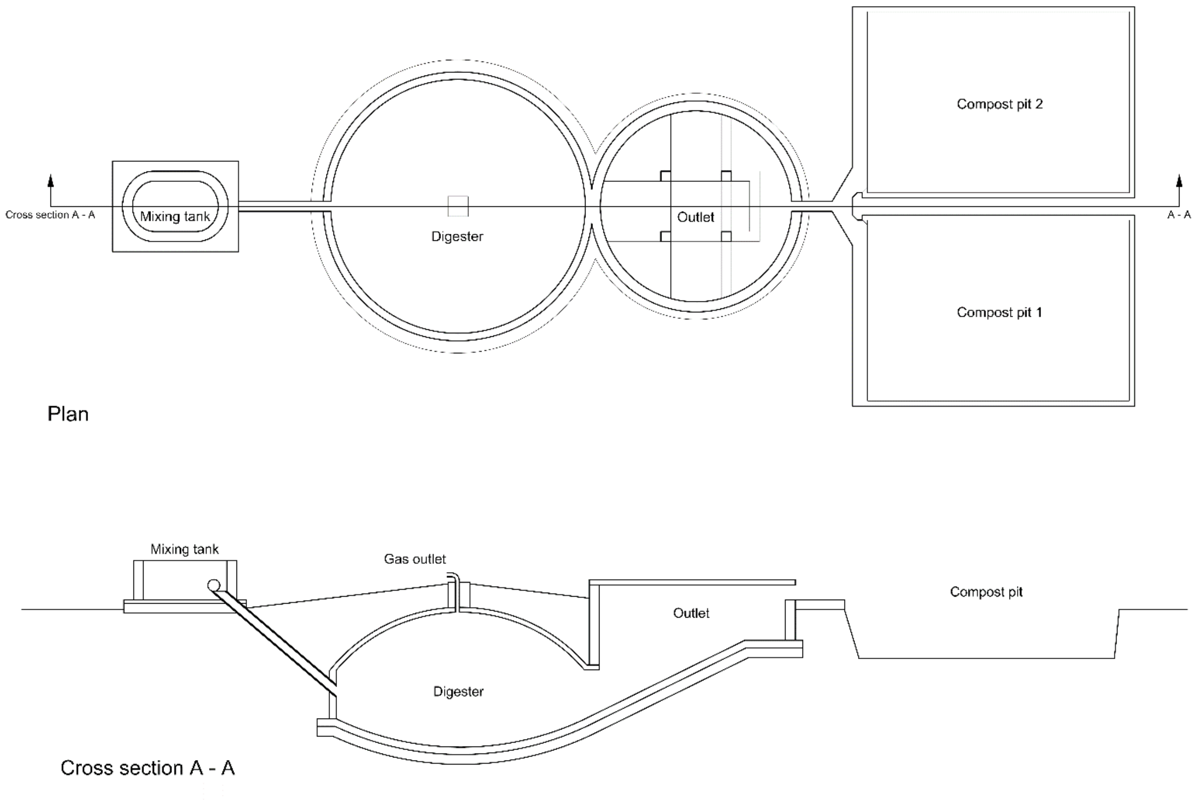

Figure 6. Plan and cross section drawing of the modified GGC fixed dome digester.

Apart from being relatively cheap, the underground digester is the most important design advantage of the fixed dome. Temperature in the soil varies, depending on time of the day and season. The variations between day and night rarely affect the soil at deeper lengths than 1 m, making the soil and vegetation an insulator against diurnal changes in temperature. Seasonal variations are more severe and can affect the soil temperature up to 6-8 m (Finlay, et al., 2013). However, the temperature in the soil lags behind the seasonal temperature variations, preventing the soil from reaching atmospheric temperatures.

The fixed dome plant is relatively cheap, durable (20 to 50 years) and easy to build and operate, making it ideal for private households (BSP-Nepal, 2005). However, the pressure that builds up in the digester can have damaging consequences if not used regularly. Biogas lamps can break if operated at high pressures and some biogas burners become less effective (Finlay, et al., 2013). This becomes a bigger problem with community plants, as the pressure increases with digester size, and limits the maximum dimensions of the plant.

4.2 Other plant designs

There are other plant designs that have successfully been used in Nepal, but have become obsolete with the popularization of the GGC plant. The floating steel drum digester is very similar in design to the GGC, but include a steel drum that functions as the roof of the digester and effectively expands or diminishes the volume of the digester, as the gas is being produced or used. This design visualizes the amount of gas stored and makes the pressure controllable by adding weight on top of the drum, as depicted in *figure 7*. However, these advantages were not enough to make up for the increase construction and operational costs. The steel drum corrodes and has to be replaced within 5 to 10 years and is not always provided locally (BSP-Nepal, 2005; Finlay, et al., 2013).

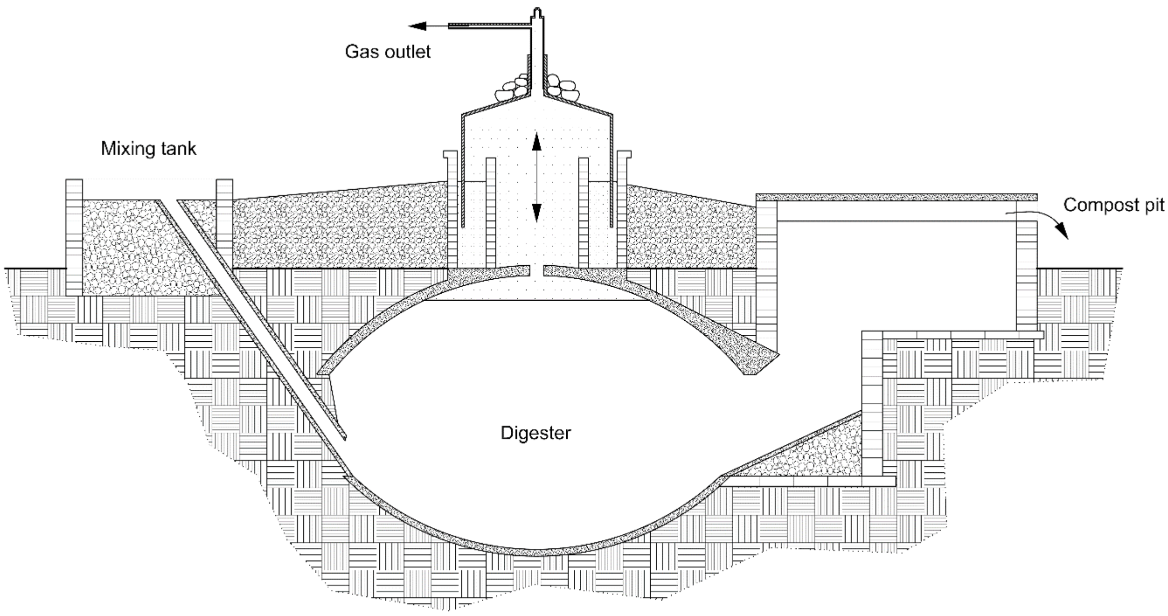

Figure 7. Schematic drawing of the floating drum design.

Another design that has been tested in Nepal is the Deenbandhu (friend of the poor) model, promoted by Action for Food Production. The design is essentially the same as the fixed dome, but with cheaper materials, using brick masonry instead of concrete. This reduced construction costs by 30 percent in India, but the same benefits were not found in Nepal due to increased labor cost of skilled masons (BSP-Nepal, 2005).

5 REVIEWS OF EXISTING PLANTS

A quality control system has been implemented in Nepal to measure the performance of constructed biogas plants and determine the reliability of various construction companies. The quality control system consists of various reports and a yearly users' survey using random sampling (BSP-Nepal, 2005). One such survey by Motherland Energy Group (MEG) in 2013 on 102 household digesters concluded that most plants were operating at a satisfactory level (97 percent operational). At the same time, about 40 percent of households surveyed in the Terai reported insufficient gas production during winter months (MEG, 2013). However, information on the status of existing community plants is very limited. One report on community and institutional plants in Kathmandu Valley by J. Forte in 2011 includes case studies from six biogas projects and concluded that most community plants financed by third parties, i.e. NGO's, have a tendency to be poorly managed due to a reduced sense of ownership compared to institutional plants (Forte, 2011). Some of the community plants were reported to produce virtually no gas, but still had some benefits in the sense that they worked for wastewater treatment and helped improve hygiene. Forte suggested that better training and more defined roles could lead to increased dedication and sense of responsibility. Similar studies, i.e. (Reddy, 2003; Bulmer, et al., 1980; Sarkar & Uddin, 213), acknowledge the difficulties in operating community biogas plants, but highlight the potential benefits of such systems and recommend solutions such as motivational support for owning community plants and a standardization of the technology.

5.1 Field visit

This section covers information on two community biogas plants in the Bardiya and Banke districts in Nepal. Most of the information is based on feasibility studies by Clean and Green Nepal (CGN) and field visits in February 2016. The plants were financed by Renewable World (RW) and Biogas Sector Partnership – Nepal (BSP-N) as part of the Community Owned Biogas for Livelihood Enhancement (COBLE) project. A 35 m^3 CCG plant in each community, with the purpose to reduce the economic costs related to wood and fertilizer.

5.1.1 Jamuni Community (Bardiya district)

The Jamuni Community plant is 35m^3 GGC plant and is estimated to produce 7,6m^3 biogas daily for 45 people in nine households. This is based on a daily influent containing 191kg manure mixed with 233L of water and a retention time of 55 days. Only manure from cows and buffalos are used and no agricultural or food waste is added and no toilets are connected. The gas is only meant to be used for cooking and is supplied directly to the kitchens through a piping system, as depicted in *figure 8*Figure 8. To prevent misuse, the gas is only available at certain times agreed upon by the community. Once the "master valve" is opened, the gas is mostly used up before it is allowed to accumulate anew.

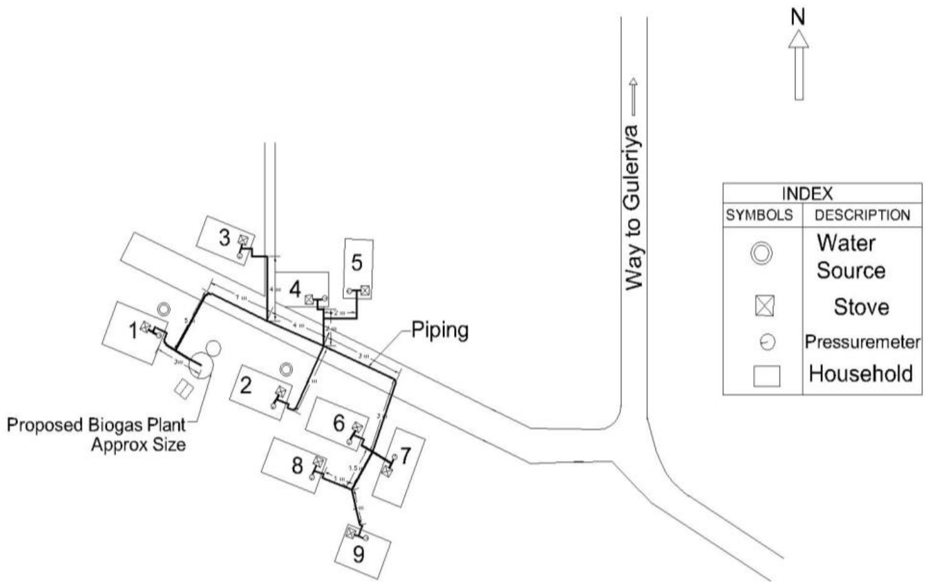

Figure 8. Plan drawing of the Jamuni community biogas plant with piping system (Cleen and Green Nepal, 2015b).

The feasibility study by CGN concluded that building the community biogas plant would be sustainable technically, environmentally and economically with a payback period of three years. However, some concerns were raised involving lack of ownership and cooperation within the community. To reduce any social conflict, it was recommended to conduct proper training; implement rules of use; set a monthly fee; and set up a community committee to manage the plant.

Despite meeting the recommendations, the plant was not operating optimally at the time of the visit. The community had problems feeding the digester because of social issues. Several families went back to use traditional fuels (*figure 9*) and gave the following reasons:

- Not enough gas produced
- Bigger families were feeding less, but consuming more gas
- Disagreements on when the gas should be available

All households were receiving gas, but the pressure was too low for any form of cooking. Only two families were using and feeding the biogas regularly, resulting in an underfed digester and low amounts of gas. The digestate was also being mismanaged and unused.

Figure 9. The roof of the Jamuni community plant being used as a spot to dry manure to be used as fuel.

5.1.2 Jahirpur Community (Banke district)

The Jahirpur community plant is also a 35m^3 GGC plant, but is estimated to produce 7,5m^3 biogas daily for 60 people in six households. The daily feedstock is assumed to consist of 183kg manure mixed with 129L water and 112kg blackwater, based on 15 cows and 23 people. No agricultural or food waste is added. The biogas plant is connected to the six households through a piping system, as depicted in *figure 10*. Similarly to the Jamuni Community feasibility study, the Jahirpur Community plant was deemed to be sustainable, but with concerns about social issues. At the time of the visit, the plant had just finalized construction, but the users had not started the feeding process for reasons unexplained.

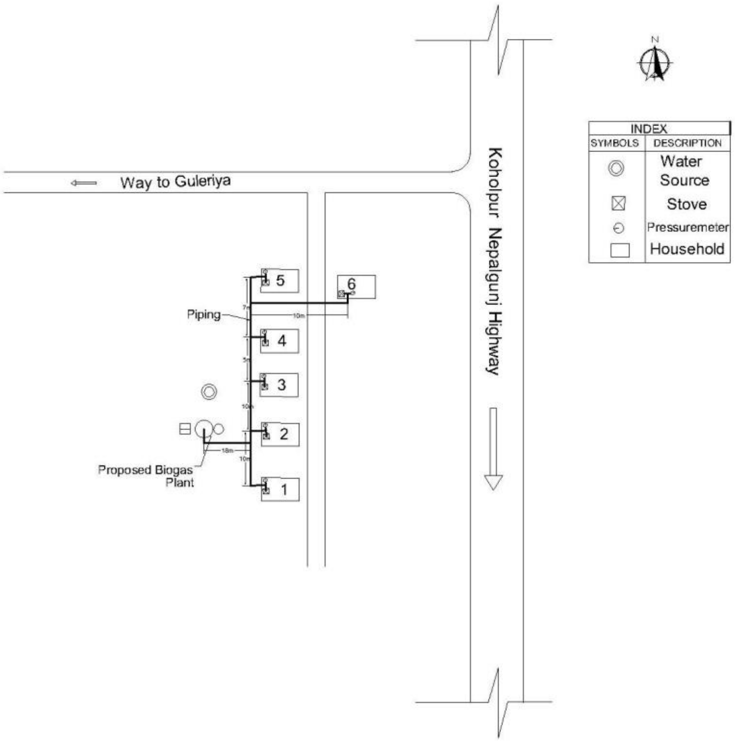

Figure 10. Plan drawing of the Jahirpur Community biogas plant with piping system.

As discussed, both the Jamuni and Jahirpur communities were having problems managing the plant. In an effort to increase the performance of the community plants, the RW, BSP-N and CGN team conducted various training programs for the communities over several days. The users were motivated to restore proper feeding of the plant and more training related to proper management of the digestate was promised. New visits following the next months will reveal whether the users are properly managing the plant or require further training.

6 IMPROVING PERFORMANCE

Based on the information presented in this thesis, there are two main limiting factors for the continued development of biogas in Nepal: technical and social limitations. The technical limitations apply to all biogas plants (household-, institutional- and community plants) and are well defined and understood.

Improving the operational conditions of the plant is important to (1) increase user satisfaction and (2) to expand biogas to areas where the current system is not viable. In Nepal, it is especially interesting to promote the use of alternative fuels in the remote mountainous regions that are outside the reach of the electric grid. This makes temperature among the most important parameters to consider for the future development of biogas, as an increase in operational temperature will increase gas production and is relevant to make biogas more impactful in the colder climates. Other areas that are being explored include how to improve slurry utilization; the use of different materials to make the technology more affordable; and the use of alternative substrates.

The social limitations include the fact that many farmers do not have the resources to invest in a biogas plant. The only way to overcome this problem is by reducing the construction and operational cost of the plant, by either changing plant design or through economic help in the form of increased subsidies and NGOs. As discussed, building community plants reduces the economic cost per volume of gas produced, making it an effective strategy to reduce the wealth requirements. However, community plants also pose new challenges in the way that the plants are managed, and internal conflict within the community often result in the demise of community biogas plants. This suggests that there is still room for improving plant design, both in terms of increasing performance and in terms of easing management. A well-designed plant is appropriate for the users in terms of their needs and capabilities, but also the constructer. The GGC model is standardized in Nepal and only small modifications to the habitual construction method should be made if possible.

6.1 Increasing digester temperature

Variance in temperature is the most important parameter for fluctuation in gas production. Reducing temperature has severe implications on the gas production rate and virtually no gas is being produced in temperatures less than 15 °C. One solution practiced in parts of northern China, is to shut down gas production during winter and only operate the plant during the 6-8 months period when gas production is at its peak (Sasse, 1988). Most biogas users still utilize traditional fuels to some degree (BSP-Nepal, 2005), but is not ideal since most of the benefits related to using biogas rely on not using firewood. There are many techniques to increase digester temperature, but they are not widespread and often require more knowledge, materials and dedication.

6.1.1 Insulation

Insulating the digester is the most energy effective method to maintain digester temperature by reducing energy losses to the environment. This can be done relatively cheap, since the materials used for insulation in conventional biogas plants are replaceable by local materials with similar properties. Cereal straws, rice husks, sawdust and shavings have good thermal conducting properties that are comparable to industrial materials, as shown in *table 7*.

Table 7. Typical values for the thermal conductivity of some materials (Finlay, et al., 2013).

Material	**Thermal conductivity, W m^{-1} K^{-1}**
Concrete	1,0
Soil (fairly dry)	1,4
Saturated soil	2,4
Saw dust (loose)	0,06
Shavings (loose)	0,06
Sugar cane fiber	*0,05*
Insulite (wood pulp)	*0,05*
Glass wool	*0,04*

The materials proposed in *table 7* are organic and turn into compost, which releases heat during decomposition and further increases the temperature of the system. A study covering the digester with compost, as in *figure 11*, reported more than a 50 percent increase in biogas production during winter months (Finlay, et al., 2013). The compost pile was 0,7-0,8 m high and was covered by a plastic sheet, giving a similar effect to a greenhouse. The disadvantages of this method is that the composting is not permanent and can give an unpleasant odor.

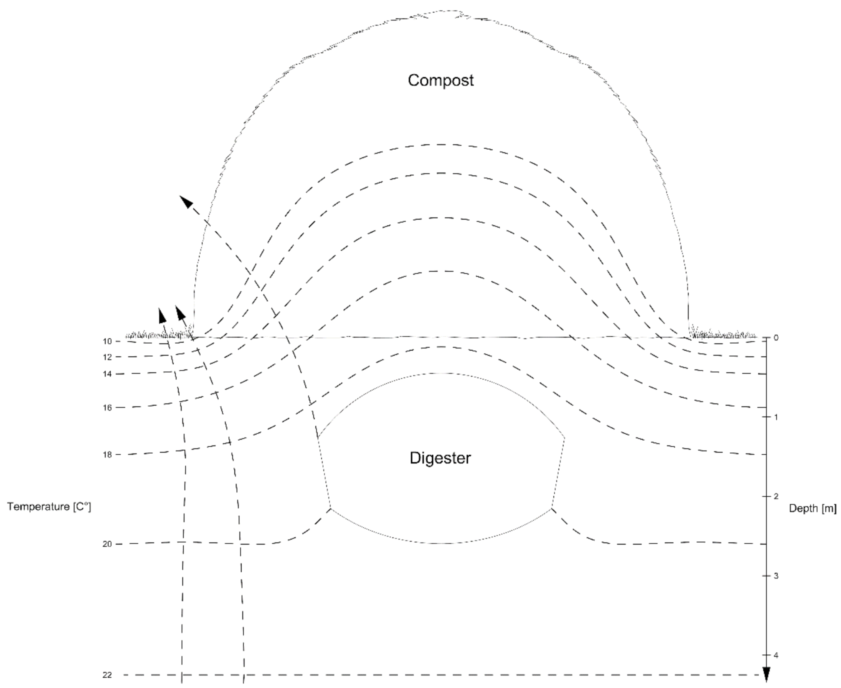

Figure 11. Shows the underground digester covered by a compost pile for insulation (out of scale). The heat flux vectors deflect sideways before emerging to the surface.

6.1.2 External heating

For simple digesters, the main source of external heating is solar radiation. The incoming energy should be maximized by placing the digester on a cleared area and facing the sun in the case of a hilly side. Preheating the feed material by mixing and leaving it in the sun is also possible. One study found an increase of influent temperature by 4,5 to 9 °C depending on daily conditions (Finlay, et al., 2013). Solar radiation does not penetrate far into the slurry, so the mixing tank was made with a large surface area, shallow and covered with a transparent plastic sheet. Solar reflectors or constructing a greenhouse above the digester has also been reported to give positive results (MinErgy Pvt. Ltd., 2014).

Most simple biogas systems operate without any complex heating system. However, it is possible to increase the temperature of the digester by using the heat loss of an engine or generator with a heat exchanger. This can also have a positive impact on the engine as it releases heat to the digester. The heat exchanger can be used to either heat up the feeding material as a form of preheating or it can be used inside the digester at the risk of corrosion damages (MinErgy Pvt. Ltd., 2014).

Other preheating methods are often expensive and underdeveloped for simple digesters. Some industrial plants use a fraction of the biogas produced to heat the same digester. However, using 20-30 percent of the produced gas to heat the digester is not viable for small-scale plants.

6.2 Pretreatment

Other pretreatment methods that do not involve heating of feed material can also improve biogas production. Increasing the biodegradability of the substrate is especially beneficial for substances that need a long retention time such as plant material with high content of cellulose. Reducing particle size i.e. by shredding increases the hydrolysis and fermentation stages of the biogas process. Separating lignin and cellulose out from manure can also obtain higher biogas yield per volume feed inlet (Møller et al., 2004 in Schnüer & Jarvis, 2009).

Co-digestion of manure and organic wastes has also been reported to successfully improve biogas production (Tafdrup, 1994 in Schnüer & Jarvis, 2009). Co-digestion of manure with easily degradable organic waste can significantly improve biogas production since manure has a relatively low methane yield. Co-digestion also helps reduce the inhibitory effects of concentrated organic waste. Another advantage is the high buffering capacity in manure, which makes the process more resistant to the inhibitory effects of volatile fatty acid accumulation (Angelidaki and Ellegaard, 2002 in Schnüer & Jarvis, 2009).

6.3 Water recycling

One of the preconditions to build a biogas plant is the availability of water. The water does not need to be pure, but the supply needs to be sufficient throughout the year and not limited during dry season. However, the water dependency of the biogas plant can be reduced by recycling some of the liquid content in the digestate. In most conventional European biogas plants, the first step in digestate processing is a solid-liquid separation. The digestate contains about 90 to 80 percent liquid, which can be partly separated through straining or using a centrifuge (Drosg, et al., 2015). The liquid can then be fed back into the digester with more manure. The separated solid fraction can be applied directly for agricultural purposes with the advantage of being easier to transport due to the reduced water content. Another advantage is that the effects of sedimentation during storage is reduced. While the possibility for water recycling exists, it is not usually practiced with simple digesters.

6.4 Social limitations (Jamuni community plant)

The community plants presented in this thesis show limited functionality. Whenever the technical aspects of the plant are functional, the main limitation is disinterest and social conflict that arises within the community. The users interact with the biogas plant whenever feeding the plant, distributing the gas and distributing the bio-manure. These interactions need to be better understood to design a more appropriate plant. The plant infrastructure can be set up in such a way that it becomes easier for the users to cooperate. Thus, the design is imperative to mitigate social conflict. Based on the superior performance of institutional and single household plants, it may be beneficial to modify the community plants to run more similarly to its counterparts.

Institutional plants are different from community plants in the way they are managed. The roles are often well defined. Specific people are chosen to undergo training and manage the plant, meaning that the economic expenses to run the plant is increased. For community plants, this would require the users to pay a monthly fee for wages. There are many different ways to manage a community plant and distribute the responsibilities, but they are not necessarily concerned with plant design and will not be further discussed in this thesis.

Single household digesters often use the same design as community plants in Nepal, but they operate very differently. Each household is dependent on the rest of the community in terms of effort and has a reduced impact on the performance of the plant. However, minor design modifications i.e. private gas storage, can increase the sense of ownership of the plant. Separate gas storage would also make the gas usage more manageable and prevent squandering.

Using the Jamuni community as reference, there seems to be a sense of imbalance regarding feeding and gas distribution: the more invested households do not receive the gas they feel they deserve. It is impossible to oversee each household's gas usage, which increases the requirement for training. A deep trust among the community members is also necessary, as one user's mistakes has consequences for the entire community.

6.4.1 Weaknesses in the distribution system

The distribution system in the Jamuni community plant consists of a piping system that directly connects the digester to nine kitchens. Some communities will find this to be the optimal design. It is very comfortable, reduces workload and is durable if managed properly. However, the system has several weaknesses and has the potential to become a major source of social conflict:

1. **Lack of control and monitoring of gas usage.** It is impossible to see how much gas each household is using and this makes it is difficult to verify fair use of the gas. Misuse can discourage contributing families to continue their efforts.
2. **The households are "bound" to the plant.** Because of the piping system, the contributing households must truly be committed to the plant. Once a family stops feeding, they cannot easily be replaced and there is a chance for the digester to be underfed.
3. **Time schedule for gas use.** The households are not free to cook whenever they want. Even though the community may have come to an agreement on a time schedule, some families may be "pushed away" from using the gas and thus losing interest in the plant.
4. **Gas misuse.** Since everyone is sharing the same gas storage, it can become a competition to use as much gas as possible before the digester is empty. If a household does not use their share of the gas, someone else will.

A modification in the distribution system for future plants should be considered.

6.4.2 Improving the distribution system

An addition to the system is being tested by BSP-N and RW using a 1,2 m^3 gastight bag called [B]pack ((B)energy, 2016). The bag weighs about 4,5 kg and is designed for easy storage and transportation with shoulder straps, as depicted in *figure 12*, and can be inflated when connected to the biogas plant. Once inflated and brought to the usage location, the [B]pack can be connected to the burner and used for cooking. Weight can be added or removed on the bag to regulate pressure. The [B]pack is already being used in countries in Europe, Africa and Asia (Siemens Stiftung, 2016). The disadvantages with the bag is that it requires space, must be refilled frequently and may be difficult to replace if damaged. Care must also be taken with placement and it is not recommended to store indoors. The bag poses no risk when fully inflated, but an explosive mixture could form if the gas leaks and is contained in a small room.

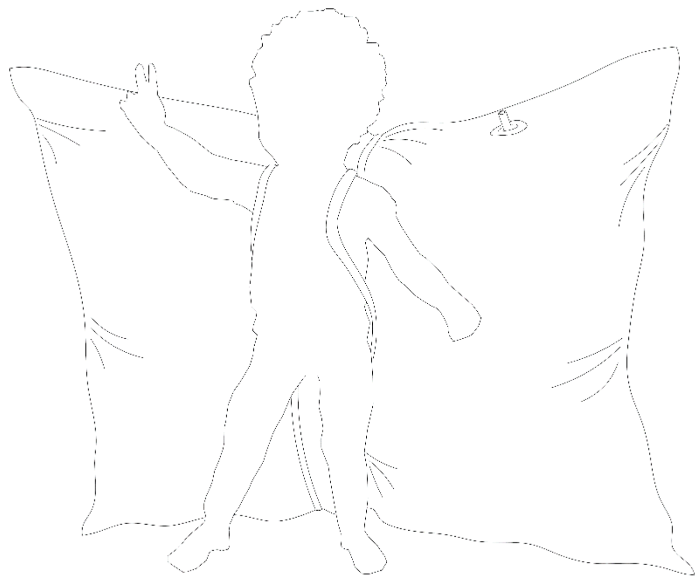

Figure 12. An illustration of the [B]pack concept.

In the case for similar designs to the Jamuni and Jahirpur community biogas plants, it is possible to replace the piping system with [B]packs. This modification adds a transportable private gas storage, which counteracts all the weaknesses in the distribution system discussed above.

1. The [B]pack makes it possible to monitor usage of each individual household. Gas usage can be compared by number of bags inflated during a week or month. Additionally, squandering only affects the household misusing the gas.
2. The removal of the piping system reduces the impact of families that end their contribution to the plant. If needed, new families can be invited to join the project. However, they still need to own cattle and live close by the plant.
3. A private gas storage removes the need for a time schedule and the users are free to cook independently from the rest of the community.
4. Misuse of the gas does not affect the entire community.

Furthermore, the easy transportation of the [B]packs makes it possible to bring biogas to households that are not connected to a plant and potentially opens up for a biogas market. In this case, the energy storage capabilities of the [B]pack should be considered and compared to firewood. The quantity of energy stored in the backpack is related to its methane content, n_{CH4}, which can be estimated through the ideal gas law:

$$n_{CH4} = \frac{PV}{RT}\, p_{CH4} \qquad (5)$$

Where n_{CH4} is the number of moles methane, [mol]

P is the absolute pressure [Pa]

V is the volume [m^3]

R is the ideal gas constant [=8,314 J/mol K]

T is the absolute temperature [K]

p_{CH4} is the portion of methane in the biogas, %

Therefore, the quantity of methane contained in the [B]pack depends on gas quality and environmental conditions during tapping. More gas is stored with low temperatures and high pressures. Assuming the same gas properties as in *table 2* and extreme conditions[1], the maximum difference in methane content varies with about 20 percent where temperature and pressure are almost equally important. However, while higher temperatures reduces the storage capabilities, it also increases gas production and thus pressure. The variation in pressure can be mitigated by alternating which days the households fill their [B]pack i.e. only half the community refill each day. If the gas production is low, a load shedding system can be put in place where the households alternate on using traditional fuels.

The energy content in the [B]pack can be compared to a wood mass equivalent. For this calculation, it is important to consider the difference in effectiveness' of the fuels as discussed in *section 3.3.1*. Assuming the overall thermal efficiency to be equal to the heat transfer efficiency ($\eta c = 1$) and ideal operational conditions, makes the heat transfer efficiency to be equal to the stove efficiency ($\eta = \eta s$) and gives the following estimate for the heat transferred from a given amount and type of fuel.

$$E_{fuel} = m_{fuel} \cdot LHV_{fuel} \cdot \eta_{s,fuel} \qquad (6)$$

Where E_{fuel} is the amount of energy transferred form the fuel to the receiving material [MJ]

m_{fuel} is the mass of the fuel [kg]

LHV_{fuel} is the lower heating value of the fuel [MJ/kg]

$\eta_{s,fuel}$ is the stove efficiency of the stove type, %

The mass of methane in the [B]pack can be estimated by combining *equation 5* with the molecular mass of biogas given in *table 2*. The lower heating value (LHV), which is the amount of heat released

[1] Temperature range from 15 to 40 °C and pressure from 0,1 to 1,2m water column.

when one 1kg of fuel undergoes complete combustion and the produced water is in vapor state, of methane is about 50 MJ/kg and can be assumed to be about 15 MJ/kg for firewood (Demirel, 2012). Finally, the stove efficiency can be found in *table 3*. Using these values in *equation 6* results in an estimate for the backpack to replace up to 8kg of wood. This should be sufficient to last at least two days based on a daily usage of 3,6 kg firewood in each household (Clean & Green Nepal, 2015a). With this comparison, it is possible to estimate the economic value of each bag refill. RW has estimated that it is possible to establish a market for biogas in the Bardiya region by selling [B]pack refills at about half the price of equivalent firewood.

Whether or not it is economically feasible to replace the piping system with [B]packs depends on the price and durability of the [B]pack. The cost reduction in building the pipe distribution system in the Jamuni community does not fully cover the cost to provide [B]packs to all households (Clean & Green Nepal, 2015a; (B)energy, 2016). Thus, modifying the distribution system for future community plants would increase the economic cost of each plant.

7 CONCLUSIONS

The rural population in Nepal still heavily depend on the use of firewood and other traditional fuels for cooking. These fuels emit large portions of toxic fumes that are damaging for the health and release greenhouse gases. In addition, the use of firewood contribute to deforestation and extensive use has proven to be unsustainable and damaging for the environment. The implementation of biogas technology has reduced the dependency on traditional fuels and thus has had a positive environmental, economic and social impact. Up until today, more than 350.000 small-scale digesters have been constructed out of a theoretic potential of over one million. This proves that the implementation of biogas has been a successful one. However, the technology has failed to reach the poorest communities because of the required wealth to invest and operate a biogas plant.

Theoretically, community biogas plants are a good option to reach a poorer portion of the population by lowering the economic barrier. Community plants are larger compared to single household digesters, resulting in a higher volume of biogas produced at a more cost effective price. The higher gas production opens the possibility for new applications with an internal combustion engine that runs entirely or partly on biogas. Thus, if implemented correctly, a community plant can be used to run commercial applications such as irrigation pumps, mills, refrigerators or generators. Unfortunately, based on the information presented in this thesis, community plants have a strong tendency to be mismanaged due to internal social conflicts within the community. In some cases, the biogas plant has been reported to produce no gas, but has improved sanitation if community toilets were connected.

The Jamuni and Jahirpur community plants that were visited in February 2016 were also being mismanaged, resulting in insufficient gas and the bio-fertilizer was being wasted.

The Jamuni and Jahirpur community plants are essentially scaled up GGC plants, which are optimized for single households. The GGC design has proven to be very reliable with an estimated 97 percent of the digesters constructed being functional and a life expectancy of up to 50 years. One of the constraints of the GGC design is its thermal properties, and is resulting in reduced performance in the more temperate regions and during winter months. Even though the design works very well for household digesters, it has not been as successful for community plants. The gas distribution system, which consists of a piping system connecting the digester directly to all the kitchens in the community, may be a significant source for social conflict in the case of the Jamuni community. Further research and development is required to optimize the design of community plants in addition to a standardization of the technology before it can be popularized. Furthermore, the complexity of each community may require different designs based on the needs and intentions of the users.

In conclusion, the development of community biogas in Nepal may be inhibited mostly by social factors. Proper user training is imperative for the functionality of the plant, but in the case for the community plants investigated in this thesis, more effort should be dedicated into improving the plant design to make management easier and thus mitigating social conflict.

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