Domestic Biogas Production and Use in Nepal – A Simple, Reliable, Clean and Cost-Effective Solution to Provide Energy Security to the Rural Households

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Abstract

Nepal is rich in natural resources with a high potential for energy supply, but it is facing an energy crisis. Electricity supply is unreliable and often in short supply. LPG and kerosene are imported, and therefore expensive and less accessible. Biogas is starting to be used for cooking but only at 17% of the total potential households. Most of the fuel used for cooking in rural areas is traditional fuelwood. It takes time and hardship to collect especially for women, emits unhealthy smoke and can lead to deforestation. As an alternative, biogas, mostly methane, has good potential for cooking and heating. It can be produced in a simple plant digester by anaerobic decomposition of biodegradable organic wastes. Cattle dung and human excreta are the main feedstocks used in domestic biogas plant in Nepal. Biogas can be a highly efficient and low carbon emission fuel as it can replace the excessive use of traditional biomass and reduce the associated adverse impacts on social, health and environmental conditions. Biogas development is one of the government's priority programmes in Nepal to provide reliable, clean and low cost energy supply particularly to rural households. However, the replication of the technology is still slow. Biogas production is lower than its full capacity and cannot cover the energy demand of a typical household all year round, especially during winter. Hence, this study aims to explore the potential solution to increase domestic biogas production and use so that its benefits for energy security and environmental emission reduction can be optimised.

Both quantitative and qualitative research approach were applied. Surveys of biogas households in Nepal were conducted to collect household-level information. Key informant interviews, informal discussions and observations were undertaken to gain insight into the context of overall renewable energy technologies, the production and use of biogas technology, and constraints and opportunities for its wider replication, especially to rural poor households.

Users' socioeconomic conditions, feedstock availability, plant design and cost are the major influencing factors for biogas production. The poor households cannot afford to purchase the system, or own fewer cattle, so less dung is available to feed the plant. Others who have enough cattle for dung are also not feeding the required quantity of dung to produce biogas but use it for field manure. Hence, the plants are under-performing in terms of their technical potential mainly due to the insufficient feedstock used. Agricultural residues are easily available, but do not realise their use with dung for co-digestion to increase biogas production.

This research thus analysed the effect of co-digestion of dung with agricultural residues to increase biogas yield. The cost effectiveness of co-digestion technology is also checked out by using financial analysis. The impacts of improved biogas production on the cost of energy, energy consumption and associated greenhouse gas (GHG) emissions reduction were obtained by using the Long-range Energy Alternative Planning (LEAP) system model.

Co-digestion of dung with crop residues could improve biogas production by approximately 50-150% and would meet most of the household cooking energy demand throughout the year. The increased availability of biogas could help address strategic gender needs by utilising the saved time more than 3.2 hours/day for fuelwood collection and cooking in traditional stoves. From the cost-effective perspective, an average total annual cost of energy after co-digestion is up to 37% cheaper than the existing biogas production condition, and even up to 45% cheaper than the energy cost of non-biogas households. Furthermore, a co-digested biogas plant has the potential to reduce average annual energy consumption by 46-57 gigajoules and GHG emissions, mainly from avoiding deforestation, by16.7-19.3 tCO_2e per household depending on region, compared to a non-biogas household.

This study, however, pointed out some important issues that are to be addressed to make this research outcome more applicable. Mainly, the design of a biogas digester should be suitable for co-digestion and the government subsidy needs to be revised accordingly to cover any potential increase in the cost of the modified plant design. The utilisation of saved time to achieve strategic gender needs can also be a priority. In summary, this study analysed all three impacts together: *energy consumption; cost of energy; and corresponding GHG emissions,* of co-digestion technology. This has not previously been reported in the literature. This study's findings can also be relevant to other developing countries where biogas can be a part of the solutions to provide energy security, gender equality and climate change mitigation.

The recent earthquake in Nepal (on 25/4/2015 a 7.9 magnitude earthquake devastated much of the country along with subsequent aftershocks) has left extremely adverse effects on all social, economic, environment and energy supply conditions. At the time of printing the scale of damage and loss of life is still being estimated, but this is clearly an extremely damaging event. It will take a long time and huge funds and a massive pace of infrastructure development to get the situation back to normal. Nonetheless, let's hope this study's outcome will also add further **importance to the biogas development to uplift the current vulnerable energy supply situation in poor rural households.**

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My sincere thanks to all my family members: parents, parents-in-law, brothers, brothers-in-law, sisters, sisters-in-law, nieces, nephews, relatives and friends for their love, support and inspiration directly and indirectly. I must not forget to acknowledge here the special contribution of my father-in-law, Mr Hari Bhakta Adhikari, and my brothers Bishwa Nath, Sudarshan and Kedar Nath Subedi, for their invaluable love, support and encouragement at every step of my life which has made it possible to reach to this stage.

Most importantly and specifically, I would like to express my heartfelt acknowledgement to my parents, Mrs Saraswati Subedi and the late Ram Nath Subedi. Thank you mom for your most precious love to me, your effort, inspirations and everyday prayers for my successful life. My father was in his 80s when he sent me here to pursue this PhD study. Dad, I did understand how difficult the moment was when you farewelled me with your tear-filled eyes and stressful face, but I left you there and forcefully moved forward to this journey, and I will never get you back in my life. I pray, may almighty God rest your soul in eternal peace, and hope you could see your mission accomplished even from heaven. My PhD degree is dedicated to you both.

At the end of this thesis write-up the extreme effect of recent earthquake in Nepal (25/04/2015) has left the whole country in grief and still at high risk. I have lost my beloved mother-in-law, many of our relatives, friends and their families, and an absolutely shocked at this moment. May God give power to the injured and affected people to cope with this pain, big loss and further risk. My sympathy to all the victims and RIP to the departed souls.

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Abbreviations and Acronyms

ADB/N	Agricultural Development Bank Nepal
AEPC	Alternative Energy Promotion Centre
APCAEM	Asia and Pacific Centre for Agricultural Engineering and Machinery
APERC	Asia Pacific Energy Research Centre
BANZ	Bioenergy Association of New Zealand
BMP	Biochemical methane production
BSP-Nepal	Biogas Support Programme- Nepal
C/N	Carbon-Nitrogen ratio
CBS	Central Bureau of Statistics
CDCF	Community Development Carbon Fund
CDM	Clean Development Mechanism
CES	Centre for Energy Studies
CFC	Chlorofluorocarbon
CH_4	Methane
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
COD	Chemical Oxygen Demand
CRTN	Centre for Rural Technology, Nepal
CSPP	Climate-Smart Planning Platform
DDC	District Development Committee
DFRS	Department of Forest Research and Survey
ENPEP	Energy and Power Evaluation Program
FAO	Food and Agriculture Organization of the United Nations
FIRR	Financial Internal Rate of Return
GDI	Gender Development Index
GDP	Gross Domestic Product
GEF	Global Environmental Facility
GGC	Gobar Gas Company
GHG	Greenhouse gas
GJ	Gigajoule
GMP	Greenhouse Gas Mitigation Potential
GoN	Government of Nepal
GPOBA	Global Partnership for Output-Based Aid

GW	Gigawatt
GWP	Global Warming Potential
HDI	Human Development Index
HOMER	Hybrid Optimization Model for Electric Renewables
IDE	International Development Enterprises
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
IPP	Independent Power Producers
IRADe	Integrated Research and Action for Development
IUCN	International Union for Conservation of Nature
KfW	Kreditanstalt fuer Wiederaufbau
KVIC	Khadi Village Industries Commission
kWel	Kilowatt electric
kWh	Kilowatt hour
LAPA	Local Adaptation Plan for Action
LEAP	Long Range Energy Alternative Planning
LPG	Liquefied Petroleum Gas
MAED	Model for Analysis of Energy Demand
MARKEL	Market Allocation Model
MDG	Millennium Development Goal
MEDEE	Modèle d'Evolution de la Demande d'Energie
MESAP	Modular Energy System Analysis and Planning
MJ	Megajoule
MSTE	Ministry of Science, Technology and Environment
Mtep	Million tonne equivalent of petroleum
MUHEC	Massey University Human Ethics Committee
MW	Megawatt
N_2O	Nitrous oxide
NAMA	Nationally Appropriate Mitigation Actions
NAPA	National Adaptation Programme of Action
NEA	Nepal Electricity Authority
NEMS	National Energy Modelling System
NPC	National Planning Commission
NRs	Nepalese Rupees
OECD	Organisation for Economic Co-operation and Development
PASA	Practical Action South Africa
PJ	Petajoule

POLES	Perspective Outlook on Long-term Energy System
PPM	Parts per million
PPP	Purchasing power parity
PVC	Polyvinyl Chloride
QDA	Qualitative Data Analysis
REDD	Reducing Emission from Deforestation and forest Degradation
RETs	Renewable Energy Technologies
RERL	Renewable Energy for Rural Livelihood
RESGEN	Regional Energy Scenario Generator
RET	Renewable Energy Technology
SD	Sustainable Development
SDGs	Sustainable Development Goals
SNV	Netherlands Development Organisation
STP	Standard temperature and pressure
tCO_2e	Tonnes carbon dioxide equivalent
TJ	Terajoule
toe	Tonnes of oil equivalent
tCO_2e	Tonnes of carbon dioxide equivalent
TPES	Total Primary Energy Supply
TS	Total Solid
UMN	United Mission to Nepal
UN	United Nations
UNDP	United Nations Development Programme
UNEP	United Nations Environment Programme
UNESCO	United Nations Educational, Scientific and Cultural Organizations
UNFCCC	United Nations Framework Convention on Climate Change
US$	United States dollar
VDC	Village Development Committee
VER	Voluntary Emission Reduction
VFA	Volatile Fatty Acids
VMP	Volumetric Methane Production
VS	Volatile solid
WECS	Water and Energy Commission Secretariat
WEM	World Energy Model
WHO	World Health Organization
WWF	World Wildlife Fund

CHAPTER ONE

INTRODUCTION

1.1 Background

Nepal is endowed with many natural resources which have high potential for energy supply. However, the potential has not been exploited adequately due to many geographical, technical, economic and political reasons (WECS, 2010). Nepal has been declared to have a state of energy crisis, and power supply shortage is a major cause (RERL, 2011). The country has low per capita energy consumption of 14.2 gigajoules (GJ)/year, significantly less than the world average (76.6 GJ/year) (IEA, 2011). Nepal has a hydropower generation potential of 43 gigawatts (GW) (WECS, 2010), but only 791 megawatts (MW) has been developed to date (NEA, 2013). In terms of electricity, it shares only about 2.7% of the total primary energy consumption (Gurung et al. 2013). Only about 50% of the population has access currently to electricity, with rural electrification accounting for only 29% of the rural population since grid electrification is costly due to scattered settlements (Malla, 2013; NEA, 2013). Even in the electrified households, they have to use other energy sources, such as fuelwood and kerosene, as a standby energy source to use during periods of load shedding, which can be more than 16 hours a day in a dry season (NEA, 2013, 2014).

Petroleum products, all of which are imported, account for 10% of the total primary energy consumption (Malla, 2013; NPC, 2013). The world fuel crisis and price fluctuations have a huge impact on Nepal's economy. Nepal spent 61.5% of its merchandise export revenue on importing petroleum products in 2009/10, compared to just 27% in 2000/01 (KC, et al., 2011; Rai, 2011). Kerosene is a major energy source for lighting in rural non-electrified areas. The use of LPG for cooking is also increasing, but not all the poor population has access to it due to its high cost.

Hence, more than 87% of the population primarily depends on traditional biomass sources (fuelwood, agricultural residues and animal dung) for their daily heat energy requirements, particularly for cooking, with the fuelwood share being about 79% of the total consumption (Malla, 2013; NPC, 2013). The high population growth rate and dependency on fuelwood are causing rapid deforestation (Link, Axinn, & Ghimire, 2012; WECS, 2010). Moreover, traditional biomass fuels are low energy efficient fuels, the use of which are the major causes of environmental emissions and other socio-economic and health-related problems in Nepal (Katuwal & Bohara, 2009; MoPE, 2004; WECS, 2010).

A sustainable, affordable and reliable clean energy source is an emerging priority in Nepal to provide energy security, particularly to the poor population. Secure supplies, affordability and minimal impact on the environment are the three often competing goals of providing energy security from a range of sources (Olz, Sims, & Kirchner, 2007). The Government of Nepal, with the objectives of providing energy security[1], decreasing the rate of deforestation and reducing the dependence on imported petroleum fuels, has been disseminating renewable energy technologies (RET), mainly micro-hydro, solar power and biogas, throughout the country. However, these energy sources do not sufficiently address the demand for energy, as they supply less than 1% of the present total demand (Malla, 2013; WECS, 2010). The majority of the rural poor people in Nepal cannot afford solar power and micro-hydro power due to the high initial investment costs of these relatively complicated technologies (KC, Khanal, Shrestha, & Lamsal, 2011).

In view of the potential and availability of other renewable energy resources, and considering the technology involved and associated costs, biogas is considered to be one of the most promising renewable energy sources for rural households (APCAEM, 2007; BSP-Nepal, 2009; Katuwal & Bohara, 2009; SNV, 2010). It is an easily available source of energy that can be managed with locally available resources, which otherwise are wasted or used inefficiently (Gewali & Bhandari, 2005). The Government of Nepal, with support from donor agencies, has been promoting construction of biogas plants as a way of bringing cleaner, more affordable energy to rural households since the early 1990s (BSP-Nepal, 2009). There is high potential in the adoption of biogas technology in Nepal due to the modular and easy-to-construct design of digesters, its proven reliability, the immediate benefits, subsidies for encouraging installation, and the long-term financial incentives from the clean development mechanism (CDM) (Bajgain & Shakya, 2005; BSP-Nepal, 2009; Gautam, Baral, & Herat, 2009). By 2014, more than 330,000 biogas plants had been constructed in Nepal, of which 95-98% remained in operation (BSP-Nepal, 2015).

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[1] Energy security is the consistent availability of adequate clean energy in affordable prices over the long term (Asif & Muneer, 2007).

1.2 Problem Statement and Rationale

Biogas technology has emerged as one of the effective alternative clean energy solutions for the scattered settlements in Nepal and has the potential to minimise the pressure on traditional biomass fuels and to reduce the country's foreign exchange expenditure (Katuwal & Bohara, 2009; SNV, 2010). Although the installation rate is increasing, only approximately 17% of total potential households have installed biogas in the more than two decades since its inception (BSP-Nepal, 2015). Despite biogas being one of the government's priorities with a subsidy for installation, replication of biogas technology is still slow. Failure to improve access to biogas systems by all potential households could result in costs to the country, in terms of deforestation to supply traditional fuels and a huge outflow of foreign currency to import petroleum products. Moreover, the poor quality traditional biomass fuels that many women use in rural areas has contributed to gender inequities because of the time needed to collect biomass fuels, ill health caused by smoke inhalation, and a high level of drudgery (Mahat, 2004).

Rao and Braral (2011) suggested that despite mature technology, the potential of biogas is not fully utilised. Low biogas yield, particularly during cold conditions, is considered a major problem for wider replication of the technology (KC, et al., 2011; SNV, 2010), since the biogas produced cannot cover the energy demand of a household (Katuwal & Bohara, 2009). Many researchers from different parts of the world are working on increasing biogas production in cold climates, although the outcomes so far are not significant (Balasubramaniyam, Buysman, Meriggi, & Zisengwe, 2008). Users have experienced low gas production, even in favourable temperature conditions (Gongal & Shrestha, 1998; Lungkhimba, Karki, & Shrestha, 2011). However, there has been insufficient evaluation of the existing production and demand of biogas to identify the daily household energy deficit and reasons for gas production that is lower than the full capacity and potential of the digester.

Almost all domestic biogas plants in Nepal are operated on cattle dung, which has a relatively low gas yield (Moller, Sommer, & Ahring, 2004), and even the quantity might not be enough to sustain biogas production throughout the year (Jingura & Matengaifa, 2009; Lungkhimba, et al., 2011). Poor households, in particular, cannot afford the large numbers of livestock needed to supply the required manure for biogas production, resulting in an even lower gas output (Gongal & Shrestha, 1998; KC, et al., 2011;

Lungkhimba, et al., 2011). The literature reveals that the use of agricultural residues[2] or energy crops with dung for co-digestion can improve digester efficiency (e.g., Alvarez, Otero, & Lema, 2010; Ward, Hobbs, Holliman, & Jones, 2008), and thus could be a viable option for improving biogas production capacity (e.g., Poschl, Ward, & Owende, 2010; Rao & Braral, 2011). However, the potential of using such organic wastes in co-digestion with animal dung in a domestic biogas plant has been inadequately explored (Jingura & Matengaifa, 2009; Lungkhimba, et al., 2011; Rao & Braral, 2011). Besides, the impact of increased biogas production through co-digestion on three wider aspects together – energy consumption, cost of energy, and corresponding GHG[3] emissions – is poorly understood.

This study, therefore, attempts to address the aforementioned problems and to contribute to the knowledge gap in this area by exploring ways to optimise biogas production and utilisation in rural poor households, and to encourage the adoption of this technology in order to provide energy security. This research is important in view of the widespread policy shift towards an increasing access of renewable energy to such households. The findings of this study will be useful in assisting BSP-Nepal and other agencies/projects promoting biogas technology in Nepal in their efforts to improve biogas production efficiency for the energy demands of rural households. The empirical results are recommended to the BSP-Nepal and relevant government agencies to adopt the modified plant design that suits the co-digestion of mixed feedstocks.

1.3 Research Hypothesis, Aims and Objectives

This study hypothesises that biogas can be a simple, reliable, cost-effective and clean energy option if co-digestion of dung with agricultural residues increases biogas production efficiency, and reduces cooking energy cost and GHG emissions.

The aims of this research are to evaluate the existing production and use of biogas, and explore the potential for improving production the efficiency of domestic biogas plants. This study specifically addresses the following research questions:

- *How can the production and utilisation of biogas systems be enhanced in order to provide energy security to rural households in Nepal?*

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[2] Agricultural residues and crop residues are used interchangeably.

[3] GHG is a gas of the atmosphere that absorbs and emits radiations within the spectrum of infrared radiation emitted by the earth's surface that causes the greenhouse effect. H_2O, CO_2, N_2O, CH_4 and ozone are the primary GHGs (Reay & Hogan, 2012).

- *What will be the impacts of improved biogas production on cost of energy, energy consumption and associated GHG emissions reduction?*

The following specific research objectives have been identified to address the above research questions:

1. Analyse the socio-economic and gender impacts of domestic biogas technology on rural households;
2. Examine the demand and consumption patterns of biogas, and analyse how the users cope with lower gas production than the full capacity potential of the digester;
3. Identify the main reasons behind the lower biogas production;
4. Assess the technical potential for improving biogas production efficiency through co-digestion of agricultural residues with dung;
5. Analyse the cost-effectiveness of co-digestion biogas technology; and
6. Analyse the impact of increased biogas on reducing fuelwood consumption and related GHG emissions reductions.

1.4 Research Approach

Both quantitative and qualitative research approaches were employed in this study. The field study was undertaken in two districts in Nepal, *Chitwan* and *Lamjung,* which are distinctly different in terms of altitude, temperature, feedstock availability, biogas subsidy policy and remoteness. Quantitative data was required for empirical data analysis which was mainly based on household survey data. However, the qualitative data was important to identify the status of biogas development, feedstock availability, the subsidy policy, plans and any constraints and opportunities for the replication of biogas technology. Socio-economic factors are also important for biogas development and replication in the context of Nepal where caste and gender-related disparities are prevalent. Hence, those issues were also addressed in this study using qualitative methods. A wide range of data was therefore collected from household to district and national levels, including household survey, key informant interviews, observation and discussion.

A household survey was undertaken in the sampled biogas households in each district. An extensive set of survey questionnaires was used to elicit specific and quick responses from the respondents. The biogas plant operation, use and associated problems were also observed and discussed with the owners and the women’s groups during informal discussions. Key informant interviews were carried out from the companies and the government representatives who produced and subsidised the biogas plants. Different strategies were employed to ensure the quality of the research, including triangulation, and reflective analysis moving between the data and emergent results. The raw data was systematically coded, entered into the spreadsheet, and was assessed using descriptive analysis in SPSS version 20.0 software (IBM Corp., 2011) for research objectives nos. 1, 2 and 3.

Research objective no. 4 was analysed using the Volumetric Methane Prediction (VMP) model. The potential biogas yield of cattle dung and agricultural residues were calculated both for *individual* and co-*digestion* conditions. The effect of temperature on biogas yield was also considered. Research objective no. 5 was assessed by the financial analysis. The cost of biogas includes installation cost, operating cost, and repair and maintenance cost. However, the overall cost-effectiveness of a biogas system was checked out mainly with respect to the cost of energy at corresponding fuel prices and under different biogas production conditions. The cost of energy before and after biogas plant installation was compared in order to identify the overall economic benefits. The quantifiable monetary benefits including saving from decreased use of fuelwood, the utilisation of saved time for other activities and the use of slurry to replace chemical fertiliser were taken into account. Then, the cost of energy after biogas was specifically compared under: *existing low biogas production condition; improved production by full dung-fed condition; and increased production by co-digestion.*

Finally, research objective no. 6 was assessed by using the LEAP model. Energy consumption and GHG emissions were analysed under different scenarios: *no-biogas; existing biogas production; increased production by co-digestion; and increased subsidy policy* conditions over a time horizon of 2012-2040. The impact of biogas to replace conventional cooking fuels in household cooking energy consumption was considered in demand analysis while the emissions from fuel combustion, the non-energy sector and transformation were considered in the GHG emission analysis.

1.5 Structure of the Thesis

This thesis is organised into 10 chapters. An introduction to the thesis is provided in Chapter One, which states the background information, the research problem and justification, the research aims and objectives, and the research approach. Chapter Two reviews the basics of biogas production and its benefits, including the contribution of biogas to sustainable development and to the achievement of the millennium development goals (MDGs), and the global status of biogas development. Chapter Three provides an overview of Nepal, its energy structure and biogas technology development in Nepal. The methodology of this research is presented in Chapter Four. Chapter Five reports the findings of the data analysis of the socio-economic background of surveyed households, the operation of biogas plants and feedstock availability, the impacts of biogas on workload reduction, and biogas production and utilisation. Chapter Six presents the technical potential of improving biogas production efficiency through co-digestion of crop residues with dung. The findings of cost analysis of a biogas plant after co-digestion are presented in Chapter Seven. Chapter Eight presents the impacts of biogas plants on reducing fuelwood consumption and corresponding GHG emissions under a number of biogas development scenarios obtained by using the LEAP model. The final two chapters, Nine and Ten, discuss the key findings of the research and present the research conclusions and recommendations.

CHAPTER TWO

BIOGAS PRODUCTION, BENEFITS AND GLOBAL STATUS OF BIOGAS DEVELOPMENT

2.1 Introduction

A review of literature on biogas technology is presented in this chapter. It first reviews the basics of biogas production to provide some understanding of biogas technology, factors affecting biogas production, and types and design of biogas plants. Benefits of biogas technology and its importance in achieving sustainable development and the Millennium Development Goals (MDGs) are then reviewed. A review of biogas development around the world provides insight into biogas production, utilisation and the potential of biogas technology worldwide. It is particularly focussed on the Organisation for Economic Cooperation and Development (OECD)[4] countries, Asia and Africa, where biogas production is widely promoted.

2.2 Biogas Basics

Biogas is a methane-rich gas that is produced from anaerobic fermentation of organic materials by the action of methanogenic bacteria in a digester (Itodo & Phillips, 2001; Karki, Shrestha, & Bajgain, 2005). It is a gas mixture comprising methane, CO_2 and other gases (Table 2.1), also known as swamp gas, marsh gas or gobar gas (Hilkiah, Ayotamuno, Eze, Ogaji, & Probert, 2007; Karki et al., 2005). Biogas is an odourless and colourless gas that burns with a clean blue flame similar to that of liquid petroleum gas (LPG), which is virtually smoke-free combustion (FAO/CMS, 1996). It has an ignition temperature in the range of 650-750°C with a calorific value of 22.4 megajoules (MJ) per m^3, and it burns with about 60% efficiency in a conventional biogas stove (FAO/CMS, 1996; Karki et al., 2005). Normally 1 m^3 of biogas is enough to cook three meals for a family of five to six members (FAO/CMS, 1996; Karki et al., 2005; Practical Action, 2006).

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[4] OECD is "a multidisciplinary international body made up of 30 member countries that offers a structure/forum for governments to consult and co-operate with each other in order to develop and refine economic and social policy" (Statistics Canada, 2008).

Table 2.1: The average composition of biogas

Substances	Symbol	Composition (% volume)
Methane	CH_4	50-70
Carbon dioxide	CO_2	30-40
Hydrogen	H_2	5-10
Nitrogen	N_2	1-2
Water Vapour	H_2O	0.3
Hydrogen Sulphide	H_2S	(0.01-0.09 ppm)

Source: Karki et. al. (2005)

Biogas technology is best suited to convert organic waste into energy and fertiliser. Of the outputs of biogas, the gas is valued for its use as a source of energy and the slurry for its fertilising properties (FAO/CMS, 1996; Sims, 2002). It is used as a clean cooking and lighting fuel, and as a substitute for fossil fuels, thereby reducing GHG emissions (Figure 2.1).

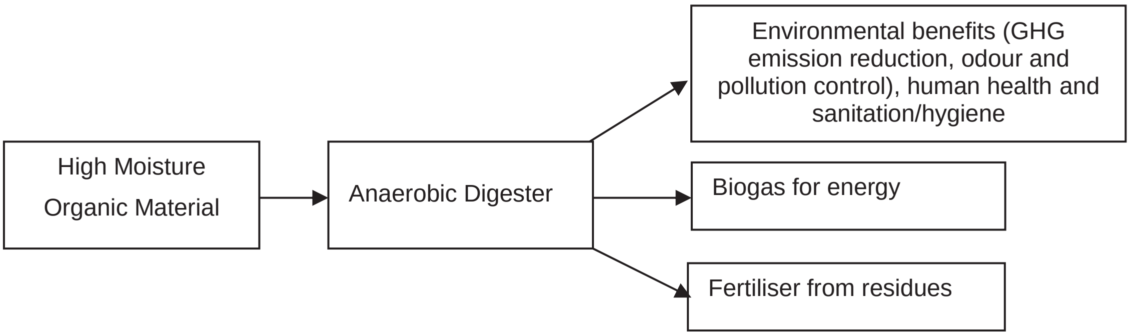

Figure 2.1: Schematic diagram of biogas production

Source: Adapted from Sims (2002, p. 171)

Any biodegradable organic material can be used as inputs for biogas production. However, some materials are more preferred than others for economic and technical reasons (Clemens, Trimbotnm, Weiland, & Amon, 2006). If the inputs are easily available biodegradable wastes it could have two-fold benefits: economic value for users and saving of environmental costs for biodegradable waste management, e.g., disposal in landfill (FAO/CMS, 1996; Sims, 2002). Its ability to generate biogas from organic wastes that are abundant and freely available is one of the main attractions of biogas technology. In many rural areas in developing countries like Nepal, small-scale biogas plants use mostly animal dung as an input, mainly because of its free availability (Clemens et al., 2006; FAO/CMS, 1996; Karki et al., 2005).

Different groups of micro-organisms carry out conversion of complex organic compounds in a sequence of four stages: solubilisation or hydrolysis, acidogenesis, acetogenesis and methanogenesis (Figure 2.2) (Balasubramaniyam et al., 2008; Karki et al., 2005). In the initial stage, during hydrolysis the large molecular complex substances are solubilised into simpler, smaller components with the help of extracellular enzymes released by bacteria. During acidogenesis, the acidogenic bacteria use the smaller compounds from the hydrolysis process under anaerobic conditions to produce volatile fatty acid, ethanol, CO_2 and H_2. Acetogenesis is the stage where acetogenic bacteria convert these fermented products into acetic acid, CO_2 and H_2. Finally, methanogenic bacteria use hydrogen and acetate and produce methane and CO_2 in the methanogenesis stage (Balasubramaniyam et al., 2008; FAO/CMS, 1996; Karki et al., 2005).

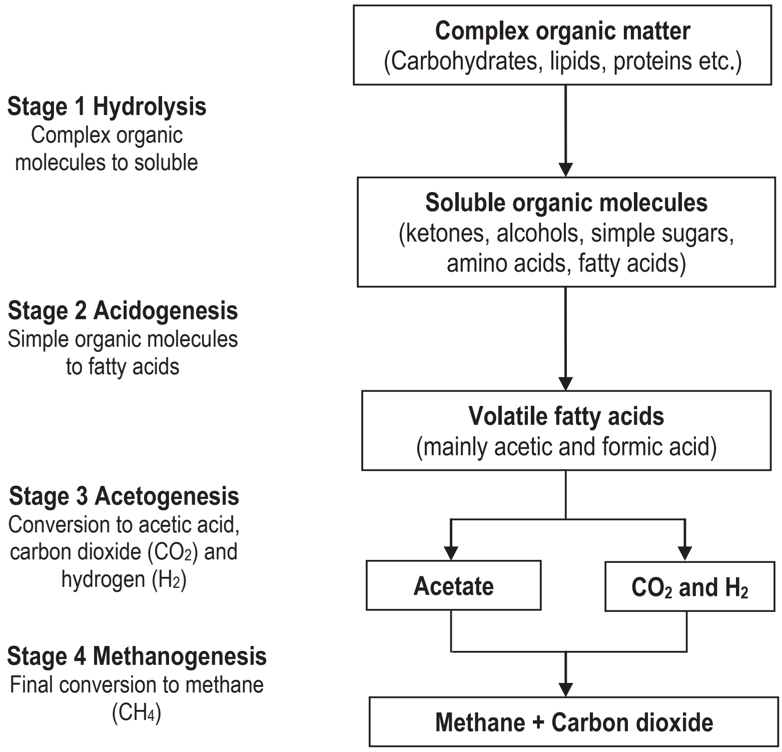

Figure 2.2: Scheme of single stage anaerobic digestion process

Source: Balasubramaniyam et al. (2008, p. 8)

A substrate or feedstock contains moisture and solid content (Figure 2.3). Substrate's solid content, which is called total solid (TS), is measured in kg/m^3. Volatile solid (VS, measured in kg/m^3) is the only organic or biodegradable content of TS that is used for bio-methanation process (Werner, Stöhr, & Hees, 1989). Anaerobic digestion converts the volatile solids into biogas. Volatile solids are constituted of protein, carbohydrate and lipid (organic fat), which are three major organic components considered for methane production (Figure 2.3) (Koch, Lubken, Gehring, Wichern, & Horn, 2010; Triolo, Sommer, Møller, Weisbjerg, & Jiang, 2011). The rate of biogas production depends on the rate of VS destruction and hence methane or biogas yield is measured in terms of m^3/kg VS destroyed (Koch et al., 2010). The non-volatile solids are essential to the bacteria as roughage and minerals, while water serves as the vital medium, solvent and transport vehicle (Werner et al., 1989).

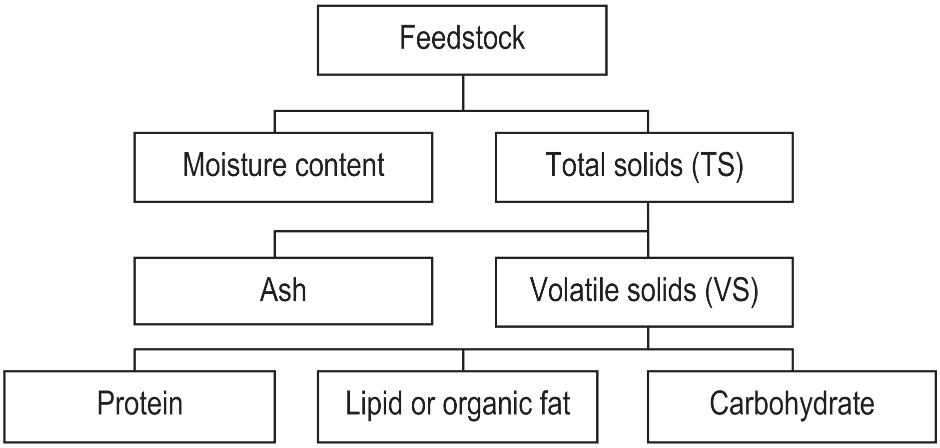

Figure 2.3: Feedstock composition
(Adapted from Koch, et al., 2010, p. 8160).

The theoretical maximum biogas yield can be determined through the basic composition of the feedstocks and their energy potential (Table 2.2). Organic fats yield higher biogas and have higher energy potential compared with other organic compounds.

Table 2.2: Energy potential of organic compounds

Material	Biogas (litre/kg)	CH_4	CO_2	Energy content (Watt-hour/gram)
		Volume fraction (%)		
Protein	704	71	29	4.96
Carbohydrate	790	50	50	3.78
Organic fat	1270	68	32	8.58

Source: Kaltwasser, 1980 cited in Werner, et al. (1989)

2.2.1 Factors affecting biogas production

Besides types and quantity of feedstocks, a number of factors affect the rate of digestion and biogas production, including temperature, carbon-nitrogen (C/N) ratio, hydraulic retention time (HRT), organic loading rate (OLR), dilution and consistency of inputs, pH value of the input mixture, toxicity, altitude and precipitation (Balasubramaniyam et al., 2008; FAO/CMS, 1996; Karki et al., 2005; Nagamani & Ramasamy, 2010). In order to understand these factors, the relevant design parameters required for biogas plants are summarised in Table 2.3, and are discussed in this section.

Table 2.3: Design parameters of a biogas plant

Parameter	Value
Digestion temperature	20 – 35 °C
C/N ratio	20 – 30
Hydraulic retention time	40 – 100 days
Daily loading rate	6 kg dung/m^{3}digester size
pH value of input mixture	6 – 7
Energy content	6 kWh/m^{3}biogas
One cow yield (dung)	9 – 15 kg dung/day
Gas production per kg of cow dung	0.023 – 0.04 m^3
Gas production per kg of human excreta	0.020-0.028 m^3
Gas requirement for cooking	0.2 – 0.3 m^3/person
Gas requirement for lighting one lamp	0.1 – 0.15 m^3/hour

Source: Werner, et al. (1989); Mendis and van Nes (1999b); Karki, et al. (2005)

Temperature

Temperature is the most important factor in biogas production because it determines the rate of hydrolysis and methane formation (Tchobanoglous, Burton, & Stensel, 2003). During the anaerobic digestion process, methanogen bacteria are inactive in extreme high and low temperatures (Daxiong, Shuhua, Baofen, & Gehua, 1990; Safley & Westerman, 1990, 1992, 1994). Research on production at different temperatures conducted in Tongliang in China revealed that the daily production rate of biogas during winter (6-10°C) was 0.05 m^3/m^3 dung; spring (16-22°C) was 0.1- 0.2 m^3/m^3 dung and summer (22-23°C) was 0.2-0.33 m^3/m^3 dung (Daxiong et al., 1990). Similarly, Kalia and Singh (1996) found that production in hilly regions of India reduced from 1700 litres/day during summer to 99 litres/day during winter, whilst Kalia and Kanwar (1998) found 23-37% lower production in winter. This implies that biogas can function throughout the year, but gas production will be much lower during winter or in colder regions.

Normally, higher temperatures that do not kill microorganisms result in higher metabolic activities (Angelidaki & Sanders, 2004). Once metabolism occurs, exothermic reaction facilitates the methane production (Karki et al., 2005). Anaerobic fermentation is, in principle, possible between 3°C to about 70°C, which can be differentiated in three temperature ranges: anaerobic fermentation or digestion at a temperature range below 20°C is referred to as psychrophilic digestion; at a temperature range between 20°C and 40°C is referred to as mesophilic digestion; and at a temperature range above 40°C is referred to as thermophilic digestion (ISAT/GTZ, 1999; Safley & Westerman, 1990; Werner et al., 1989). Satisfactory gas production occurs in the mesophilic range, the optimum temperature being 35°C (Balasubramaniyam et al., 2008; Safley & Westerman, 1992). The rate of bacteriological methane production increases with temperature, but the amount of free ammonia increases with temperature, which could inhibit or reduce bio-digester performance. If the temperature of the biomass is below 15°C, biogas production is no longer economically feasible (ISAT/GTZ, 1999). Biogas production drops as much as 75% during winter, and it virtually stops when the ambient temperature goes below 10°C (Balasubramaniyam et al., 2008; FAO/CMS, 1996).

In colder climates or higher altitude regions, the temperature of fermenting substances in the digester needs to be raised up to 35°C for optimum biogas production (Karki et al., 2005). This adds additional costs which could make less affordable to the rural poor households. Thus the process of anaerobic digestion is very sensitive to changes in temperature. The relationship between temperature and biogas yield has been illustrated in several studies (e.g., Hashimoto, Varel, & Chen, 1981; Safley & Westerman, 1992; Tchobanoglous et al., 2003; Toprak, 1995), although the outcomes in terms of specific yield at different feedstocks and temperature conditions so far are not significant (Balasubramaniyam et al., 2008; Karki et al., 2005).

Carbon-nitrogen ratio

A C/N ratio is the relationship between the amount of carbon and nitrogen present in organic materials. Carbon (C), hydrogen (H), oxygen (O) and nitrogen (N) are the major elemental compositions of any organic matter that greatly influence methane production (Koch et al., 2010). The largest percentage of carbon is assumed to be readily degradable, but only degradable nitrogen is used for an anaerobic digestion process (Sreekrishnan, Kohli, & Rana, 2004). Thus the amount of carbon and nitrogen present in a feedstock could be an important indicator to determine the methane yield and the ratio of co-substrates for co-digestion. During anaerobic decomposition, microorganisms utilise carbon 25-30 times faster than nitrogen, and to meet this requirement the C/N ratio of 20-30 is considered favourable for biogas production (Demirbas, 2006; Karki et al., 2005; Lin et al., 2011). A very high C/N ratio of the organic material results in rapid consumption of nitrogen by methanogens for meeting their protein requirements, after which they will no longer react on the left-over carbon content of the material, resulting in a low gas production (FAO/CMS, 1996; Lin et al., 2011). When the C/N ratio is very low, nitrogen will be liberated and accumulated in the form of ammonia (NH_4), which will increase the pH value of the content in the digester, showing a toxic effect on the methanogen population and this decreases biogas production (Amon et al., 2007; FAO/CMS, 1996). Co-digestion of substrates with a higher C/N ratio could help to achieve the desired C/N ratio of the mixture for increased methane production potential by stabilising the fermentation process (Amon et al., 2007; Demirbas, 2006; Lin et al., 2011).

Hydraulic retention time

Hydraulic retention time is the average duration of time a feedstock remains in the digester. It is calculated by dividing the total volume of the digester by the volume of slurry added daily (Safley & Westerman, 1990, 1992). On average, a retention time of 40 to 60 days is required depending upon the temperature for a cow dung plant, but retention time varies per temperature; a lower temperature condition requires a longer retention time (Safley & Westerman, 1992). Werner et al. (1989) mentioned that 10-16 days is suitable for thermophilic and 30-60 days for mesophilic fermentation conditions, while it needs more than 100 days of retention time for a psychrophilic condition of 3-20°C. But for a human excreta mixed plant as practised in Nepal, a longer retention time (70 to 90 days) is needed in order to kill the pathogens present in human faeces (Karki et al., 2005).

Retention time also affects methane yield. Alvarez, et al. (2006) reported the positive effect of longer retention time in methane production and suggested a time of 50 days as appropriate for cow and llama manure. However, Bouallagui et al. (2004) obtained the best daily biogas production from the shortest hydraulic retention time (10 days). New Zealand Standard (1986) and ISAT/GTZ (1999) suggested a retention time of 15-30 days suitable for various feedstocks. A longer retention time is required in lower temperatures to achieve a similar gas production to higher temperatures (Safley & Westerman, 1992, 1994; Sutter & Wellinger, 1988; Zeeman, 1991). Sutter and

Wellinger (1988) showed the relationship between temperature and retention time as the gross biogas production by a digester operating at 20°C and a retention time of 40-50 days is comparable to a digester operating at mesophilic temperature but at half the retention time. Similarly, Safely and Westerman (1994) evaluated the performance of anaerobic digesters under low temperature and revealed that digestion is feasible at a minimum digester temperature of 10°C with a minimum hydraulic retention time of 50 days at the maximum loading rate of 0.12 kg VS/m^3/day.

Loading rate

The correct rate of loading is important for efficient gas production, and is fundamental to digester design and operation. Loading rate is defined as the quantity of feedstock loaded into the digester per unit time, usually expressed as kilograms of total dry solids per cubic metre of digester volume per day (VS/m^3/day) (New Zealand Standard, 1986, Werner, et al. 1989). The amount of raw materials fed per unit volume of digester capacity per day has a significant effect on biogas production (FAO/CMS, 1996). According to Werner, et al. (1989), the lower limit for digester load for a typical agricultural biogas plant of a simple design is roughly 1.5 kg volume of solids per m^3 per day. A general rule of thumb is that 6 kg of dung per m^3 volume of digester is recommended for a domestic biogas plant (FAO/CMS, 1996; Karki et al., 2005; Mendis & van Nes, 1999a). A lower loading rate results in less gas production because an overfed plant inhibits methane production due to acid accumulation inside the digester (FAO/CMS, 1996).

Researchers have suggested different results for loading rates on biogas yield. Safely and Westerman (1994) suggested that biogas production is higher for the lower loading rates (0.1 VS/m^3/day) compared with higher loading rates (0.2 VS/m^3/day). However, the relationship between the methane productivity and the loading rate depends on the manure. The manure with high solids content, because of its energy density, could result in high methane yield, and hence a relatively low amount of manure with high solids content could satisfy the energy requirements of a household (R. Alvarez et al., 2006; Werner et al., 1989).

The loading rate is inversely proportional to volume of digester and retention time (Balasubramaniyam et al., 2008; Safley & Westerman, 1990). This implies that increasing the volume of bio-digester and retention time can also achieve the same methane yield at a lower temperature. Thus, a digester designed to operate at lower temperatures should have a lower loading rate per unit volume and a proportionately larger volume to achieve similar methane compared to a reference digester at higher temperatures (Safley & Westerman, 1992). Compared to a conventional digester at 25°C, the volume of a digester at a 2°C temperature should be 10 times as large and at a 5°C temperature should be around seven times larger (Balasubramaniyam et al., 2008).

Dilution and consistency of inputs

Dilution and consistency of inputs also affect biogas production. The input material, e.g., fresh cattle dung, should be mixed thoroughly with water before feeding it into the digester. The ratio between solid and water should be 1:1 on a unit volume basis for proper solubilisation of organic materials, but the total solid content should be maintained at 5-10% (FAO/CMS, 1996; Karki et al., 2005). In the case of dry organic material, more water is required to make the desired consistency, where solid to water ratio could vary from 1:1.25 to 1:2. Too diluted or too thick slurry may not result in optimum gas production (FAO/CMS, 1996; Karki et al., 2005). However, Ranade et al. (1990) argued that varying levels of total solid content do not affect the methane content of biogas, and hence suggested following a higher total solid content of 14% cattle dung (2:1 dilution) in areas of water scarcity, rather than discontinuing the operation of biogas.

pH value of the input mixture

The pH of the input mixture is also important in methane formation, since an acidic condition is not favourable for the methanogenic process. Methanogenic bacteria are very sensitive to pH and do not grow well below a value of 6.0 (Karki et al., 2005). The optimum biogas production is achieved when the pH value of input mixture in the digester is between 6 and 7 (FAO/CMS, 1996). However, retention time also affects the pH in a biogas digester. The pH inside the digester can decrease to below 5 during the initial period of fermentation when large amounts of organic acids are produced by acid-forming bacteria. Later when the concentration of NH_4 increases due to digestion of nitrogen, it increases the pH value to above 8. But the pH range remains stable between 7.2 and 8.2 when the methane production level is stabilised (FAO/CMS, 1996; Karki et al., 2005). If industrial waste is used as feeding material, it tends to decrease the pH of the digester, which needs to be adjusted by the addition of the right amount of lime ($CaCO_3$) (Karki et al., 2005).

Toxicity

Toxic materials such as mineral ions, heavy metals and detergents affect the production of biogas (FAO/CMS, 1996; Lam & ter Heegde, 2010; Nagamani & Ramasamy, 2010). Although a small amount of mineral ions (e.g., sodium, potassium, calcium, magnesium, ammonium and sulphur) stimulates the growth of bacteria, a heavy concentration of these ions will have a toxic effect (FAO/CMS, 1996; Karki et al., 2005). Similarly, the addition of small quantities of heavy metals, e.g., copper, nickel, chromium, zinc, magnesium, iron, increase the methanogenic population in a digester and enhance biogas production (FAO/CMS, 1996). However, the addition of detergents including soap, antibiotics and organic solvents should be avoided, since these materials hinder the activities of methane-producing bacteria (FAO/CMS, 1996; Lam & ter Heegde, 2010).

Altitude

Altitude affects biogas production and efficiency. Normally, the temperature decreases as altitude increases and so does the air pressure. So, the higher the altitude, the lower the temperature exists and so it is with the biogas yield (ISAT/GTZ, 1999). Besides, research has shown that the calorific value of biogas decreases at higher altitudes; the calorific value of biogas at sea level and 20°C is about 6 kWh/m^3, whereas that at 1,000m above sea level at the same temperature is 5.36 kWh/m^3 (Sasse, Kellner, & Kimaro, 1991).

Precipitation

The impact of precipitation on anaerobic fermentation is mainly indirect (ISAT/GTZ, 1999). High precipitation can increase groundwater levels, which may cause problems in construction and the operation of biogas plants. Low precipitation or water scarcity, on the other hand, may lead to the insufficient availability of water for substrate mixture. In addition, low precipitation does not support intensive systems of animal husbandry, resulting in less dung availability (ISAT/GTZ, 1999).

2.2.2 Types and design of domestic biogas plants

Hundreds of biogas plant designs were experimented in the past by various scientists, engineers and academicians (FAO/CMS, 1996; Karki et al., 2005). The designs of the digester have been horizontal, rectangular, spherical, underground and above ground with various construction materials from mild steel to plastic sheet and masonry work like bricks, cement, concrete (Karki et al., 2005). However, the design principle of a simple domestic biogas plant should include simple operation, cost-effectiveness and durability, and efficiency (optimum gas production per unit volume of a biogas plant for given type and quantity of input). It should be constructed from local materials as far as possible and should have minimal repair and maintenance requirements (Karki et al., 2005; K. J. Singh & Sooch, 2004; Werner et al., 1989). Of the various types of biogas plants designed, two models of domestic biogas plant have gained widespread acceptance, particularly in developing countries (Karki et al., 2005; K. J. Singh & Sooch, 2004; Werner et al., 1989), which are discussed briefly in this section.

Floating drum biogas plant

A design of a floating drum biogas plant was developed in India in 1956, which gained popularity in India and the sub-continent as a KVIC design after its approval by the Khadi Village Industries Commission (KVIC) of India (GMII, 2011; Karki et al., 2005; K. J. Singh & Sooch, 2004). The digester chamber is constructed from brick masonry in cement mortar. A mild steel drum is kept on top of the digester chamber that floats on the slurry to store the gas produced (Figure 2.4). When methane gas is produced, the gas pressure pushes the mild steel drum upwards, and as the gas is being used the drum gradually lowers down. Since the mild steel drum practically floats above the digestion chamber, it is known as the floating drum gas-holder biogas plant.

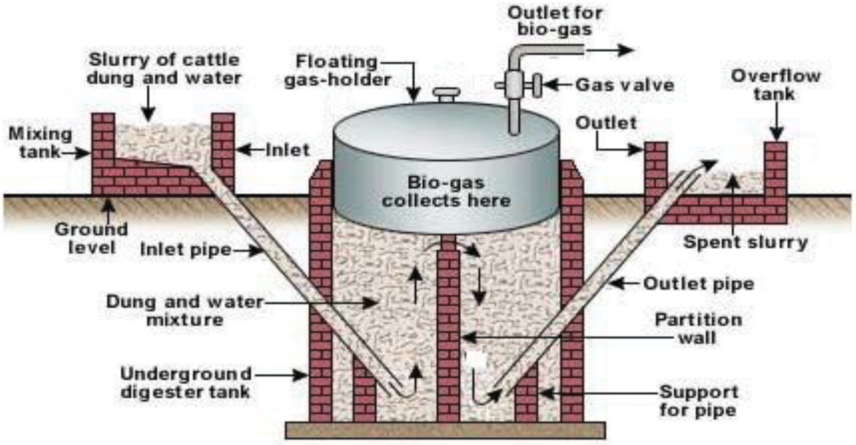

Figure 2.4: Schematic diagram of floating drum biogas plant

Source: GMII (2011)

Since the floating gas-holder drum is made of stainless steel, it is expensive and requires continuous maintenance and supervision for non-rust (GMII, 2011). The drum needs to be replaced within 5-10 years due to the corrosion on the drum (Karki et al., 2005). For these disadvantages, the floating drum plants became obsolete with the introduction of the fixed-dome Chinese design biogas plant.

Fixed-dome design biogas plant

A fixed-dome Chinese model biogas plant (drumless digester) was first experimented in China around the mid-1930s. It consists of a cylinder with a round bottom and top with an underground brick masonry (cement mortar) compartment for the digestion chamber and a concrete dome on the top for gas storage combined as one unit (Figure 2.5) (FAO/CMS, 1996; Karki et al., 2005; K. J. Singh & Sooch, 2004; Werner et al., 1989). This design is superior to the floating drum design because it eliminates the use of a costlier steel gasholder drum and the life of a fixed-dome type plant is longer (20-50 years) (Karki et al., 2005).

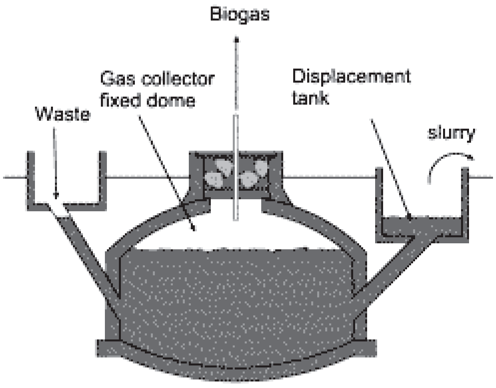

Figure 2.5: Schematic diagram of Chinese fixed-dome biogas plant
Source: Karki et al. (2005)

Based on the principles of the fixed-dome Chinese model, various countries have modified designs to suit their local conditions (FAO/CMS, 1996; Karki et al., 2005; K. J. Singh & Sooch, 2004). A modified Deenbandhu model, which has the dome structure constructed of brick masonry instead of concrete, is widely used in India (Figure 2.6). It is reported as 30% cheaper than the Chinese fixed-dome model (K. J. Singh & Sooch, 2004).

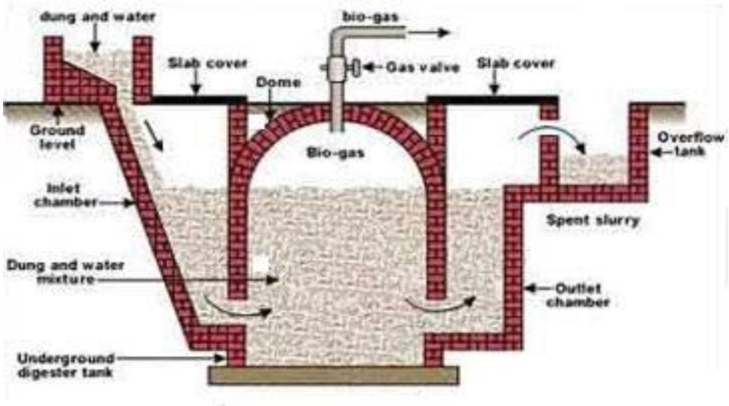

Figure 2.6: Schematic diagram of Deenbandhu model

Source: GMII (2011)

Another modified version of the fixed-dome Chinese plant, CAMARTEC model, was developed in Tanzania which has a simplified structure of a hemispherical dome shell based on a rigid foundation ring only (Figure 2.7) (Karki et al., 2005).

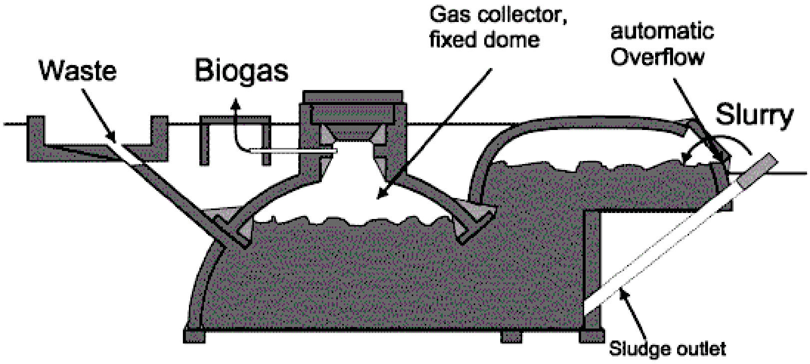

Figure 2.7: Schematic diagram of CAMARTED fixed-dome design

Source: Karki et al. (2005)

In Nepal, the Gobar Gas and Agricultural Equipment Development Company (GGC) modified the fixed-dome Chinese model, which is known as the GGC-2047 model in Nepal (BSP-Nepal, 2009a). This model is easier to construct as this structure has less curved profiles (e.g., digester bottom is horizontal instead of concaved) (Figure 2.8). Although this design is compact and well insulated as it is constructed underground, occupies less space and the earth-filled plant maintains inner temperature during the cold season, gas leakage is a still a problem (Karki et al., 2005; Mendis & van Nes, 1999a).

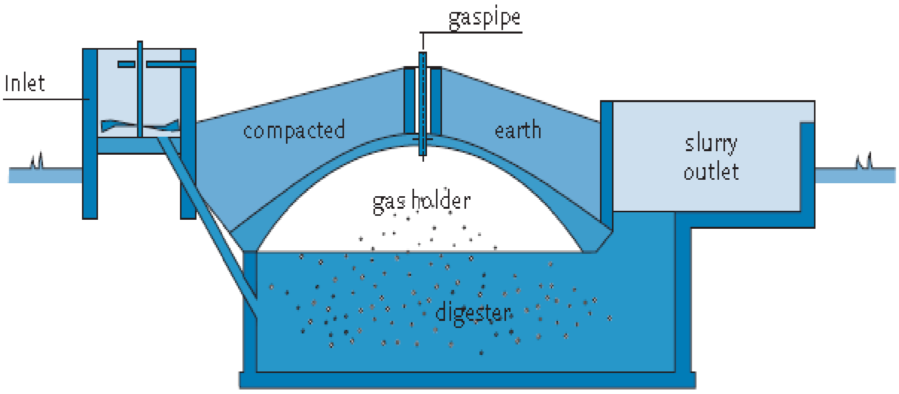

Figure 2.8: Schematic diagram of GGC 2047 fixed-dome biogas plant
Source: Mendis and van Nes (1999a)

Besides these, a Taiwanese polyvinyl chloride (PVC) bag digester, a plug flow digester, an anaerobic filter, a tunnel type plant and an upflow anaerobic sludge blanket model are other designs that have been experimented in various countries (Karki et al., 2005). The next section discusses the major benefits of small-scale domestic biogas technology.

2.3 Benefits of BiogasTechnology

Biogas technology provides multiple economic, social, and environmental benefits from household to national and global levels (e.g., APCAEM, 2007; Bajgain & Shakya, 2005; EAC, 2011; SNV, 2010; Winrock International, 2007) (Figure 2.9). Direct economic benefits can be derived from reduced use of conventional fuels, reduced use of chemical fertilisers, job creation and increased involvement in income-generating activities, and carbon trading as a CDM. Social benefits of biogas technology include gender benefits, educational opportunities and health and sanitation benefits. Reduction in GHG emissions from reduced burning of emission-intensive fuels and reduced deforestation are the major environmental benefits. Impacts of biogas on reducing consumption of traditional biomass fuels, mitigating GHG emissions, reducing drudgery of women and improving health and sanitation conditions are significant (SNV, 2010).

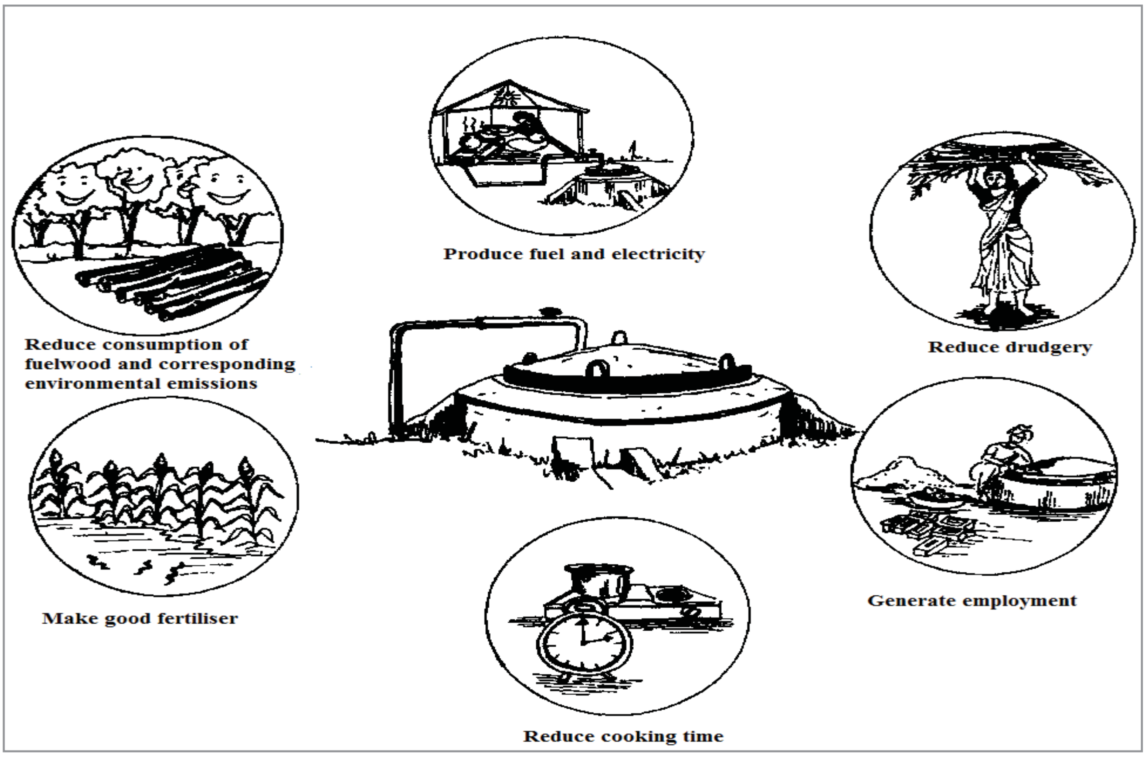

Figure 2.9: Benefits of biogas technology

[Source: EAC (2011)]

While biogas may not provide direct benefit to those farmers who have no cattle and land, they could benefit indirectly from increased employment opportunities, increased availability of fuelwood and reduced climate change effects (Bajgain & Shakya, 2005).

2.3.1 Economic benefits

Benefits from reduced use of traditional biomass fuels

Due to the lack of easy access to other fuels as well as economic compulsions, many poor rural households in developing countries, particularly in Asia and Africa, are still forced to use fuelwood and agricultural residues as major fuels for cooking and heating (e.g., Amigun & von Blottnitz, 2010; APCAEM, 2007; BSP-Nepal, 2009a; Chen, Yang, Sweeney, & Feng, 2010; Dhussa, 2010; Winrock International, 2007). The introduction of biogas technology has succeeded in replacing these primitive fuels with more environmental-friendly fuel, offering savings on fuel costs for the user households who would otherwise have to purchase it, or saving on labour for those who spend much time on its free collection (Bajgain & Shakya, 2005; KC, Takara, Jasinki, & Khanal, 2013). Fuelwood in many rural households is collected by family members due to the lack of cash to purchase it and the lower opportunity cost of their time (Section 7.2). The potential of biogas technology in reducing consumption of traditional biomass fuels is analysed in Chapter 8.5.1.

Studies suggest that, on average, a biogas plant of 6 m^3 size can save about 2-3 tonnes of fuelwood and 1 tonne of crop residues annually (East Consult, 2004; SNV, 2010). According to CMS (2007), installation of biogas plant in Nepal has reduced the expenditure on fuelwood purchase by US$ 265/year/household (see Section 7.7.1). This is a significant amount for the Nepali population considering that their per capita income is a mere US$489 per year (MOF, 2014). The primary economic benefit from the reduction in the use of agricultural residues is the organic value of the residues when ploughed back into the soil, while animal dung is fed into the biogas system. This clearly shows that use of biogas has made a significant economic contribution in the lives of users since they save money, curtailed from fuelwood purchase or time/labour saving, to be utilised in other needful/productive activities (CMS, 2007). In Vietnam, saving on total fuel expenses before and after the installation of biogas was 65%, with saving on fuelwood being 81% (Dung, Hung, & Hoa, 2009).

Benefits from reduced use of petroleum fuels

Many rural households in developing countries still use kerosene as a major fuel for lighting and cooking and the use of LPG for cooking is increasing (e.g., Amigun & von Blottnitz, 2010; APCAEM, 2007; Chen et al., 2010; Dhussa, 2010; Winrock International, 2007). Although none of the surveyed households reported using biogas for lighting[5], other studies suggested that the use of biogas for lighting and cooking purposes displaces a minimum of 32-69 litres of kerosene per system annually (G. Devkota, 2007; East Consult, 2004; P. C. Ghimire, 2005, 2007; SNV, 2010). According to CMS (2007), the use of biogas in Nepal substantially reduced the kerosene consumption saving at least US$75/year/household in 2007. Moreover, since kerosene is one of the high products of incomplete combustion-emitting fuels, its reduction also contributes towards decreasing health hazards and environmental emissions (Karki et al., 2005). Similarly, the use of biogas can replace about 6 LPG cylinders a year, saving about US$130/year (Vaid & Garg, 2013).

Benefits from slurry and reduced use of fertilisers (agricultural benefits)

Application of digested bio-slurry, a by-product of biogas, as a bio-fertiliser can generate economic benefits to the user households. The slurry comes at the equal volume of feeding dung, but has more nitrogen, phosphorus and potassium content (2.7:1.9:2.2) (FAO/CMS, 1996), and can significantly improve agricultural productivity

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[5] Biogas was used for lighting in households without electricity. However, households stopped using it for lighting because the lamps were not energy-efficient (0.1-0.5m^3 gas/hr) and got very hot, causing fire hazards when hanging directly below the wooden/thatch roofs (Karki et al., 2005). Besides, the mantles were expensive and did not last long. Using biogas lamps resulted in much less gas available for cooking.

(BSP-Nepal, 2009a). Studies suggested that use of bio-slurry has positive impacts on crop, vegetable and fishery production (Dung et al., 2009; Katuwal & Bohara, 2009; Winrock International, 2007). In India, wheat and cotton yields were increased by 15 and 16%, respectively (K. B. Karki, 2001), whereas a 10-20% increase in yield was observed in China (Z. Li, Tang, C., Luo, & Zhong, 2005). Increase in vegetable yield was even higher (20-50%) in kitchen gardens (CMS, 2007; K. B. Karki, 2001; Katuwal & Bohara, 2009). Use of slurry as fish food also increased the growth rate of Grass carp and Common carp by about 2 tonnes/ha (Mahadevaswami & Venkataraman, 1990). A large number of households (42%) also experienced an increase in income from the sale of surplus food due to increased crop productivity after the use of slurry (Katuwal & Bohara, 2009).

Acharya, et al. (2005) and Karki, et al. (2005) reported that a biogas plant produces about 1.7 tonnes of organic fertiliser annually, which can replace the use of chemical fertiliser that is not environmental-friendly, saving the cost of its purchase (Gautam et al., 2009) and reducing users' dependency on it (e.g., Amigun & von Blottnitz, 2010; Z. Li et al., 2005; Winrock International, 2007). It is estimated that one average size biogas plant can save 39 kg nitrogen, 19 kg phosphorous and 39 kg potash per year (East Consult, 2004; Karki et al., 2005; SNV, 2010), which is equivalent to an annual financial saving of about US$26[6] per household.

Benefits from job creation and involvement in income generation

Biogas technology has the potential to increase employment opportunities. Cherian (2009) highlighted that the use of renewable energy in developing countries like India, Nepal, Brazil and parts of Africa can stimulate local economic and social development through employment opportunities. The renewable energy sector already accounts for about 2.3 million jobs worldwide (UNEP, 2008). About 11,000 people in Nepal are employed in different sectors such as manufacturing, construction, financing, services, quality control and administration (Bajgain & Shakya, 2005; BSP-Nepal, 2009a).

Moreover, biogas technology enables increased involvement in income generation activities (IGAs) (Bajgain & Shakya, 2005; BSP-Nepal, 2009a; Winrock International, 2007). Use of biogas saves time spent on household activities such as cooking, cleaning utensils, collecting fuelwood and livestock caring (BSP-Nepal, 2012b). According to CMS (2007), about 31% biogas households in Nepal were involved in the

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[6] Based on the 2010 chemical fertiliser price in Nepal (*Urea*-Rs. 18/ kg, DAP- Rs. 32/kg, Potash Rs.17/kg).

IGAs, thus earning revenue to improve their livelihoods. This benefit has been analysed in Section 5.4.

Benefits from clean development mechanism

Biogas technology has started providing economic benefits from carbon trading too (SAESUP, 2010). Biogas has been identified as a CDM, since it reduces the GHG emissions from directly reducing the burning of biomass, and hence it is used for carbon trading (Katuwal & Bohara, 2009). Under the Kyoto protocol, the Non-Annex[7] countries with a low contribution of GHG can trade their reduced carbon emission with other developed countries (UNFCC, 2014). Biogas in Nepal has been started providing economic benefits from carbon trading since 2005; Nepal has been selling saved GHG emissions through Voluntary Emission Reductions (VERs) managed by the World Bank (SAESUP, 2010). Nepal has the potential to earn more than US$5 million per year by selling carbon credit to the developed countries (Katuwal & Bohara, 2009). Thus it has become a good source of income for the development of the biogas sector, since the carbon credit earned from CDM could provide alternative financing for the sustainability of biogas programmes (BSP-Nepal, 2014) (Section 8.5.3).

2.3.2 Social benefits

Gender benefits

Gender is a socially defined role for men and women, which can be defined as a *"socially constructed power relations between women and men that establish the roles, responsibilities, opportunities and decision-making authority of women and men, usually positioning women as subordinate to men*" (SNV, 2012, p. 2). Traditionally, managing household energy is considered as women's business in most of the rural communities, but women's role in decision-making is limited (Clancy, Ummar, Shakya, & Kelkar, 2007; Mahat, 2004; P. A. Nepal, 2009). Energy policy in most of the countries is gender blind (Clancy et al., 2007) and women suffer more from energy poverty[8] (Cecelksi, 2004). In this context, biogas systems have been able to meet both practical and strategic gender needs[9] and have positive implications for both women and men (Bajgain & Shakya, 2005).

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[7] Non-Annex countries are mostly the developing countries which are especially vulnerable to the adverse impact of climate change (UNFCCC, 2014b).

[8] Energy poverty is the absence of sufficient choices in accessing adequate, affordable, reliable, high quality, safe and environmentally friendly energy services to support economic and human development (A. K. N. Reddy, 2000).

[9] Molyneux (1985) defined practical gender needs as women's immediately perceived needs from their everyday roles and work in society such as the need for shelter, clothing and food. Strategic gender needs, however, arise out of women's desire to emerge from their subordinate position to men and to formulate '...an alternative, more satisfactory

Reduction of workload, mainly for women and children, in fuelwood collection and cooking is one of the most significant social benefits of biogas (G. Austin & Blignaut, 2007; CMS, 2007; Dung et al., 2009; Gurung & Thakali, 2014; Katuwal & Bohara, 2009) (see Section 5.4). Rural women spend most of their time (almost 12 hours a day) on household activities such as fetching water, livestock caring, fuelwood and fodder collection, cooking food and cleaning utensils (G. Austin & Blignaut, 2007; Dung et al., 2009; Katuwal & Bohara, 2009). On average, a biogas plant could reduce the drudgery for women and female children of collecting fuelwood and cooking by over 3 hours per day (CMS, 2007; Dung et al., 2009; Katuwal & Bohara, 2009; Ratnayake, 2000; SNV, 2010). Barnes and Sen (2003) revealed that there is little need for fuelwood collection after the use of biogas.

The time saved by the use of biogas has given rural women more time to utilise in social and religious works, IGAs, recreational activities, child care and education or visiting friends (G. Austin & Blignaut, 2007; Bajgain & Shakya, 2005; Dung et al., 2009; Katuwal & Bohara, 2009). Researchers found that about 25-30% women were involved in the IGAs, while a higher percentage (32%) of them have used the saved time in recreational activities such as watching television and listening to the radio (CMS, 2007; Katuwal & Bohara, 2009; SNV, 2010). About one-third of women spend their saved time in social and community activities, e.g., participating in a mothers' group, forest users' groups, cooperatives and youth clubs, which not only increases women's participation in community development activities, but also empowers women to take decision-making roles in such activities (Katuwal & Bohara, 2009).

Although biogas has fulfilled some strategic gender needs by providing female members some free time to take part in discussions on the internal household and community matters, and to participate in social and community works (G. Austin & Blignaut, 2007; Dung et al., 2009; Katuwal & Bohara, 2009), the traditional gender roles or patterns of labour division have not been necessarily changed after the introduction of biogas (G. Austin & Blignaut, 2007; Bajgain & Shakya, 2005). Mostly female members contribute to the biogas sector as construction labourers and their participation at institutional/decision-making levels is still negligible (ENERGIA, 2010). Nevertheless, the reduction of women's workload can be considered as an important

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set of arrangements' (Molyneux, 1985:232-3), which could include attaining political equality, abolishing the gendered division of labour, securing women's rights to traditionally-held land, gaining protection against male violence and having the burden of domestic labour alleviated (Molyneux, 1985:233). Thus, practical gender needs are concerned with women's condition, while strategic gender needs are about women's position in society (Kabeer, 1994).

achievement in providing opportunities for women to increase their skills and awareness in the biogas sector, be involved in the IGAs, and organise and participate in the decision-making level of community development activities (G. Austin & Blignaut, 2007; Bajgain & Shakya, 2005).

Health and sanitation benefits

Biomass fuel for cooking and heating, and kerosene fuel for lighting, increase indoor air pollution and are the major risk factors for acute respiratory infections in childhood, chronic obstructive pulmonary disease and lung cancer (Bruce, Parez-Padilla, & Albalak, 2000; Pokhrel et al., 2010; Smith, Samet, Romieu, & Bruce, 2000). According to the World Health Organization's estimate, more than 1.6 million deaths and over 38.5 million disability-adjusted life-years can be attributable to indoor smoke from solid fuels affecting mainly children and women, and indoor air pollution was ranked as fourth among preventable risk factors contributing to the burden of disease in the underdeveloped countries (Torres-Duque, Maldonado, Pérez-Padilla, Ezzati, & Viegi, 2008). In India, indoor air pollution is responsible for over 500,000 premature deaths (Smith, Samet, et al., 2000), whereas acute lower respiratory infection due to indoor air pollution accounts for over 30% of total deaths in Nepal (Winrock Nepal, 2004). Similarly, chronic obstructive pulmonary disease (chronic bronchitis), which is the third cause of mortality in the world, could be attributed predominantly to biomass smoke inhalation (Torres-Duque et al., 2008). Studies have also suggested a linkage between biomass smoke and tuberculosis, asthma and lung cancer in women (e.g., Mishra, Retherford, & Smith, 1993; Smith, Mehta, & Maeusezahl-Feuz, 2004). It is noted that 5,000-7,000 people die in Nepal from tuberculosis every year (NTC, 2013). Similarly, absorption of biomass smoke condensates, including polycyclic aromatics and metal ions into the eye lens, leads to oxidation changes and causes eye ailments such as cataracts, which is another big health problem in developing countries including Nepal (Bruce et al., 2000).

In this context, use of biogas has positive impacts on the health of its users. Biogas as cooking fuel significantly improves indoor air quality due to a drastic reduction in smoke exposure, with much lower concentrations of carbon monoxide, nitrogen and sulphur oxides, formaldehyde and respiratory suspended particles (Katuwal & Bohara, 2009; Smith, Samet, et al., 2000). Total respiratory suspended particles are high in biomass combustion (8.2 mg/m^3 for wood, 5.74 mg/m^3 for crop residue), followed by kerosene (3.48 mg/m^3) and LPG (1.5 mg/m^3), but are quite low in biogas (0.25 mg/m^3) (M. Acharya et al., 2005; NHRC, 2002; Smith, Samet, et al., 2000; Winrock Nepal, 2004).

Acharya, et al. (2005) and Katuwal and Bohara (2009) argued that respiratory problems, asthma, eye infections and lung problems had decreased drastically after displacing dirtier biomass fuels with biogas. Obviously, the reduction of the diseases was most effective among women and children, since they spend more time in kitchens than their male counterparts in developing countries. Thus, Acharya, et al. (2005) reiterated that the health benefits of biogas are as equally important as other benefits, and hence it cannot be underemphasised in terms of national programmes and budgeting.

Besides a decrease in the incidence of diseases, biogas helps to improve the general sanitation condition around the households through dung management and attachment of sanitary toilets to biogas digesters. Toilets attached to plants can solve the problem of unmanaged human excreta and wastewater that is widespread in rural poor communities, thus reducing another major risk factor for the spread of several infectious bacterial/viral diseases (G. Austin & Blignaut, 2007; Bajgain & Shakya, 2005; Dung et al., 2009; Gautam et al., 2009; Katuwal & Bohara, 2009). Improved health and sanitation conditions in the rural households also leads to savings on health-related expenses.

Education benefits

Use of biogas has direct implications for the education of children. Before the installation of biogas, many children, mostly girls, were kept out of school to assist in household chores and the collection of fuelwood and water (Clancy, Skutsch, & Batchelor, 2002; Hunt, 2008). With reduced workload and more time after the use of biogas, female children are better able to attend school and have extra time for education at home (G. Austin & Blignaut, 2007; Bajgain & Shakya, 2005). Their absence rate at school has also decreased with reduced childhood respiratory and diarrheal illnesses as a result of reduced indoor air pollution (Winrock Nepal, 2004). In addition, adult women gained time to be involved in adult literacy classes (Katuwal & Bohara, 2009).

2.3.3 Environmental benefits

Dependency on fuelwood for cooking energy needs is one of the major causes of deforestation, while deforestation has caused a fuelwood crisis (Katuwal & Bohara, 2009). Deforestation is responsible for 17-25% of all anthropogenic GHG emissions in the world (Strassburg, Turner, Fisher, Schaeffer, & Lovett, 2009). Around 40% of the world's population depends on fuelwood, and fuelwood is becoming scarce (Amare, 2014). Increased burning of fuelwood leads to increase GHG emissions, which have negative consequences on the environment, both locally and globally. A decrease in fuelwood consumption displaced by biogas contributes to reducing the prevailing high rate of deforestation and associated soil erosion, particularly in the developing countries, thereby increasing the carbon sink (G. Austin & Blignaut, 2007; CES, 2013; Karki et al., 2005) (see Section 8.5.2). On a global scale, the use of biogas contributes significantly in reductions in GHG emissions since the global warming potential of fuelwood is high in comparison to biogas (Kojima, 1998; SEI, 2010).

The ever-increasing population, fossil fuel burning and deforestation have resulted in the alteration of the chemical composition of the atmosphere through the build-up of GHGs, particularly CO_2, CFCs, methane and nitrous oxide, and the increased atmospheric concentration of these GHGs has significantly raised the threat of global warming (Kojima, 1998). IPCC (2013) has indicated that the global averaged combined land and ocean surface temperature increased by 0.85 (0.65-1.06)°C over the period 1880-2012. It has been calculated that a doubling of CO_2 concentration would lead to an increase in temperature ranging anywhere from 1.5°C to 4.5°C (IPCC, 2013).

Dhingra, et al. (2011) argued that biogas households had as much as 54% lower global warming commitment, i.e., the warming effects of GHG emissions from cooking, than non-biogas households, and the monetary value of a biogas system was conservatively estimated at US$28.30 based only on the averted GHG emissions over 10 years. Based on the emission coefficients of approximately 1.5 tonnes CO_2-equivalent (tCO_2e) per tonne of *non-sustainable* fuelwood and 2.5 tCO_2e per 1000 litres of kerosene as suggested by the IPCC guidelines (1995), a rural household with biogas reduces 4.5 tonnes of CO_2e emissions per year by reducing the use of fuelwood and kerosene (Katuwal & Bohara, 2009). Considering the carbon emission factor of biogas as 30.6 tC/terajoule (TJ), Pokharel (2007b) concluded that each biogas plant can replace about 6.2 tCO_2/year. Since biogas is assumed to be produced on a sustainable basis, the CO_2 produced by the biogas combustion is reabsorbed by growing fodder and food for the animals and people (Mendis & van Nes, 1999a). Although such reduction at the household level might not produce significant results, it can be very significant when seen from a national perspective.

A study carried out in India explicitly highlighted the amount of carbon emissions generated when burning various biomass and fossil fuels, and revealed how much carbon emissions ar saved when biogas replaces these fuels (Smith, Uma, et al., 2000)

The amount of carbon emissions depends on the type of fuel burning as well as the type of stove used (Table 2.4). Because of their poor combustion conditions, the traditional stoves using fuelwood or agricultural residues are thermally inefficient and thus divert a significant portion of the fuel carbon into products of incomplete combustion, which generally have a greater impact on climate than CO_2 (Smith, Uma, et al., 2000).

Table 2.4: Carbon emissions from burning of various biomass and fossil fuels

Source	Carbon emission (gram)
1 kilogram of wood burned in a traditional mud stove	418
1 kilogram of agricultural residue in a traditional mud stove	381
1 kilogram of dung in a traditional mud stove	334
1 kilogram of kerosene in a pressure stove	834

Source: Smith et al. (2000)

2.4 Dis-benefits of Biogas

Although biogas has several benefits, it has a few dis-benefits too. An increase in the mosquito and fly population due to slurry flow from a toilet attached biogas plant is reported as a main dis-benefit (P. C. Ghimire, 2005; Karki et al., 2005). Likewise, users consider daily feeding of animal dung mixed with water as an extra burden. Collection of water is also a problem if the water source is far from the biogas plant (Karki et al., 2005). Use of biogas does not generate daily direct income, so farmers have limited income-generating opportunity to utilise the time saved from biogas plant installation (SNV, 2010). Besides, a biogas stove requires more matchsticks to light up.

2.5 Biogas and Sustainable Development

The widely accepted definition of sustainable development was published in the Brundtland Report in 1987 as “the development that meets the needs of the present without compromising the ability of future generations to meet their own needs” (WCED, 1987, p. 43). Sustainable development addresses the concerns about the interactions between human society and environment, which can be framed in an interdependent and reinforcing three-pillar model – economic development, ecological protection and social development (UN, 2005). Domestic biogas is compatible with the definition of sustainable development as it contributes to achieving the three pillars of sustainable development: economic development, by saving costs, generating income and boosting productivity (Section 2.3.1); social development, by improving living standards through promoting gender equity, improving health and sanitation conditions (Section 2.3.2), enhancing energy access (Section 2.4.1) and energy security (Section 2.4.2); and environmental protection, by reducing indoor pollution and environmental degradation/emissions (Section 2.3.3) (APCAEM, 2007; ICC, 2010; OECD/IEA, 2011; Sathaye et al., 2011).

Marchaim (1992) argued that biogas production can contribute to resource conservation and sustainable development as it combines short-term economic benefits to the rural communities and reduces the ecological degradation. Several literatures have described biogas as the best way for sustainable development of energy systems to obtain a win-win situation, as it provides efficient energy, income and health benefits for poor beneficiaries at the local level; sustainable environment and economic benefits at the national level, and social relationship with foreign investors through CDM at the international level (APCAEM, 2007; A. Karki et al., 2005; MoPE, 2004; Munasinghe, 1992; Parikh & Parikh, 2002; SAESUP, 2010; Sathaye et al., 2011).

2.5.1 Contribution of biogas to provide energy access

Energy access can be defined as access to clean, reliable and affordable energy services for cooking, lighting, heating, communication and productive uses (Sathaye et al., 2011). Access to these energy services is fundamental to developing countries for reducing poverty, improving health, increasing productivity, enhancing competitiveness, and promoting economic growth (OECD/IEA, 2011). However, energy access is context dependent as it depends on energy consumption, which is largely shaped by income, and choice and pattern of energy. It can be explained with the help of an energy ladder (Smith et al., 1994). The energy ladder theory hypothesises that with a rise in income or other socio-economic factors, a household shifts from lower quality fuels (e.g., traditional biomass) to more modern and efficient fuels, which have substantially lower emissions of health-damaging pollutants (Smith et al., 1994) (Figure 2.10).

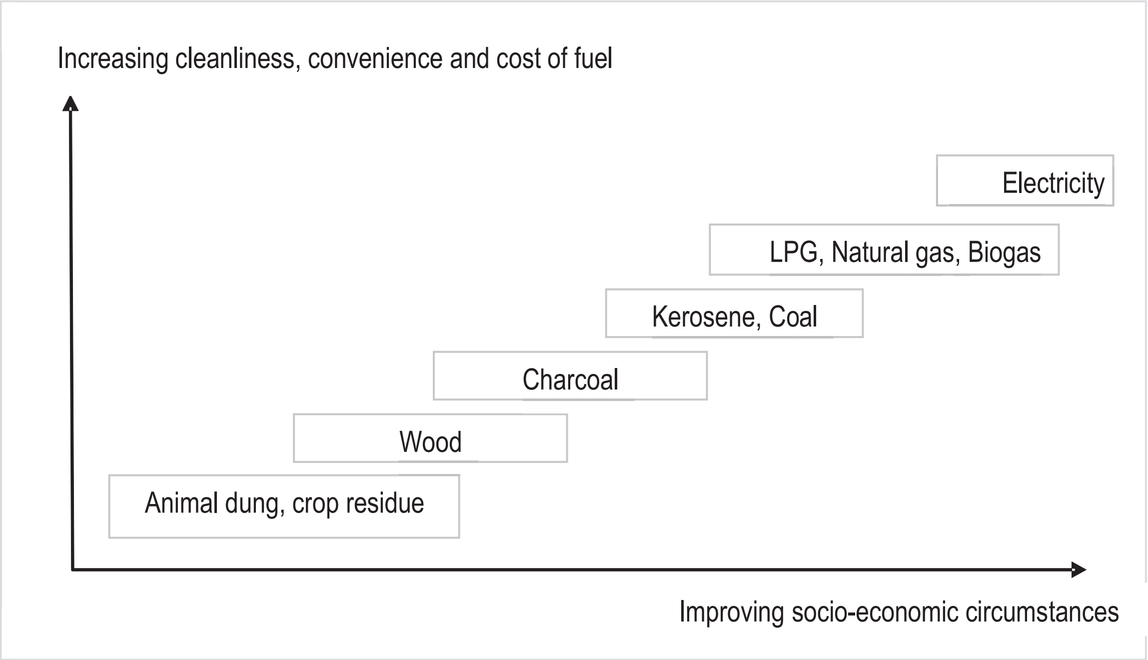

Figure 2.10: The energy ladder

Source: Adapted from Smith, et al. (1994)

In this context, simple and effective off-grid renewable technologies such as biogas can deliver clean, efficient and affordable energy access to poor communities and reduce the vulnerability of the poor (Olz et al., 2007; Smith et al., 1994). A number of governments around the world have adopted policies to promote biogas as the lowest cost option for energy access (e.g., G. Austin & Blignaut, 2007; Chen et al., 2010; Dung et al., 2009; GoN, 2006; Liu, Kuang, Huang, Wu, & Xu, 2008; Lucena et al., 2009; Mahapatra, Chanakya, & Dasappa, 2009; Urmee, Harries, & Schlapfer, 2009). Biogas is considered as the largest component to provide clean cooking facilities in the world, and the OECD/IEA (2011) estimates that biogas will attract almost 60% of investment in the energy sector with an estimated investment of US$37 billion from 2010-2030 in order to provide biogas access to all who are currently deprived of modern energy access. About 1.3 billion people did not have access to electricity and 2.7 billion relied on traditional biomass fuels for cooking in 2009 (OECD/IEA, 2011).

Subsidy is an important part of financing biogas systems (SNV, 2011a). Lower income households may need support in getting easy access to credit to cover part of the costs of a biogas system (ADB, 2009; UNDP, 2009). Support from multilateral and bilateral development agencies, developing country government sources and private sector sources are the major financing sources for energy access investments (OECD/IEA, 2011). Utilising the existing financing mechanisms such as CDM and the climate change funds can ensure access to energy for the poor. Various international co-financing supports are available from the Global Environment Facility (GEF), Global Partnership for Output-based Aid (GPOBA), the Climate Investment Funds and the CDM, which could be tapped to reduce the national burden of huge investment for providing energy access for all (Bhattacharyya, 2012).

2.5.2 Contribution of biogas to provide energy security

By improving energy access and energy efficiency, biogas can contribute to energy security goals in terms of availability and reliability of clean energy source. Asif and Muneer (2007) have defined energy security as a consistent availability of adequate energy at affordable prices over the long-term. Secure supplies, affordability and minimal impact on the environment are the three often competing goals of providing energy services from a range of sources to meet society’s needs (Olz et al., 2007). Energy security has been realised as a major issue worldwide because of depleting fossil fuel sources. Reserves, production and exports of fossil fuels are spatial and very uneven, and concentrated in a few regions (Lloyd & Subbarao, 2009).

A biogas system represents a greater share of the solution to address energy poverty and provide energy security for rural off-grid people in developing countries, who are not grid-connected due to the high cost of electricity transmission in remote locations (OECD/IEA, 2011). Although other renewable energy technologies, such as solar power and wind energy, can also contribute to energy security and in reducing GHG emissions while displacing traditional biomass and fossil fuels, the poor communities cannot afford them due to their high initial investment costs/life cycle costs (ADB, 2004; Olz et al., 2007). Biogas, on the other hand, not only has low life cycle costs compared to other renewable energy technologies, but also is characterised by simple technology and abundant availability of feedstock (ADB, 2004), which makes it an affordable, accessible and sustainable energy source to the rural poor households.

2.6 Contribution of Biogas to Achieving the Millennium Development Goals (MDGs)[10]

The Millennium Declaration of the eight MDGs to be achieved by 2015 is the world's most urgent development need (GoN/UN, 2010). Although energy is not mentioned in any of the MDGs, every goal is related to energy (Modi, McDade, Lallement, & Saghir, 2006). The UNDP (2011) states that none of the MDGs can be met without improving the quality and quantity of energy services in developing countries. Modi, et al. (2006) highlighted the role of energy services to both social and economic development and stressed that much wider and greater access to energy services is important in achieving the MDGs. Recognising the strong link between energy access and seven of the MDGs, the UN high level meeting recommended measures to be taken to achieve the MDGs, which included enabling use of modern energy for 50% of those who at present use traditional biomass for cooking, thus enabling access to reliable modern energy services for all urban and peri-urban poor (Practical Action, 2009a).

The overriding objective of the MDGs is the removal or significant reduction of poverty with improved equity (GoN/UN, 2010). There are several definitions of poverty in literature. The United Nations has defined poverty as:

> "Fundamentally, poverty is a denial of choices and opportunities, a violation of human dignity. It means lack of basic capacity to participate effectively in society. It means not having enough to feed and clothe a family, not having a school or clinic to go to, not having the land on which to grow one's food or a job to earn one's living, not having access to credit. It means insecurity,

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[10] Fifteen years of effort to achieve eight measurable and universally agreed objectives set out in the MDGs in 2000 was mostly successful by 2015, but still need to accelerate the momentum for uncompleted goals (UNDP, 2015a) In light of this, the concept of Sustainable Development Goals (SDGs) was born during the United Nations Conferences on Sustainable Development (Rio +20) in 2012 (Loewe, 2012; Sachs, 2012; UNDP, 2015a). The objective was to produce a set of universally applicable goals that balance the three dimensions of sustainable development: environmental; social; and economic. On 25 September 2015, the UN Member States adopted the SDGs which include 17 goals to be achieved by 2030 (UNDP, 2015a).

The 7th goal of SDG targets to *ensuring universal access to affordable, reliable and modern energy services to all and* the 13th goal relates to combating climate change and its impacts by 2030 (UNDP, 2015a). This project, which declares biogas as an affordable, reliable and clean renewable energy resource, will contribute to achieving those two targets directly. It also will contribute to SDG 1 to 6, namely 1) poverty reduction; 2) zero hunger; 3) good health and wellbeing; 4) quality education; 5) gender equalities; and 7) sanitation targets indirectly. This thesis write-up was started in 2012. It was expected then that this research's outcome will assist in accomplishing MDGs targets. However, now at the end of 2015, it is expected that those benefits will be automatically streamlined to achieve SDGs targets until 2030.

> powerlessness and exclusion of individuals, households and communities. It means susceptibility to violence, and it often implies living on marginal or fragile environments, without access to clean water or sanitation" (UN Statement, June 1998, signed by the heads of all UN agencies) (Gordon, 2005, p. 3).

Access to energy services can help poor people to remedy two of the pervasive problems that keep them in poverty – low productivity and a limited range of productive options. Modi et al. (2006) argued that without investing enough in energy services, most of the poor countries will not meet the targets of MDGs within the given time frame. Simple effective technologies to deliver clean and efficient energy to poor communities are available, but many of them are associated with some constraints such as high costs, limited power supply and limited resources availability (Practical Action, 2009a). Thus, biogas, one of the prominent modern energy sources with lower life cycle costs, simple technology and abundant resource availability, can significantly contribute to achieving the goals and targets of MDGs (Lam & ter Heegde, 2010). The contribution of biogas systems includes both the direct impact of energy on raising income and the indirect impacts on health, education, gender issues and environment.

2.6.1 Eradicate extreme poverty and hunger (MDG 1)

The economic benefits of biogas technology (Section 2.3.1) contribute to achieving MDG 1. Installation of biogas plant helps to eradicate poverty and hunger through saving money on fuel costs, increasing income through utilising the time saved from reducing the burden of time-consuming domestic labour in the IGAs, providing economic opportunity by creating jobs in this sector, and earning income through increased agricultural production from using bio-slurry as fertiliser (Dutta, 2005; Lam & ter Heegde, 2010). The biogas dissemination process and the resulting reduced claim on common ecosystem services affect the livelihood conditions of poor non-biogas households as well. For example, biogas savings on the use of traditional cooking fuels increases the availability of these fuels for poor members of the community (G. Austin & Blignaut, 2007).

2.6.2 Achieving universal primary education (MDG 2)

Biogas technology indirectly helps to achieve MGD 2 of achieving universal primary education due to its education benefits as described in Section 2.3.2. In addition, installation of biogas plants in schools could improve the energy access and sanitation of schools creating better environments for education (G. Austin & Blignaut, 2007; Lam & ter Heegde, 2010; Winrock International, 2007).

2.6.3 Promote gender equality and empower women (MDG 3)

The energy-poverty nexus has distinct gender characteristics, women and men having different access to resources and decision-making both at household and community levels (Clancy et al., 2002). Women have more restricted access to decision-making in general, which has limited their ability to influence decision-making processes and resource allocation on many issues, including energy (Clancy et al., 2002). The responsibility for energy provision is generally allocated to women, but the decisions about which energy technology to use are made by the male members of the household. Such decisions do not address women's strategic needs as they do not replace any of the women's tasks (Barnett, 2001; Clancy et al., 2002; Wright & Kealotswe, 2006). There is gendered division of labour and gender inequalities, which has consequences for energy use, needs and priorities (Wright & Kealotswe, 2006). Women's social position and energy institutions' attitude on gender issues are the major factors for an energy-blind policy (Clancy & Feenstra, 2006).

The link between gender, energy and MDG 3 is that women and girls suffer more from energy poverty and hence stand to gain more from improved energy services (Clancy et al., 2007; Dutta, 2005). As discussed in Section 2.3.2, biogas has been successful in promoting gender equality by reducing women's time and hard workload of collecting firewood, and improving their health conditions (G. Austin & Blignaut, 2007; Keizer, 1993; A. K. N. Reddy, 2000; RUDESA, 2002; Winrock International, 2007) (see Section 5.4). This enables them to spend more time and labour on other productive activities such as education, income generation and community development, which can contribute to their social and economic empowerment, and increase their capabilities for their rights in their society (Clancy et al., 2007). However, how biogas programmes can improve women's livelihood opportunities, their empowerment for larger, social changes and bring about better gender relations within households and communities still needs to be explored (ENERGIA, 2010; Havet, 2003).

2.6.4 Health benefits (MDGs 4, 5 and 6)

The health benefits of biogas technology (see Section 2.3.2) are linked to achieving MDGs 4, 5 and 6 of reducing the children under-five mortality rate, improving maternal health, and combating malaria and other diseases. Biogas contributes to the reduction of the mortality rate of under-five children and achieving MGD 4 by eliminating indoor smoke pollution and associated health risks by substituting conventional inefficient cook stoves and energy sources. Biogas, by reducing the drudgery for women of carrying heavy fuelwood loads on their back or head, lessens their suffering from back problems, uterine prolapse and a risk of miscarriages (Cecelski, 2000; Haile, 1991; Subedi, 2010), and thus helps improve maternal health. By improving manure and human excreta management, biogas improves the sanitary conditions of the household and its immediate surroundings and lowers exposure to harmful infections generally related to polluted water and poor sanitation (Lam & ter Heegde, 2010; SNV, 2011b). Besides this, application of biogas slurry could improve agricultural production, contributing to food security for the better health of the household members.

2.6.5 Environmental sustainability (MDG 7)

Large-scale adoption of domestic biogas programmes positively influences national policies on sustainable development and usually supports government policies and programmes that have positive environmental impacts (SNV, 2011b). As mentioned earlier in Section 2.3.3, the increased use of biogas can help reduce pressure on local forests and biodiversity, thus reducing forest degradation and associated soil erosion. Accelerated deployment of renewable energy and energy-efficient systems like biogas can reduce indoor air pollution and GHG emissions contributing to MDG 7 of ensuring global climate change mitigation (UNDP, 2010).

2.7 Global Status of Biogas Development

Biogas technology is a proven and established technology in many parts of the world due to its many benefits (Holm-Nielsen, Al Seadi, & Oleskowicz-Popiel, 2009; Naskeo, 2009; Wilkinson, 2011). The French Agency for the Environment and Energy Management (ADEME) estimates that biogas resources are comparable with the yearly consumption of fossil natural gas worldwide (1,800 Mtep[11]/year) if all the waste is treated through anaerobic digestion. But the feasible potential of biogas worldwide is estimated at 140 to 300 Mtep/year, as this energy is too dispersed in the world to be easily recoverable (Table 2.5) (Naskeo, 2009). Although the feasible potential of biogas can substitute 8-17% of natural gas consumption worldwide, only about 0.5% of the total potential has been used so far (Naskeo, 2009).

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[11] Million ton equivalent of petrol.

Table 2.5: Status of biogas resources worldwide

Resources	Total potential (Mtep/yr)	Feasible potential (Mtep/year)
Urban and industrial solid waste	750	60 – 100
Urban and industrial waste water	50	40 – 50
Agricultural by-products	1000	40 – 150
Total	1800	140 – 300

Source: Naskeo (2009)

Biogas has become a popular source of energy in both developed and developing countries. It is widely used in OECD countries, Asia and Africa (Wilkinson, 2011). Biogas in the developed countries is mostly produced from large-scale, joint co-digestion plants, and is utilised as vehicle fuel, a substitute for natural gas or to produce electricity and heat (Plöchl & Heiermann, 2006). Most of the developing countries in Asia and Africa have focused on promotion of small-scale domestic biogas plants, and biogas is mostly used for cooking and heating purposes (Holm-Nielsen et al., 2009). Another major difference in biogas technology between developed and developing countries is the use of feedstock materials. Farm manure, energy crops and municipal/industrial organic wastes are used as feedstock in the developed countries, whereas animal manure is the main input material in the developing countries (e.g., Abraham, Ramachandran, & Ramalingam, 2007; G. Austin & Blignaut, 2007; Chen et al., 2010; Dung et al., 2009; Holm-Nielsen et al., 2009; Karki et al., 2005; Raven & Gregersen, 2007). This section presents a brief review of biogas development in the selected countries in the OECD, Africa and Asia.

2.7.1 Biogas development in OECD

Biogas development in Europe

The European Union (EU) renewable energy policy has set a goal of supplying 20% of the European energy demands from renewable energy sources and reducing GHG emissions by 20% by the year 2020, with reduced energy consumption through improved energy efficiency (European Commission, 2010; Holm-Nielsen & Oleskowicz-Popiel, 2007). Biogas has been considered as a mature technology in the New Common Agricultural Policy that can contribute significantly to meeting the target of supplying of renewable energy and mitigation of GHG emissions (Pilzecker, 2008; Poeschl, Ward, & Owende, 2010). Holm-Nielsen and Oleskowicz-Popiel (2007) argue that there is a huge potential of biogas production from anaerobic digestion of animal manure and suitable organic wastes in Europe, and at least 25% of all the bioenergy in the future can come from biogas produced from wet organic materials, such as animal manure, crop silages and wet organic food/feed wastes. European countries have enough material available for biogas production. Biogas production from agricultural crops and residues and animal manure has a huge potential to contribute to national energy balances in European countries (Plöchl & Heiermann, 2006). In the EU-27[12] alone, more than 1500 million tons of animal manure are produced every year (Holm-Nielsen et al., 2009). The total energy potential of cattle and pig manure in the EU-27 is estimated at 827 petajoules (PJ), with a potential GHG emissions reduction of 18.5 Mtoe (Holm-Nielsen & Oleskowicz-Popiel, 2007). Nevertheless, total annual biogas production in Europe by mid-2007 was estimated at 1.85×10^9 m^3, and the total energy production was estimated at 50.02PJ (Birkmose, Foged, & Hinge, 2007).

The large amounts of animal manure produced by the agricultural sector and organic wastes from the overall society have created a constant pollution risk with a potential negative impact on the environment, such as emissions of GHGs and leaching of nutrients and organic matter to the natural environment (Holm-Nielsen et al., 2009; Plöchl & Heiermann, 2006). Biogas technology is considered to have an important role in meeting the overall pollution prevention objectives set by the Kyoto agreement through sustainable recycling of animal manure and organic wastes (Hjorth et al., 2009; Holm-Nielsen et al., 2009; Wilkinson, 2011).

Although many types of biogas plants can be found in Europe, depending on types of digested substrate, technology applied and their size. The common biogas plants that digest manure and agricultural residues or green energy crops are categorised as agricultural biogas plants, which can be categorised into the farm-scale biogas plants and the large-scale centralized joint co-digestion plants (Holm-Nielsen et al., 2009). The farm-scale biogas plants co-digest animal manure, agricultural residues and bioenergy crops from one single farm, or sometimes two or three smaller neighbouring farms. Such plants are usually established at large dairy or pig farms (Holm-Nielsen et al., 2009; Wilkinson, 2011). The large-scale biogas plants co-digest animal manure collected from several farms, mixed with suitable organic residues from industries and townships, the digester capacity of which ranges from a few hundred to several thousand cubic metres (Holm-Nielsen et al., 2009; Wilkinson, 2011). However, the applied technology for both types of biogas plants is similar. European digesters, which are of sizes between 500 to 3000 m^3, are mainly made of concrete with steel skeleton

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[12] EU-27 is the unity of 27 countries in Europe namely: Austria, Belgium, Bulgaria, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden and UK.

with a cylindrical form standing upright (Plöchl & Heiermann, 2006). The digester tanks are equipped with insulation and a heating system in order to control temperature conditions inside the digester, and a system to agitate or stir the digesting slurry. The biogas produced is collected in an internal gas tank above the slurry (Plöchl & Heiermann, 2006).

Although large biogas potential is identified in many of the European member states, Denmark and Germany are the EU countries where the agricultural biogas plants are developed mostly (Holm-Nielsen et al., 2009), and hence biogas development in these countries is reviewed briefly here.

Biogas development in Denmark

Biogas production is still relatively small in Denmark in terms of its contribution to the total energy consumption, producing less than 1% of electricity consumption in the country (Raven & Geels, 2010; Raven & Gregersen, 2007). Development of biogas in Denmark was investigated as one of the alternative energy sources after the 1973 energy crisis. Although the initial experiences of biogas plants were disappointing as it suffered major technical problems and negative economic returns due to low biogas yields, lessons from previous experiences and several research and development activities led to successful biogas production (Raven & Gregersen, 2007; Sannaa, 2004). One important lesson from the failed projects was that bigger plants could reduce production costs and increase biogas yields, and hence the concept of large-scale centralised biogas plants first emerged in Denmark (Raven & Gregersen, 2007). Similarly, another outcome was that co-digestion of manure with organic waste substantially increased biogas yield improving the economic feasibility of biogas plants for processing waste which otherwise is dumped at landfill sites (Raven & Geels, 2010).

The potential for biogas production in Denmark is estimated at 39 PJ, where 80% is represented by animal manure. However, only about 10% of the total potential is exploited so far (AEBIOM, 2009; Frandsen, 2011). Denmark has 21 large centralised biogas plants with capacity ranging from 50-500 tonnes feedstock (80% manure and 20% organic wastes from food industries and municipalities) per day. Similarly, 60 small agricultural biogas plants owned by individual farmers are in operation (Frandsen, 2011). Other types of biogas plants in Denmark include 61 waste water treatment plants, 25 landfill plants and five plants built in connection with big industrial companies (Frandsen, 2011). The biogas produced in anaerobic digestion is converted in a combined heat and power production facility. Total feed-in of electricity from biogas cogeneration is about 150,000 MWh/year (Frandsen, 2011).

Support from the government, both policy and financial, was the key factor for the development of biogas technology in Denmark. A bottom-up approach, farmers' ability to exploit the opportunities through a good innovation process, research and development activities, and cooperation among farmers for communication, experiences and learning sharing were other factors (Raven & Geels, 2010; Raven & Gregersen, 2007). Energy and agriculture regimes (the government's rejection to nuclear power and stricter agro-environmental rules for reducing nitrates leaching), and the government policy of investment grants up to 40% of the costs boosted the development of biogas technology in Denmark (Frandsen, 2011; Raven & Geels, 2010).

Biogas development in Germany

Germany is one of the leading countries in larger biogas production, where about 3,900 farm-scale biogas plants were installed by 2008 (AEE, 2008; Poeschl et al., 2010). Total output of the installed plants was approximately about 10TWh[13] electricity in 2008, which corresponds to 1.6% of total power consumption (AEE, 2008; Poeschl et al., 2010). The electric power supplied to the national grid from biogas plants was 350 Kilowatt electric (kWel)[14] in 2008 (Poeschl et al., 2010). Biogas technology generated about 10,000 jobs in 2007 and the technical potential of biogas production is estimated to be about 60 TWh per annum (GBA, 2008).

Prospects for the expansion of biogas in Germany are influenced by European policy strategies, which includes strategies for increasing security of energy supplies locally through increased utilization of renewable resources to 20% of energy consumption reducing energy consumption through improved energy efficiency, and reducing GHG emissions by 20% by the year 2020 (European Commission, 2010; Pilzecker, 2008; Poeschl et al., 2010). Germany has an ambitious target of 25-30% electricity and 14% heat generation from renewable energy resources (Poeschl et al., 2010). Biogas technology is recognised as a mature technology that can deliver a significant part of the national target since Germany already has a system for injection of bio-methane (upgraded biogas) into the natural gas grid (Poeschl et al., 2010).

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[13] 1 TWh = 1,000 GWh = 1,000,000 MWh.

[14] 1 kWel = 1,000 watts of electric capacity.

Subsidies to renewable energy generation; research, technology development and investment grants to look for innovations in biogas systems; tax reliefs for biogas energy; and subsidies for production of energy crops to be used in biogas plants are the major incentives for the promotion and expansion of biogas (Lantz, Svensson, Bjornsson, & Bjornsson, 2007; Poeschl et al., 2010; Wilkinson, 2011). However, environmental protection and economic considerations for the optimum location of biogas and the planning permission and safety permissions incur extra cost to expand biogas in Germany (Poeschl et al., 2010). Regulations about feedstock pre-treatment, high cost of gas upgrade technology and competition with alternative energy conversion are some of the barriers for expanding biogas programme (Lantz et al., 2007; Poeschl et al., 2010; Wilkinson, 2011).

Biogas development in New Zealand

New Zealand has abundant renewable natural resources, and 73% of electricity in 2009 was generated from renewable sources, which is one of the highest in the OECD (MED, 2010). The share of biogas on electricity generation in 2009 was just 0.5%, but the country has a target of 30 PJ of biogas energy per year by 2040 based on anaerobic digestion (BANZ, 2011; MED, 2010). This makes New Zealand worth discussing for its biogas production policy and potentiality.

Biogas technology is still relatively new in New Zealand (MWH, 2008). The main driving force for promoting biogas digesters in New Zealand is for waste disposal rather than energy production (Cox & Souness, 2004). Biogas produced so far comes from anaerobic digestion in landfills and wastewater treatment plants, and is mostly used to generate electricity. However, biogas produced from waste has the potential to meet a significant proportion of the community's natural gas demand, since the residential consumption of natural gas in 2009 was 5.5 PJ, while biogas production in the same year was 4.0 PJ. (BANZ, 2011; MED, 2010). Maunsell Limited (2007) argues that the existing natural gas reserve of New Zealand could be depleted within 10 years if no other resources are found. In this context of declining natural gas reserves, increasing world oil prices and consumers' concerns about sustainable gas supply, production of reliable and more environmentally-friendly fuels like biogas can play a significant role in the future energy supply of New Zealand (Maunsell Limited, 2007).

New Zealand's current gas demand of approximately 100 PJ/year for power, industrial, commercial and residential use could easily be produced from biogas (BANZ, 2011; Maunsell Limited, 2007). If biogas substituted 100 PJ of natural gas, it could reduce the

CO_2 emissions by 5.5 million tCO_2e every year, generating a value of NZ$110 million/year at a value of NZ$20/$tCO_2e$ (Maunsell Limited, 2007). The national strategy of New Zealand related to biogas production is stated to produce 30PJ biogas energy per year by 2040 from anaerobic digestion (BANZ, 2011). Anaerobic digestion is used in many wastewater treatment plants in New Zealand to manage sludge. If modified to use agro-industrial or green waste, such facilities can produce additional biogas (Burt, 2010; Itskovich, 2010). However, lack of skilled labour and experience, risk premiums for investment capital, materials and equipment cost are the constraining factors which need to be addressed to expand the biogas technology in New Zealand (BANZ, 2011).

2.7.2 Biogas development in African countries

Many rural African communities are characterised by low population densities and are remotely situated, making centralised energy generation and transmission costly (Amigun & von Blottnitz, 2010). Traditional biomass is still the major energy resource for most of the rural population, which accounts for about 67% of the total energy consumption in Africa (Jingura & Matengaifa, 2009). Implementation of decentralised energy generation technology, such as biogas, could be more cost-effective in the African countries to serve dual purposes of energy generation and environmental pollution reduction (Amigun & von Blottnitz, 2010; Jingura & Matengaifa, 2009). Since biogas technology is a simple and readily usable technology that does not require a complicated capacity to construct and manage, it is also feasible in poor African countries (Gunnerson & Stuckey, 1986; Taleghani & Kia, 2005). Moreover, considering the number of households with access to water and the number of domestic cattle per household, the technical potential for domestic biogas in Africa is estimated at 18.5 million biogas plants (ter Heegde & Sonder, 2007).

The first biogas plants were installed in South Africa and Kenya in the 1950s, while those introduced in other African countries were later (Amigun & von Blottnitz, 2010). The efforts of various international organizations and foreign aid agencies have stimulated promotion of biogas in Africa (Parawira, 2009a). The ‘Biogas for Better Life: An African Initiative’ vision aims to promote biogas digesters for affordable sustainable energy in 2 million households by 2020 for improved household livelihood of African people (ter Heegde & Sonder, 2007), which might be a vital component of the alternative rural energy programme in Africa (Amigun & von Blottnitz, 2010).

Biogas is mostly used for domestic cooking and heating purposes in Africa. Three different sizes and types of biogas plants are found in Africa: the household/family type, institutional/community type, and large-scale systems in selected industries (Amigun & von Blottnitz, 2010; Jingura & Matengaifa, 2009). Various types of feedstock such as waste from slaughterhouses, waste from urban landfill sites, industrial waste (such as bagasse from sugar factories), animal dung and human excreta are used to produce biogas. Biogas plants have also been installed in commercial farms (chicken and dairy farms in Burundi), public latrine blocks (Kibera, Kenya), prisons (Rwanda), and health clinics and mission hospitals (Tanzania) (Winrock International, 2007). However, wastage or under-utilisation of energy was reported in a few African countries (e.g., Zimbabwe) where biogas produced at sewage treatment plants is not used for commercial purposes (Jingura & Matengaifa, 2009).

Despite technical feasibility, viability and acceptability, biogas technology has still not been widely adopted by African households (Amigun & von Blottnitz, 2010; Bensah & Brew-Hammond, 2010; Jingura & Matengaifa, 2009). Several site-specific issues such as availability of water and organic materials have limited the scope of biogas in sub-Saharan Africa (Amigun & von Blottnitz, 2010; Parawira, 2009a). High initial investment costs compounded with lack of credit schemes, poor design and construction of digesters, poor dissemination strategies, and failure by the government to support biogas technology through a focused energy policy are the major factors for poor development of biogas technology in Africa (Amigun & von Blottnitz, 2010; Bensah & Brew-Hammond, 2010; Jingura & Matengaifa, 2009).

In this context, Amigun and von Blottnitz (2010) stressed that biogas promotion in Africa could benefit from the success story of biogas technology in Nepal. They appreciated Nepal’s biogas programme as:

> “The Nepal biogas experience is a good example of how a national program can, through linked subsidy and quality control mechanisms stimulate demands for biogas digesters, encourage entry of commercial companies to produce them, and provide incentives for high quality installations. …. For a national program like Nepal’s Biogas Support Program (BSP) to succeed, a major prerequisite is that it be independent and free from political interference. …. A simple, transparent, and sustained subsidy policy has been instrumental in increasing the adoption of biogas plants. …. A progressive subsidy structure, which provides larger subsidies to smaller plants, has made smaller household plants more affordable to poorer households. …. In order to reduce initial investment costs, households are encouraged to contribute their own labour and provide local construction materials (Amigun & von Blottnitz, 2010, p. 65).

2.7.3 Biogas development in Asian countries

The use of household bio-digesters has gained widespread acceptance in the Asian countries. Many countries have shown a strong interest in the application of anaerobic digestion and plans are being made accordingly to promote biogas programmes (APCAEM, 2007). Successful biogas programmes have already been established in China, India, Vietnam and Nepal (SNV, 2011a). Development of biogas technology in Nepal is discussed in Section 3.7. This section reviews biogas development in China, India and Vietnam.

Biogas development in China

China has the highest number of household biogas plants in the world; more than 42 million biogas plants were installed by 2012 (X. Li, 2013). The number was over 26 million in 2007 leading to the production of over 10.5 billion m^3 of biogas, which was equivalent to more than 100 million tons of standard coal (Chen et al., 2010). China has a long history of using biogas. Although the first test to ferment biogas took place in the 1880s, the development of household biogas was accelerated in the 1970s (Chen et al., 2010). After 1975, biogas was prioritised as 'biogas for every household' which led to the construction of 1.6 million digesters per year in China, mainly the fixed-dome digester constructed of clay, brick and concrete, which is well-known in the world for Chinese model of biogas digester (Zeng, Ma, & Ma, 2007).

China has a huge biogas potential; about 140 million rural households are suitable for biogas construction (Chen et al., 2010). Dependency on low energy-efficient traditional biomass sources and standard coal for energy needs and sufficient availability of feedstocks for anaerobic digestion has created opportunities for biogas development in China. The Chinese government formulated the National Plan for Rural Biogas Construction in 2003 to accelerate the large-scale promotion of biogas plants in rural households, with the goal of increasing biogas use to a total of 80 million households and a total annual production of 38.5 billion m^3 by 2020, benefitting more than 300 million people (Liu et al., 2008; NDRC, 2007). The National Plan supported the implementation of rural biogas projects by providing financial subsidies for the construction of domestic biogas plants. Moreover, the renewable energy law in China, 2005, emphasised on biogas production as an environmentally-friendly and efficient energy source (Abraham et al., 2007; Chen et al., 2010).

In recent years, an integrated agricultural bio-energy system, such as a 4-in-1 biogas system (combining a biogas digester, latrine, pigsty or poultry house and solar energy greenhouse) or a 3-in-1 biogas system (fruit plantation, biogas digester and pig farming) has been promoted in China as an ecological model for rural energy based on the principle of ecology, economics and system engineering (Cheng, Li, Shih, Du, &

Xing, 2010). Although such integrated systems promote environmental benefits as well as providing economic incentives for farmers to adopt them, the higher establishment costs of the system are a great concern for rural households (Cheng et al., 2010).

Biogas development in China is also hampered by poor digester performance. Only about 60% of the total biogas digesters constructed in China are operating normally without any disruptions. Lack of regular maintenance, insufficient gas production and poor efficiency of the plants are major problems (Chen et al., 2010). In this context, the findings of this current study could also help the biogas sector in China to improve digester performance.

Biogas development in India

India is another successful biogas promoting country in Asia with about 4.4 million plants constructed by mid-2011 (SNV, 2011a). The first floating dome model (popularly known as an Indian model) biogas plant was constructed in India in 1962. However, the promotion of biogas technology was intensive when the Government of India launched a national biogas programme countrywide in 1979 (Abraham et al., 2007). Three designs of anaerobic digesters are prevalent for biogas production from cattle manure in India: the Khadi and Village Industries Commission (KVIC) floating drum design with a cylinder digester; fixed-dome model with a brick reinforced, moulded dome (Janata model); and fixed-dome model with a hemisphere digester (Deenbandhu model) (Dhussa, 2010; K. J. Singh & Sooch, 2004) (Section 2.2.2).

About 80% of rural energy consumption in India comes from non-sustainable traditional biomass sources, which amounts about 320 million tonnes of fuelwood, animal dung and agro-wastes, whereas more than half of rural households in India still do not have access to electricity and about 80 million households still use kerosene for lighting (Dhussa, 2010; J. Singh & Gu, 2010). This situation creates opportunities for biogas development in India. The country, being one of the largest domestic cattle producer countries in the world, (Dhussa, 2010; Nagamani & Ramasamy, 2010; K. J. Singh & Sooch, 2004) has a total potential of 12 million biogas plants from anaerobic digestion of animal waste (SNV, 2011a). However, India has potentiality to generate biogas from the anaerobic digestion of municipal solid waste. An estimated 30 million tonnes of solid waste and 4,400 million m^3 of liquid waste are generated every year in urban areas of the country (Abraham et al., 2007; EAI, 2011), but more has to be done to generate biogas from municipal waste (Abraham et al., 2007).

Supportive policy is a major factor for the successful promotion of biogas technology in India. The National Biogas and Manure Management Programme provides subsidies for the installation of biogas plant (20-50% of the installation costs) (Nagamani & Ramasamy, 2010). Capacity building support through training of officials and constructors, training of plant users and information dissemination and sponsorship for biogas research and development are other government support activities to promote biogas technology in India (APCAEM, 2007; Dhussa, 2010).

Despite the successful implementation of the biogas programme, there are a few barriers to promote the technology in the rural areas. Water scarcity or difficulty in obtaining water from a distant source has imposed constraints on the viability of biogas technology in rural India (Nagamani & Ramasamy, 2010; J. Singh & Gu, 2010). Technical feasibility of biogas plants all year round due to low winter temperatures is another barrier (Nagamani & Ramasamy, 2010). Moreover, the biogas programme in India is still not able to cater the needs of the poorest and marginalised people, who do not have the financial and technical resources to construct and maintain a viable plant. Due to their poverty, they cannot keep the three to four cattle that are needed to provide the necessary quantity of dung (Nagamani & Ramasamy, 2010; J. Singh & Gu, 2010).

Biogas development in Vietnam

Vietnam is another Asian country with successful biogas production. It won the Energy Global Award in 2006 and the prestigious Ashden Awards for Sustainable Energy in 2010 for its significant contribution to reducing climate change (SNV, 2011a). Given a livestock population of about 30 million, the biogas production potential in Vietnam is estimated at 2 billion m^3 (Chau, 2009; USAID, 2007)$^.$ Thus, an important part of the fuel and electricity needs of the country can be supplied in Vietnam if its abundant biomass resources are utilised more efficiently (Chau, 2009; Dung et al., 2009).

Implementation of domestic biogas production was started in Vietnam in the past 50 years, but large-scale dissemination of biogas technology began about 10 years ago with the aim of alleviating acute energy shortages for household users (Abraham et al., 2007). Bio-digesters of various origins and designs, e.g., Indian-type, Chinese-type and ferro-cement-type digesters were installed and evaluated (Chau, 2009; Dung et al., 2009). The major barriers for the adoption of the concrete digesters were the high cost of the digesters, difficulty in installing them and difficulty in obtaining spare parts for replacement (Abraham et al., 2007). However, the biogas plant installation rate increased after the establishment of the Vietnam Biogas Programme with the support from the Netherlands Government (SNV). By 2013, over 130,000 biogas digesters had been constructed in 44 of Vietnam's 64 provinces, directly benefitting more than 500,000 rural people (Nexus, 2014). The country plans to install a total of 180,000 plants by 2018 benefitting above 800,000 people with improved energy services (SNV, 2011a; Teune, 2007). By focusing on attaching latrines to the digesters and the use of biogas among pig farmers, the biogas programme in Vietnam is also helping to solve the country's waste problem (SNV, 2011a).

Despite its huge potential in Vietnam, the country lacks long-term strategies and policies for biogas development (Chau, 2009; Dung et al., 2009). There are similar technical barriers in the operation and maintenance of biogas plants causing poor performance of the plants as in other Asian countries. Most of the biogas plants constructed in Vietnam are of small-scale, since larger-scale biogas technology requires high installation costs (Chau, 2009; Teune, 2007). Biogas development in Nepal is discussed in the next chapter.

CHAPTER THREE

OVERVIEW OF NEPAL, ITS ENERGY STRUCTURE AND BIOGAS TECHNOLOGY DEVELOPMENT

3.1 Introduction

This chapter provides a contextual description of the energy structure in Nepal in order to understand the essential context of the research problem and its significance. First, it presents a general background to Nepal which covers geography, climate, administrative structure, demographic and socio-economic-cultural contexts, and development and gender issues. It then provides a brief description of the energy resource bases of Nepal which includes traditional biomass, hydro, renewable and fossil fuel resources. The status of energy consumption pattern in the country by fuel type and sector, and national plan and policy for renewable energy development is then described, followed by a brief description of the country's status of overall GHG emissions. Finally it discusses the biogas development status in Nepal.

3.2 General Background to Nepal

3.2.1 Geography

Nepal is a small landlocked country, bordered by China and India, with a total land area of 147,181 sq. km. It is located between 26^0 22' and 30^0 27' north latitude and 80^0 04' and 88^0 12' east longitude (MoPE, 2004). The country has roughly a rectangular shape expanding from east to west to about 885 km and stretching from the Himalayas in the north, through rugged terrain in the centre, to the Terai Plains in the south with width ranging from 130-260km (MoPE, 2004). The altitude in Nepal ranges from 70m above mean sea level in the south to the 8,848m peak of Mount Everest in the north (WECS, 2010).

Tremendous variation in altitude within a relatively short distance has endowed Nepal with three distinct ecological belts: the Mountain, Hill and the Terai, lying from east to west in almost a parallel way (WECS, 2010; Winrock Nepal, 2004) (Figure 3.1). The mountain region is situated in the north above 4,800m and covers 35% of the total land (CBS, 2012a; WECS, 2010). Most of the areas in this region are covered with snow during winter. The Hill region, in the middle, extends between 700m to 4,800m occupying 42% of the total land areas, while the Terai, below 700m elevation, occupies 23% of the country's land area (CBS, 2012a; WECS, 2010).

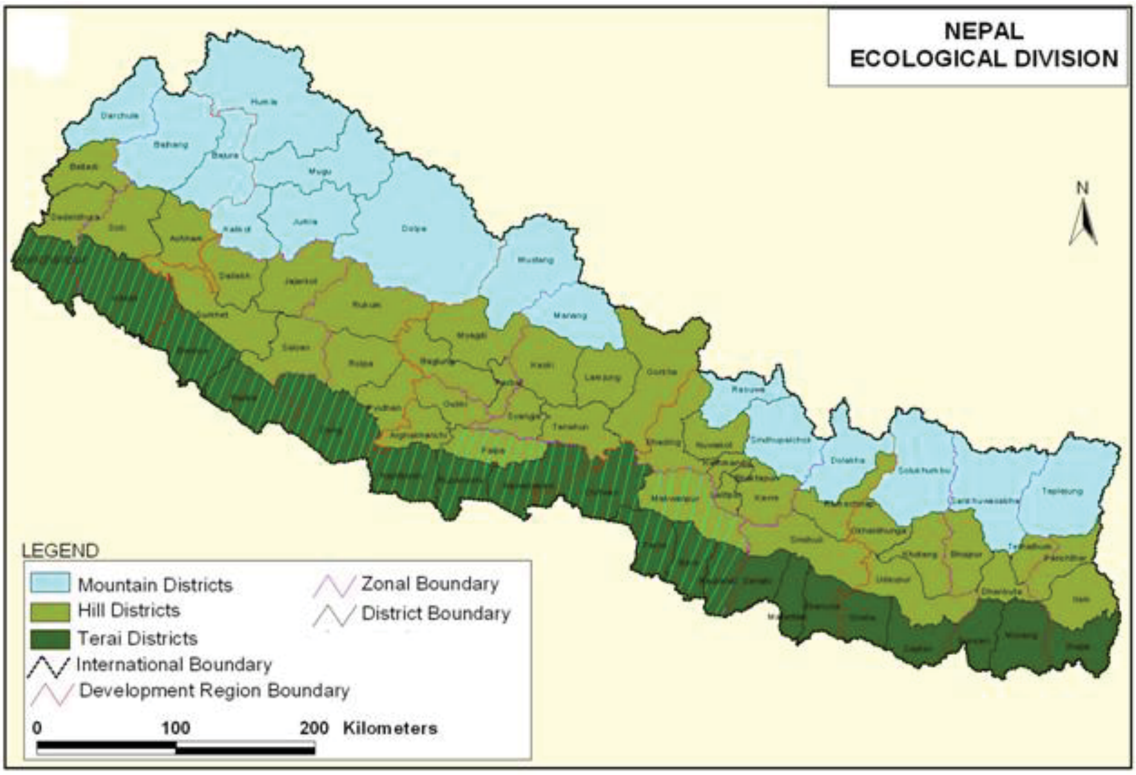

Figure 3.1: Ecological and administrative division of Nepal

Source: UNEP, 2001

3.2.2 Climate

At a global level, Nepal lies within the subtropical monsoon climatic region (Figure 3.2) (WECS, 2010; Werner et al., 1989). But the climate is greatly affected by its unique topographic and physiographical features and the country experiences enormous climatic and ecological diversity within a short north-south distance ranging from sub-tropical in the southern Terai to Arctic in the northern high Himalayas (WECS, 2010). These differences in climatic conditions are primarily related to the range of altitude.

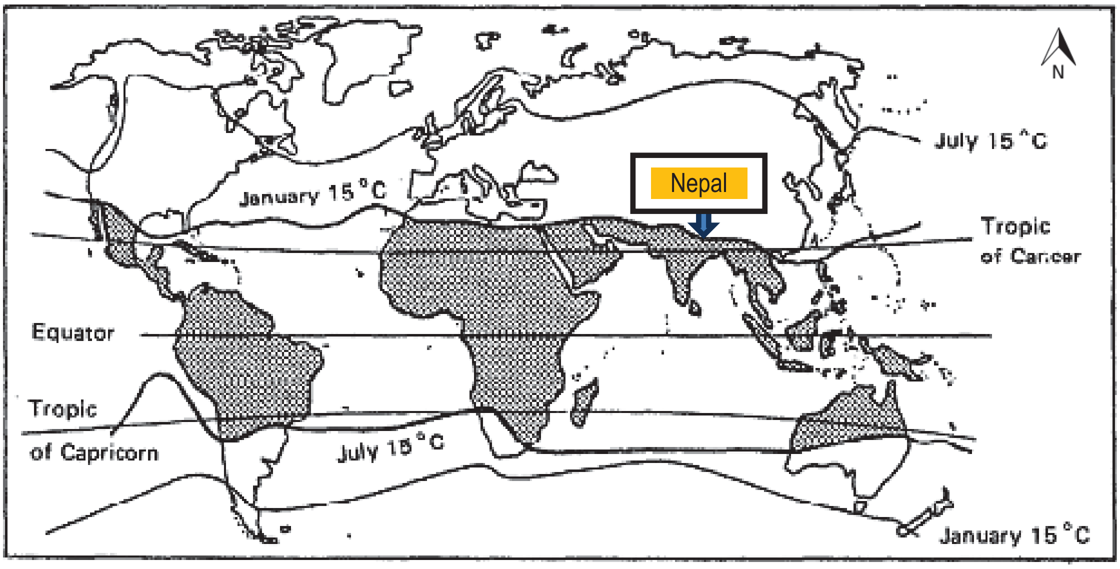

Figure 3.2 : The geographical position of Nepal in global temperature zone

Source: Werner, et al. (1989)

The country is divided into five distinct climatic zones (Practical Action, 2009b). High mountains above 4,200m elevation are dominated by a tundra type of climate with perpetual frost and cold desert conditions and an alpine climate with cool summers and frosty winters, whereas a sub-alpine climate is found in the lower mountains between 3,000 to 42,00m altitudes with mean annual temperature below 8°C. A temperate monsoon climate is found in the hill between 2,000-3,000m altitude with mild, wet summers and cool, dry winters and mean annual temperature of 8-15°C (Practical Action, 2009b). The lower Hill region (700-2,000m) is characterised by a sub-tropical climate with a mean annual temperature of 15-21°C. A hot monsoon with hot, wet summers and mild, dry winters is found in the Terai region and the mean annual temperature ranges between 20-25°C (Practical Action, 2009b; WECS, 2010). The seasonal variation of temperature can broadly be categorised into summer and winter temperature. The summer season (April to September) is hot and rainy and temperature goes above 30°C in the Terai, but reduces gradually with the altitude in the mountain region (Practical Action, 2009b). The winter season is characterised by very cold conditions in the mountain and hill regions but mild in the Terai region (WECS, 2010).

Like temperature, precipitation also varies greatly with altitude and on a seasonal basis. The country has an average annual rainfall of 1,856mm that varies from 250-4,500mm, most of which (nearly 80%) occurs during the monsoon season (June to September) (Practical Action, 2009b; WECS, 2010). The high mountain region is generally drier than the lowlands. The southern slopes of the Annapurna range in the western development region receives the highest rainfall, while north of the Annapurna range near the Tibetan plateau receives the lowest, less than 150mm rainfall (Practical Action, 2009b). The average annual rainfall in the Terai and Hill region ranges between 1,000-2,500 mm and 1,700-3,000 mm, respectively (WECS, 2010).

3.2.3 Administrative structure

Nepal is divided into many administrative regions and sub-regions for development planning and administration purposes. It is divided into five development regions: Eastern, Central, Western, Mid-Western and Far Western Development Regions (MoFALD, 2014). The development regions are sub-divided into 14 zones and further divided into 75 districts (Figure 2.1). There are 39 districts in the Hill region, while 20 districts are situated in the Terai region and 16 in the Mountain region. District Development Committee (DDC) is the district level local development institution of the government system. The districts are further divided into municipalities in urban areas and Village Development Committees (VDC) in rural areas. There are 130 municipalities in Nepal of which 72 were newly established in May 2014 and 41 were established in July 2011 (MoFALD, 2014). The VDC remains under the DDC for administrative processes. Each district comprises about 60-70 VDCs depending on the population of the district, and each VDC includes about 500 households (WECS, 2010). The VDCs are the lowest administrative units of the government system and there are 3,625 VDCs in the country (MoFALD, 2014).

3.2.4 Urban and rural division

Apart from geographical, climatic and administrative division, Nepal is divided into urban and rural areas. About 83% of the total population reside in rural areas with larger household size (5.02) than the national average (4.88) or urban average (4.32) (CBS, 2012a). Particular differences between urban and rural areas can be seen in the variation in development indicators such as access to information, the state of health and education facilities, better economic and employment opportunities, transportation facilities and presence of other public services (Winrock Nepal, 2004). The urban population growth rate is almost three times higher than the rural population growth rate due to rural to urban migration (UN, 2013).

3.2.5 Demography and socio-economic-cultural context

Population

According to the population census of 2011[15], the population of Nepal reached 26.5 million, with an average family size of 4.9, population growth rate of 1.35% per annum and average population density of 180 per sq. km (CBS, 2012a). The share of male and female population was 12.85 million (48.5%) and 13.65 million (51.5%), respectively. Nepal's population structure is comprised of 36% children (under 15 years of age) and 7% elderly people (above 60 years of age) (CBS, 2012a), with life expectancy at birth of 67.2 years in 2011. The population density, however, is much higher (almost 10 times) in urban areas than in rural areas mainly due to better infrastructure facilities, land productivity, transportation facilities, government and public services, and education/employment opportunities (WECS, 2010). The population distribution, in terms of ecological zones, is very unequal. Approximately 43% of the population live in the Hill region, whereas the Terai supports 50.3% of the population and the rest live in the mountain region; the average population density in the Mountain, Hill and Terai regions being 34, 186 and 392 per sq. km, respectively (CBS, 2012a).

Language and religion

Nepal is a multi-linguistic country, where 123 languages are spoken as mother language. About 45% of the total population speaks only Nepali language, followed by Maithili (11.7%), Bhojpuri (6%), Tharu 5.8%), Tamang (5.1%), Newar (3.2%), Magar (3.0%), Doteli (3.0%) and Urdu (2.6%) (CBS, 2012a). Nepal, once officially a Hindu state is a secular state post-2006. Still the majority of the population is Hindu (81.3%), followed by Buddhist (9%), Muslim (4.4%), Kirant (3.1%) and Christian (1.4%) (CBS, 2012a).

Caste system and ethnicity

Nepal is a multi-ethnic and multi-cultural country. A complex interplay of different social, economic and political processes has resulted in the formation of caste and ethnic identities. These are deep-rooted in the historical caste system that was initiated prior to 1950 with the promulgation of the first legal code of Nepal, the *muliki ain*in 1854x(Bista, 1991; Hofer & Sharma, 2004). The code divided the society into four broad caste groups, namely *Brahmin, Chhetri, Baishya* and *Sudra* and 36 *Vernas* (ethnicities). Division of these groups was mainly based on their occupation and

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[15] In Nepal, a population census is taken every 10 years. The latest national population census was taken in 2011 (CBS, 2012a).

services to the country. Brahmins were priests and religious teachers; Chhetries were rulers and fighters in security forces; *Baishyas* were traders/businessmen; and *Sudras* were the lowest status groups, treated as untouchables, whose major occupation was blacksmithing, tailoring, shoe-making (Bista, 1991). Such a discriminatory country code was later replaced with a new civil code in 1990, where discrimination based on caste, ethnicity or gender was totally restricted (HMGN, 1991). However, the discrimination, which is deeply rooted in the caste system still exists in society (J. P. Pandey, Dhakal, Karki, Poudel, & Pradhan, 2013).

The 2011 population census identified 126 castes and ethnic groups in Nepal (CBS, 2012a). The caste groups are broadly divided into three categories: high castes, Janajatis or ethnic groups, and Dalits. The high castes (e.g, *Brahmin, Chhetri*), comprising 45.7% of total population, have historically been superior in economic and socio-religious terms. Janajatis (e.g., *Magar, Tharu, Tamang*) that constitute 42.5% of the total population are indigenous people who have been excluded from the mainstream and many of them live in poverty (CBS, 2012a). The lower castes or *Dalits (e.g., Kami, Damai, Sarki)* who represent only 11.8% of the population are seen as inferior and are discriminated against within socio-economic-religious activities and they are often prohibited from entering public places or mixing with higher castes at social gatherings. Despite the legislation on Caste-Based Discrimination and Untouchability in 2011, *Dalits* are still treated as untouchables (J. P. Pandey et al., 2013).

The caste system, which denotes both caste and ethnic group, is still the major determinant of social relationships in Nepal. It continues to guide social, economic, cultural and political activities and interactions between different castes (Bhattachan, Sunar, & Bhattachan, 2007; Chhetri, 1999). *Dalits* and minority ethnic groups, in general, still have poor access to major economic opportunities, social services and physical structures (M. Acharya, Subba, Regmi, & Aryal, 2004; Bhattachan et al., 2007). About 48% of Dalits live in poverty and 25% of the Dalits are landless (CBS, 2011a). The caste and ethnic group disparity has also impacted on social and health outcomes. From the National Demographic and Health Survey, 2011 data, the inequalities can be seen in the under-five child mortality rate high among *Dalit*s (98 per 1000 live births) when compared to the national average of 61 per 1,000 live births in 2006 (MoHP, 2007, 2012). The average life expectancy for *Dalit males and females is 51 and 58 years respectively, which is* much lower than the national average of 66.2 years (CBS, 2011a).

Literacy

According to the 2011 population census, the literacy rate[16] in Nepal increased to 65.9% in 2011 from 54.1% in 2001 (CBS, 2012a). However, there is a significant variation in the rate within caste groups or ethnicity; higher caste groups have the highest literacy rate, whilst lower caste groups have the lowest rate (CBS, 2012a). The school attendance of Dalit children was 1.6 times less than the average national rate (CBS, 2011a).

Similarly, gender and rural/urban areas are the other variables that affect literacy. The male population is more literate (75.1%) than the female population (57.4%), which reflects the differential, access to education between men and women in Nepal. Similarly, people living in urban areas have a higher literacy rate (86.3%) than in rural areas (47.8%) (CBS, 2012a). A lower level of literacy is also considered as one of the social barriers to adoption of renewable energy technologies (RETs) (AEPC, 2000a, 2008a).

Economy

Agriculture is the mainstay of Nepal’s economy, and provides livelihoods for over 80% of the population (WECS, 2010). In the FY 2012/13, Nepal's real GDP was US$6.7 billion, of which the contribution of the agriculture sector was US$2.4 billion. The per capita GDP of the country was US$707 and per capita gross national income was US$276 (MOF, 2014). Nepal is listed as a least developed country (REN21, 2014), and is characterised as one of the poorest countries in the world (UNDP, 2014). Poverty is widespread in Nepal, and a large section of the poor are living on fragile and vulnerable ecosystems (CBS, 2011b; MoPE, 2004). According to the UNDP Human Development Index 2014, over 40% of Nepal’s population still lives below the international poverty line of $1.25 per day (UNDP, 2014). Poverty in Nepal is still a rural phenomenon. The ‘Nepal Living Standard Survey 2010/11’ identified that approximately 25% of the total national population is below the national poverty line[17] (CBS, 2011b), where approximately 36% of the total rural population are found below the poverty line (CBS, 2012a). Poverty is also associated with a significant disparity across castes and ethnicity. The incidence of poverty is highest among the lower castes living in the Hill, where nearly 48% of them live below the poverty line. About 43% of the total population of Janajatis in the Hill was identified as living below the poverty line (CBS, 2012a).

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[16] The population census 2011 defined a person of 5 years or above as being literate if s/he could read and write.

[17] The national poverty line has been derived by using the cost of basic need method, which is based on the nutrition requirement of 2,124 calories per capita per day (CBS, 2011b).

3.2.6 Development and gender issues

The urban-biased development in Nepal has resulted in distinctly high poverty in rural livelihoods (Francis, 2002). There is large disparity in government services and facilities between urban and rural areas. From a regional perspective, the human development index[18] (HDI) was lower in the Mountain region (0.440) than in the Hill (0.520) and in the Terai (0.468) (NPC, 2014a).

The gender development index (GDI)[19] is also lower in rural areas due to low life expectancy and low adult female literacy (NPC, 2014a). Women's participation in politics, professional and administrative jobs is only about one-third of men, and despite about 40% of women being economically active, many of them are involved in unpaid family work (ADB, 2010). Their involvement in social/public activities/places is still highly discouraged which causes adverse effects on their access to information, services and development interventions (CDS, 2013). As mentioned earlier, women's literacy rate (57.4%) is far less than men (75.1%), and the literacy of rural women is even less (CBS, 2012a).

Besides linguistic, caste and ethnic diversity, the majority of communities in Nepal are patriarchal (ADB, 2010). This patriarchal system is historically reflected in the practice of inheritance property rights, patriarchal descent and family relations. Such patriarchal dominated socio-cultural norms and values discourage women's ownership over

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[18] HDI is a tool developed by the UN to assess the development of a country based on the people, their capability and economic growth. HDI is a summary measure of three basic dimensions of human development achievement in a country: a) Long and healthy life; b) Access to knowledge; and c) Have a decent standard of living. Healthy life is assessed by life expectancy at birth. Level of knowledge is measured by means of years of schooling for adults aged 25 or more and expected years of schooling for children of school entering age, while standard of living depends on gross national income per capita (UNDP, 2015b). Between 1980-2014, Nepal's HDI value increased from 0.279-0.548 with an annual increase of about 2% (UNDP, 2015b). Like all averages, the HDI mass inequality in the distribution of human development across the population is at the country level.

[19] GDI is a measure to the HDI based on the sex-disaggregated human development index. It is defined as a ratio of the female to the male HDI. GDI measures gender inequalities achievement in three basic dimensions of human development: a) health, measured by female and male life expectancy at birth; b) education, measured by female and male expected years of schooling for children and mean years of adults aged 25 years and older; and c) command over economic resources measured by female and male estimated GNI per capita (UNDP, 2015b). The GDI shows the figure of how much women are lagging behind their male counterparts and how much they need to catch up within each dimension of human development. It manifests a good figure about real gender gap in human development achievements that is useful to design policy tools to close the gap. In 2014, the female HDI value for Nepal was 0.521 in contrast with 0.574 for males resulting in a GDI value of 0.908 (UNDP, 2015b).

property rights and put women in an inferior position in the society (ADB, 2010). As a result of gender inequalities in land and other economic resource ownership, only less than 20% of households showed female ownership of fixed assets, which stands for 18% in rural areas (CBS, 2012a).

Gender disparities in the energy sector are also apparent. Women manage fuel for the home and carry out most energy related tasks such as fuelwood collection and cooking. Carrying heavy loads of fuelwood exposes women to injuries from falls including fractures, uterine prolapse and miscarriages (Wan, Colfer, & Powell, 2011; Winrock Nepal, 2004). Female children drop out of schools to do household chores, mainly to collect fuelwood or to look after small children while their mothers collect fuelwood (Winrock Nepal, 2004). In addition, women spend more time cooking in a fuelwood burning kitchen and hence more women suffer from respiratory diseases such as chronic bronchitis than men (M. R. Pandey, 2012; Winrock Nepal, 2004). Despite their higher involvement, women have little voice in decision-making on energy choices and use (Mahat, 2013; Winrock Nepal, 2004). There is a vicious circle of gender and energy poverty[20] (Cecelksi, 2004; Clancy et al., 2002) (Figure 3.3). Although several institutions are focusing on development and expansion of energy technologies that reduce women's drudgery and enhance employment opportunities, they lack a pro-poor energy strategy with focus and linkages between energy and poverty, and policy on gender mainstreaming in the energy sector (ADB, 2010).

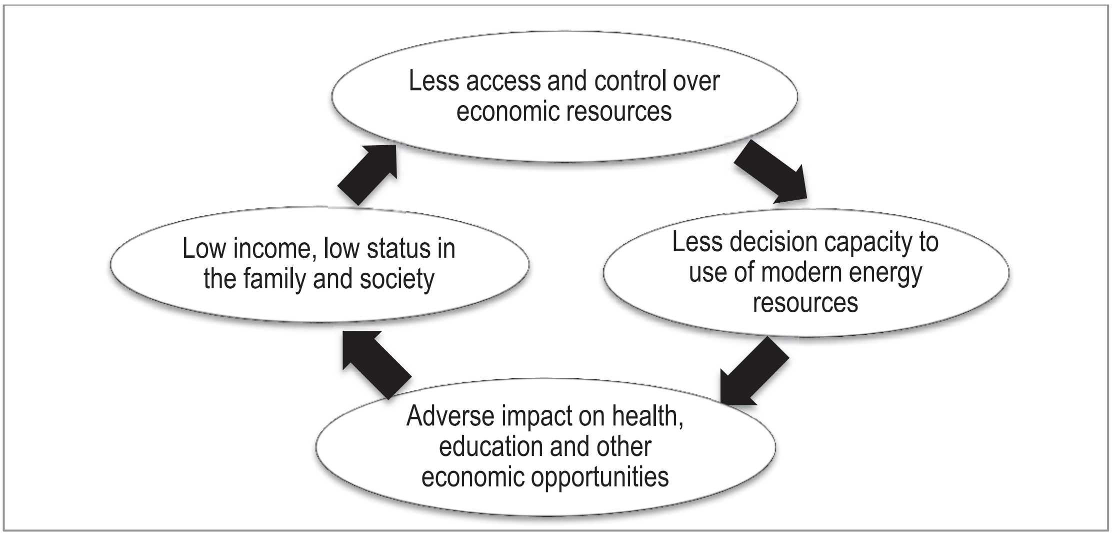

Figure 3.3: Vicious circle of gender and energy poverty

Adapted from Cecelski (2004)

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[20] Energy poverty refers to the lack of affordable, reliable and environmentally friendly energy services for the basic needs of cooking, warmth and lighting, and support of economic and human development activities (Practical Action, 2009a; A. Reddy, Annecke, & Blok, 2010).

3.3 Energy Resource Base of Nepal

Energy is derived from different fuel resources in Nepal. The availability of energy sources is sufficient to fulfil the residential energy demand of the country (WECS, 2010). However, the country is still facing an energy crisis due to the lack of capital, lack of vision/strategy and political commitment, political instability, lack of technical expertise and geographical constraints (B. Lamichhane, 2013; UNDP, 2013). The major energy resource bases available in Nepal and their potential are elaborated on in this section.

3.3.1 Traditional biomass energy resources

Traditional energy resources mainly include common biomass fuels derived from plants and animals. Biomass is the major sources of energy in Nepal. Major biomass based energy resources used in Nepal are fuelwood from forest and tree resources, animal dung and different agricultural crop residues (WECS, 2010).

Fuelwood

Fuelwood, the mostly used resource amongst the biomass based energy resources, consists of woody biomass and charcoal, the primary sources of which are forests and other wooded lands, such as shrub lands, grasslands and plantations, and non-forest lands (agricultural land, agro-forestry systems, home gardens) (WECS, 2010). According to DFRS (1999)[21], the total area of woody vegetation is about 39.6% of the country's land area, where forest area constitutes 29% of the total land (4.2 million ha), of which only about 51.5% is reachable forest. The remaining forest areas are non-reachable, and are either under protected area systems or located on steep slopes or surrounded by steep slopes, landslides and other obstacles (DFRS, 1999). The forests in the Terai are more accessible and productive than in the Hill. The per capita forest area in the Terai and the Hill is 0.14 and 0.29ha, respectively (UNEP, 2001).

The global forest resource assessment in 2000 and 2005 estimated that the total forest area in Nepal shrank to 26.5% in 2000 and 24.7% in 2005. The area of shrub lands, on the other hand, was increased to 11.9% in 2000 from 10.6% in 1990s and to 12.9% in 2005 (FAO, 2001, 2006). The dependency on fuelwood for energy might be the cause of deforestation and degradation of Nepal’s forests. A recent study showed that the forest area in the Terai is decreasing (by 16,500ha between 2001 to 2010) due to growing pressure from rapid migration, human encroachment and transboundary

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[21] The most recent data/studies on forest area in Nepal were not available at the time of writing.

smuggling of logs into India, whereas forest in the Hill has increased by over 300,000ha in the same period due to the implementation of community forestry programme[22], decreasing population pressure due to out-migration and increasing use of alternative fuels such as biogas and LPG (ClimateAction, 2015; FRA/DFRS, 2014).

The energy content of fuelwood depends on the species and moisture content. The net energy content in fuelwood at 20% moisture content is 15.5 GJ/tonne (Leach & Gowen, 1987). The energy efficiency of a fuelwood stove commonly used in the rural households of Nepal is only 10% (WECS, 2010), and the emission factor[23] is 418 gm per kg fuelwood (Smith, Uma, et al., 2000). Burning of fuelwood has several adverse impacts on the quality of lives of the people and environment. Hard labour and longer time to collect, and indoor air pollution (total suspended particles is 5.31 mg/m^3) from its burning, make it an environmentally-unfriendly and unsustainable energy resource (M. Acharya et al., 2005). Moreover, women and girls are more affected from the use of fuelwood (see Section 2.3.2).

Animal residue

Animal residue, particularly dung, is another important biomass-related energy resource used in Nepal historically, since woody biomass supplies were not sufficient to meet the traditional energy needs of the people. Animal dung secures the second largest position in primary energy consumption (WECS, 2010). Despite the very low energy content due to high moisture content (12.0 GJ/tonne), animal dung in the form of dried cake has been a common energy source for the poor households in Nepal. A dung cake is a dry rigid mixture of animal dung with small pieces of agricultural waste and woody biomass. Use of dung cakes is more common in the rural parts of the Terai region than in the Hill, where forest resources are not available in nearby areas (WECS, 2010).

The WECS (2010) estimated a total of about 15 million tonnes of animal dung production in the country annually, out of which about 12 million tonnes (80%) is available for utilisation. The dung production in the Mountain, Hill and Terai is estimated at 1.6, 7.4 and 6 million tonnes, respectively, which is enough to meet 40% of the total energy demand of the country if used only for energy purpose (WECS, 2010). However, only about 15% of the total potential of dung production is used for

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[22] Community forestry is a participatory approach for forest management, where a part of national forests is handed over to a local users' group for its protection, management and utilisation for the collective interest. By December 2013, more than 17,500 community forest user groups are managing above 1.6 million ha of forests (DoF, 2014).
[23] Emission factor is the chemical composition of the fuel that comes during combustion (SEI, 2013).

energy purposes, the remainder of which is used as compost manure to increase agricultural productivity to sustain the subsistence agricultural system of Nepal (WECS, 2010).

Agricultural residues

Agricultural residue is another important alternative traditional fuel for domestic energy, particularly in rural areas of Nepal where fuelwood availability is limited. It includes field residues or processing residues of agricultural crops, e.g., rice, corn, wheat, millet, jute, and oil seeds, in dry form, and constitutes the third largest indigenous biomass source of energy consumption in Nepal (KC et al., 2011). The WECS (2010) estimated agricultural residue production potential in Nepal at 19.4 million tonnes in a year. In terms of energy, this is equivalent to around 240 PJ, which is about 60% of the total national primary energy consumption in the country (WECS, 2010).The Terai region has the highest potential of 11.6 million tonnes, followed by the Hill (6.8 million tonnes) and the Mountain (1.0 million tonnes). Paddy is the largest contributor (47% of total residues), followed by corn (25%), wheat (12%) and sugarcane (7%). It is estimated that at least 50% of the total agricultural residues could be used for energy purposes without affecting soil nutrient status or livestock feed demand (WECS, 2010). Supply potential of agricultural residues varies greatly between regions with rice straw the largest source of crop residue in the Terai (58%) and corn stover more predominant in the Hill and Mountain regions (nearly 50%). However, the supply potential cannot be realised without intervention to manage these resources for energy production.

Agricultural residues are also the major feed source for domestic animals in Nepal. Considering the fodder value of residues, at least 50% of the total agricultural residues can be considered for fuel purpose without affecting their other uses (WECS, 2010). However, the net energy content of agricultural residues is 1.92 GJ/tonne and total suspended particles from its burning is 5.47 mg/m^3 (M. Acharya et al., 2005), which makes it the lowest quality cooking fuel with the highest indoor air pollution.

3.3.2 Hydro resources

Nepal is one of the richest countries in the world in terms of water resources (MoPE, 2004). About 6,000 rivers and streams flow through the country, with a total length of around 45,000km and the annual run-off of 202 billion m^3 (Gewali & Bhandari, 2005; Upadhyay, 2000). An estimated area of about 4,063 sq. km is covered by water surface, the majority of which (97.3%) is under the rivers (MoPE, 2004). Nepal is also endowed with 3,252 glaciers and 2,323 glacier lakes. Similarly, the Terai region has rechargeable ground water potential. The ground water table occurs at a depth of 5 m and the artesian aquifers yield about 100 m^3 per hour (MoPE, 2004). Ground water is mainly used for irrigation and meeting drinking water needs.

The steep topography and high run-off has created huge opportunities for hydropower generation in Nepal. On the basis of average flow, the theoretical hydropower potential has been estimated at about 83 GW, of which 45 GW is technically feasible, whilst 42 GW is economically feasible (Table 3.1) (Shrestha, 1966 cited in WECS, 2010).

Table 3.1: Hydropower generation potential in Nepal

River Basin	Theoretical potential (MW)	Technical potential		Economic potential	
		Capacity (MW)	No. of sites	Capacity (MW)	No. of Sites
Sapta Koshi	22,350	11,400	53	10,860	40
Sapta Gandaki	20,650	6,660	18	5,270	12
Karnali and Mahakali	36,180	26,570	34	25,125	9
Southern Rivers	4,110	980	9	878	5
Country Total	83,290	45,610	114	42,133	66

Source: Shrestha, 1966 cited in WECS (2010)

By 2013/14, the total installed capacity of hydropower generation in Nepal was 791 MW (Table 3.2), out of which 156 MW (23%) is owned by the Independent Power Procedures (IPP), but is grid connected (NEA, 2014). However, the total electricity production decreases to about 450 MW during the dry season when snow-fed rivers shrink (NEA, 2014). This shows that there is a huge gap between demand and supply, resulting in a load shedding of above 30 hours a week. Load shedding occurs in Nepal at least 3 hours a day in wet seasons and up to 16 hours a day in dry seasons (NEA, 2014).

3.3.3 Fossil fuel resources

Nepal's fossil fuel deposits are known to be small and unprofitable to extract (WECS, 2010). Although the total reserve of natural gas is estimated to be around 300 million m^3, no exploration work has been initiated yet (MoPE, 2004). Few leakages of inflammable gas have been noted at locations such as Kathmandu valley, near the shrine of Muktinath in Mustang and in Dailekh (mid-western Hill district) area. A petroleum product that could be exploited commercially has not been found so far in Nepal (WECS, 2010). All petroleum products consumed in Nepal are imported mainly from India.

Nepal has small and sporadic deposits of low-grade coal (WECS, 2010). A confirmed coal reserve is about 2 million tonnes located in Dang district (mid-western Terai district) (Gewali & Bhandari, 2005), which supplies only about 5% of the total demand of coal in Nepal (M. P. Sharma & Thapa, 2000). The quaternary lignite deposit identified in the Kathmandu Valley is of some economic significance but has not been commercially exploited yet. A total of about 15,000 tonnes of coal was produced in Nepal in 2008/09. Unmet demand of coal is imported from India and abroad.

3.3.4 Other renewable energy resources

The several adverse impacts of traditional biomass fuels on the quality of lives of the people and the environment, lower availability of electricity and higher cost of imported petroleum fuels demand for replacing those energy resources by modern forms of renewable energy systems. The major potential renewable energy resources/technologies installed in Nepal that generates power from locally available energy resources are solar and wind energy resources (Gurung, Karki, Cho, Park, & Oh, 2013; WECS, 2010). These renewable energy sources are un-interruptible and available infinitely, and are environmentally-friendly due to their little or no negative impacts on GHG, climate and other environment.

Solar energy resources

Nepal has a high potential of solar energy generation as the country has about 300 sunshine days in a year. Nepal receives sufficient solar radiation (3.6-6.2 kWh/m^2/day) for solar energy generation and has an average of 6.8 sunshine hours/day and solar insulation intensity of about 4.7 kWh/m^2/day (WECS, 2010). Solar electricity generating systems, which are easy and quick to install, and do not need any fuel or extensive infrastructure, could be an option to provide energy security in many parts of the country. Using PV module of 12% efficiency, assuming peak sun to be 4.5 hours a day, the solar electricity generation potential of the whole country will be 17.7 TW (WECS, 2010). Considering just 0.01% of Nepal's total area, the solar electricity generation potential will be 2,920 GWh/year (WECS, 2010). However, the AEPC estimate of the commercial potential of solar power for grid connection is only 2,100 MW (AEPC, 2008b).

By the end of 2011/12, a total of 185,000 solar water systems and 284,100 solar home systems of a total installed capacity of 7.44 MW were installed in Nepal (Gurung et al., 2013). However, acceptability and affordability of the technology due to its high costs of installation are major barriers to utilise this potential (Gurung et al., 2013; KC et al., 2011). Moreover, solar thermal devices are not suitable in those regions with long and harsh winters where temperature falls below freezing (KC et al., 2011).

Wind energy resources

Although Nepal is a mountainous country with a high potential for wind energy (Upreti & Shakya, 2009), power generation capacity is affected by the diverse topography and consequent variation in the meteorological conditions (WECS, 2010). The AEPC (2008b) estimates the wind power generation of 3,000 MW from a potential area of about 6,074 sq. km, but only about 448 MW is commercially viable (Upreti & Shakya, 2009). Specific viable wind energy generation areas have been identified in Nepal, but the commercial generation of wind power is still in its infancy stage (KC et al., 2011). A total of 21 off-grid stations were installed throughout the country by 2011/12 with the installed capacity of 8.6 MW (Gurung et al., 2013). In addition, most of the potential areas are very site-specific in mountainous locations without infrastructure support and limited human settlement (Gurung et al., 2013; KC et al., 2011).

3.4 Status of Energy Consumption Patterns

Nepal is characterised as one of the least per capita energy consumption countries in the world, with a per capita total primary energy supply of 0.34 tonnes of oil equivalent (toe) for the year 2011, which is very low compared to the average for the OECD countries (4.28 toe), Asia (0.69 toe), Africa (0.67 toe) and the worldwide average (1.88 toe) in the same year (IEA, 2013). The ever-increasing population growth is one of the major hindrances to Nepal’s energy sector development. Total energy consumption has been increasing by about 2.5% per year, but the energy supply is not increasing by the same ratio to meet the energy demand of the population increase (WECS, 2010).

Table 3.2: Energy-related indicators for Nepal

Indicator	Unit	2005	2007	2008	2009	2011
Gross domestic product (GDP)	Billion 2000US$	6.35	6.92	7.31	7.65	10.53
GDP (Purchasing power parity, PPP)	Billion 2000US$	37.43	40.85	43.09	45.10	33.71
Energy Production	Million tonne oil equivalent (Mtoe)	8.15	8.53	8.73	8.82	9.04
Net Energy Imports	Mtoe	1.02	1.10	1.14	1.21	1.45
Total Primary Energy Supply (TPES)	Mtoe	9.17	9.55	9.80	9.96	10.39
Electricity Consumption	Terawatt-hour (TWh)	1.88	2.27	2.57	2.68	2.87
CO_2 Emissions	Million tonne CO_2	3.05	3.21	3.33	3.40	4.06
TPES/Population	toe/capita	0.34	0.34	0.34	0.34	0.34
TPES/GDP	toe/000 2000US$	1.44	1.38	1.34	1.30	0.99
TPES/GDP (PPP)	toe/000 2000US$	0.24	0.23	0.23	0.22	0.31
Per capita electricity consumption	kWh/Capita	69	81	90	91	94
CO_2 /TPES	tCO_2/toe	0.33	0.34	0.34	0.34	0.39
CO_2 /population	tCO_2/Capita	0.11	0.11	0.12	0.12	0.13
CO_2 /GDP	$kgCO_2$/2000US$	0.48	0.46	0.46	0.45	0.39

Source: IEA (2007, 2009, 2010, 2011, 2013)

Total energy production in Nepal was 8.15 million toe (Mtoe) in 2005 with net energy imports of 1.02 Mtoe, which increased to 9.04 Mtoe in 2011 with net energy imports of 1.45 Mtoe (IEA, 2007, 2013) (Table 3.3). Total energy consumption in the year 2008/09 was about 9.8 Mtoe, which has increased by about 2.4% per year (WECS, 2010). Total per capita electricity consumption increased to 94 kWh in 2011 from 69 kWh in 2005 (IEA, 2007, 2013). Of the total energy consumed in rural Nepal, 64% was used for cooking and 8.5% for heating, while 1.3%, 3.4% and 16.5% was used for lighting, agro-processing and animal feed preparation, respectively (CRTN, 2005).

3.4.1 Energy consumption by fuel type

Energy is derived from different fuel resources in Nepal, which can be broadly divided into three categories: traditional, commercial and renewable. All types of biomass resources used conventionally for energy production are traditional energy resources (WECS, 2010). Commercial energy includes all the energy resources with well-established market prices, whereas energy production from renewable resources is grouped as renewable energy. Table 3.4 presents the trend of total energy consumption and the proportional share of different energy sources over time.

Table 3.3: Total energy consumption trends in Nepal by fuel type (PJ)

Fuel Type	2000/01	Proportion (%)	2008/09	Proportion (%)	2011/12	Proportion (%)
Fuelwood	259	77.2	311	77.7	359	79.0
Animal dung	19.5	5.8	23	5.7	23.4	5.1
Agricultural residue	12.7	3.8	14.7	3.7	13.6	3.0
Traditional total	*291.2*	86.7	*348.7*	87.1	*396*	87.1
Kerosene	11.5	3.4	2.5	0.6	0.15	0.0
LPG	2	0.6	5.7	1.4	9.1	2.0
Electricity*	4.6	1.4	8.1	2.0	12.3	2.7
Coal	7.4	2.2	7.8	1.9	8.3	1.8
Other petroleum	17.8	5.3	24.8	6.2	25.05	5.5
Commercial Total	*43.3*	12.9	*48.9*	12.2	*54.9*	12.1
Micro/pico-hydro**	0.04	0.01	0.11	0.03	0.14	0.03
Solar**	0.0003	0.0001	0.006	0.002	0.03	0.01
Biogas	1.2	0.4	2.6	0.6	3.4	0.7
Renewable Total	*1.2*	0.4	*2.7*	0.7	*3.6*	0.8
Energy Total	335.7	100	400.3	100	454.5	100

* Includes electricity generated from hydropower (> 1 MW capacity), thermal plant and import from India.

** Energy from micro/pico-hydro and solar are not included in electricity.

Source: WECS (2010); Malla, et al. (2013); Gurung, et al. (2013)

Traditional energy

Nepal relies heavily on traditional energy resources, which comprises about 87% of total energy consumption, and fuelwood alone accounts for about 79% of total traditional fuel (Table 3.4) (Malla, 2013; WECS, 2010). The consumption of traditional energy has increased from 349 PJ in 2008/09 to 396 PJ in 2011/12. The share of animal dung and agricultural residues to total traditional energy consumption in FY 2011/12 was 5.1% and 3%, respectively, which was decreased slightly from FY 2008/09.

Table 3.4: Percentage of households by main traditional fuels used for cooking by urban and rural areas and geographic regions

Area	Fuelwood	Animal dung	Agricultural residues
Urban	25.7	1.5	1.3
Rural	73.1	12.5	1.1
<u>Geographic region</u>			
Mountain	94.8	0.4	1.1
Hill	67.0	0.1	0.9
Terai	56.5	22.0	1.8

Source: CBS (2012a)

Traditional fuels are used mostly by rural households. About 73% of rural households are dependent on fuelwood for their cooking energy needs, and about 12% of them use dried animal dung (Table 3.5) (CBS, 2012a). In terms of geographic regions, about 95% of households in the Mountain use fuelwood, followed by the Hill (67%) and the Terai (56.5%). Burning of dried animal dung is more common in the Terai region than in the Hill and Mountain; about 22% of households in the Terai burn animal dung for cooking compared to less than 1% of households in the Hill and Mountain. A higher proportion of households in the Terai (1.8%) use agricultural residues, followed by the Mountain (1.1%) and the Hill (0.9%) (Table 3.5) (CBS, 2012a).

Commercial energy

Commercial energy includes grid electricity, coal and petroleum products, which comprised almost 12.1% of total energy consumption in FY 2011/12 (Table 3.4). Commercial energy consumption in Nepal is increased by 1.6% per year (WECS, 2010). However, within commercial energy sources, electricity consumption increased with an annual rate of about 10% comprising about 3% share of total energy consumption in 2011/12. The demand for electricity is largely supply-driven, and about 50% of the population still does not have access to electricity (NEA, 2014).

Consumption of LPG, which is partly replacing kerosene, fuelwood and crop/animal residues, increased by more than 25% per year, particularly in urban areas (WECS, 2010). Consumption of LPG is about 68% of urban households compared with only about 10% rural households (CBS, 2012a). LPG in rural areas is mostly used to supplement fuelwood and other energy sources. About 30% of households in the Hill, 15% in the Terai and 3% in the Mountain use LPG. Consumption of kerosene is mostly replaced by LPG and is decreasing sharply due to its ever-increasing price and poor supply system. Coal and other petroleum (mainly imported diesel and petrol) are not used in the residential sector, but only used by industries and transportation sector (CBS, 2012a; WECS, 2010).

Renewable energy

Although consumption of renewable energy increased by more than 15% per year, it constitutes only less than 1% share in total energy consumption (Malla, 2013; WECS, 2010) (Table 3.4). There is a slow increase in the installation rate of solar energy systems. But installation of biogas plants is becoming more popular in the rural areas as a reliable source of clean energy (BSP-Nepal, 2009b; Karki et al., 2005; WECS, 2010). Biogas presently contributes about 0.7% of the total energy consumption in

Nepal (BSP-Nepal, 2012b). The contribution of other renewable energy is much lower than biogas.

3.4.2 Energy consumption by sector

Energy consumption sectors in Nepal can be divided into five groups: residential, transport, industrial, commercial and agriculture. The trend of energy consumption by different sectors in Nepal is presented in Table 3.6.

Table 3.5: Trend of sectoral energy consumption in Nepal (PJ)

Sector	2001	2002	2003	2004	2005	2006	2007	2008	2009
Residential	301.1	314.6	320.2	326.2	331.5	337.6	345.4	351.2	356.8
Transport	13.6	12.0	12.7	13.1	13.9	13.5	14.5	15.0	20.9
Industrial	13.0	12.5	12.0	13.7	12.8	16.8	12.8	14.0	13.4
Commercial	4.1	4.9	5.2	5.3	5.3	5.3	4.7	4.9	5.1
Agricultural	3.2	2.8	2.9	2.9	3.1	2.9	3.0	2.5	3.6

Source: WECS (2010)

Residential sector

The residential sector consumed almost 89% of the total energy consumption (357 PJ) in Nepal in 2008/09 (Table 3.6), with an average annual increase rate of 2.3%, and is supplied by a mix of biomass, electricity and kerosene (WECS, 2010). The energy consumption was mainly for cooking, heating, lighting and animal feed preparation (KC et al., 2011; WECS, 2010). About 85% of the residential energy is consumed by the rural population who represent about 80% of the country’s population (KC et al., 2011). Yet the rural population has limited or no access to commercial fuels such as kerosene, LPG and electricity (WECS, 2006, 2010). Thus, the rural population still depend on biomass resources to meet their energy demand. (M. Acharya, 2001)

Transportation sector

The transportation sector is the second largest energy consuming sector in Nepal, and consumed about 21 PJ in 2008/09 (Table 3.6). This was 5.2% of the total energy consumption (WECS, 2010). Total energy consumption in this sector is increasing at an annual rate of 8.9%. Petroleum fuels, e.g., diesel (67%), gasoline (20%), air turbine fuel (11%) and LPG (1%), are the major energy sources used in this sector (KC et al., 2011; WECS, 2010). Road transport dominates all other modes of transportation, and consumes 86.5% of the total transportation sector's associated energy consumption, followed by the aviation sector (13.4%) (KC et al., 2011; WECS, 2010).

Industrial sector

The industrial sector is the third largest energy consuming sector in Nepal, and consumed 13.4 PJ in 2008/09 (Table 3.6), which is 3.3% of the total energy consumption (WECS, 2010). Energy consumption in this sector has a marginal annual growth rate (0.4% per year). Process heating, motive power, boilers and lighting are the main energy usages. Coal is the major energy source consumed, and supplies about 58% of the consumption, followed by electricity (23%), agricultural residue (10%) and fuelwood (5%). Petroleum fuels supply only about 3.5% of the industrial energy requirement (WECS, 2010).

Commercial sector

The commercial sector, which includes academic, health, institutions, retail shops, hotels, entertainment, police/military barracks and other public lighting, consumed about 5.2 PJ energy in 2008/09 (Table 3.6), accounting for about 1.3% of the total energy demand in that year (KC et al., 2011; WECS, 2010). The largest end use in this sector is cooking consuming about 68% of the total energy consumption, followed by lighting (19%), and space heating and cooling (5%) (KC et al., 2011). Petroleum fuels (mainly LPG and kerosene), fuelwood and electricity are the main fuels used; petroleum fuels supplied about 53% of the total demand, whereas fuelwood and electricity supplied about 36% and 11% of the demand, respectively (KC et al., 2011; WECS, 2010). The energy consumption has been increasing at the rate of 3% annually. The LPG consumption rate is increasing in this sector by about 22%, whereas fuelwood and electricity consumption is increased by about 2.1% and 9%, respectively (WECS, 2010).

Agricultural sector

The agricultural sector consumed only about 3.6 million GJ of energy in 2008/09 (Table 3.6), and accounted for 0.9% of total energy consumption in the country (WECS, 2010). But this did not include human and animal draft power, the estimate of which is unavailable (KC et al., 2011). Petroleum, especially diesel fuel (95%) and electricity (5%) are the two types of energy sources consumed in this sector. Annual consumption of electricity and petroleum is increased by 8% and 11%, respectively (WECS, 2010).

3.5 National Plans and Policies Supporting Renewable Energy Development

Promotion of renewable energy technologies has increasingly received attention in Nepal from the Seventh 5-Year Plan (1985-1990) (Table 3.7). The Perspective Energy Plan (1991-2017) also acknowledged the development and promotion of alternative energy resources and technologies as an integral part of rural development activities (NPC, 1991). The Eighth Plan (1992-1997) envisaged the need for a coordinating body for large-scale promotion of alternative energy technologies in Nepal, and hence the Alternative Energy Promotion Centre (AEPC), as a government umbrella body to coordinate the development of renewable energy technologies, was established (NPC, 1992). The Ninth Year Plan (1997-2002) formulated a long-term vision about the development of rural energy systems to increase opportunity through the gradual replacement of traditional energy with renewable energy (NPC, 1997). In order to achieve the objectives of the plan, the Renewable Energy Subsidy – 2000 and the Renewable Energy Subsidy Delivery Mechanism – 2000 were formulated and implemented (AEPC, 2000b). The Tenth Plan (2002-2007) focused on promotion of renewable energy technologies to improve energy security to the rural population (NPC, 2002).

Table 3.6: National plans and policies supporting renewable energy development in Nepal over recent decades

National Policy and Plan	Major focus
Seventh 5-Year Plan, 1985-1990	Attention given to the promotion of renewable energy technologies
Perspective Energy Plan, 1991-2017	Acknowledged the development and promotion of alternative energy resources and technologies as an integral part of rural development activities
Eighth 5-Year Plan, 1992-1997	Established the Alternative Energy Promotion Centre (AEPC) as a coordinating body for large-scale promotion of alternative energy technologies
Ninth 5-Year Plan, 1997-2002	Formulated a long-term vision for the development of rural renewable energy systems
Renewable Energy Subsidy, 2000 and Renewable Energy Subsidy Delivery Mechanism, 2000	Designed and facilitated subsidy to the farmers for installation of renewable energy technologies
Renewable Energy Perspective Plan, 2002-2020	Envisaged development of the renewable energy sector from technical, financial and socio-economic sustainability perspectives
Tenth 5-Year Plan, 2002-2007	Set sustainable energy goals as to improve energy access for rural

National Policy and Plan	Major focus
	poor and to reduce rural poverty by providing high quality renewable energy systems to poor households at an affordable price. The Plan specifically identified targets in renewable energy technology, such as installation of additional 200,000 biogas plants during the plan period
Rural Energy Policy, 2006	Linked renewable energy promotion to economic activities
Policy for Renewable (Rural) Energy, 2009	Ensured effective flow of subsidy to farmers
Three Year Interim Plan, 2007-2010	Emphasised promotion of renewable energy to improve energy security to the rural poor people
Subsidy Policy for Renewable Energy, 2013	Increase in subsidy to increase access to the renewable energy technologies to low income households by reducing the initial upfront cost.

Source: WECS (2010), NPC (1991, 1992, 1997, 2002, 2007), BSP-Nepal (2009a), AEPC (2000a, 2000b, 2009), MSTE (2013b)

The Renewable Energy Perspective Plan of Nepal 2002-2020 has envisaged the development of the renewable energy sector from a technical, financial and socio-economic sustainability perspective (BSP-Nepal, 2009a). The Tenth 5-Year Plan (2002-2007) specifically identified targets in renewable energy technology such as the installation of additional 200,000 biogas plants during the plan period (NPC, 2002). The Rural Energy Policy 2006 has linked renewable energy to economic activities (WECS, 2010). The Government of Nepal recently approved a new subsidy policy – Subsidy Policy for Renewable Energy 2013 – to ensure an effective flow of subsidy to the farmers (MSTE, 2013b). Nepal is committed to increasing the share of renewable energy in the national energy supply and has set up a target to increase the share from less than 1% to 10% by 2020 under the Scaling-up Renewable Energy Programme (SREP, 2011).

3.6 Status of GHG Emissions in Nepal

Nepal is a Non-Annex[24] country recognised by the United Nations Framework Convention on Climate Change (UNFCCC). The total GHG emission contribution of Nepal is very modest (0.025%) compared to the global annual emissions (MoPE, 2004). Nepal's contribution in global CO_2 emissions from fuel combustion in 2013 was only 0.01%, which was just 0.21% and 0.11% of India and Asia's emissions (Figure

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[24] Developing countries, which are the more vulnerable to the adverse impacts of climate change.

3.4) (IEA, 2013). Although Nepal is one of the lowest GHG emitters in the world, the country is highly vulnerable to climate change[25] impacts (MoEST, 2012). It ranks fourth on the climate change vulnerability index as being at extreme risk from climate change effects due to a high level of climate change risk exposure and low adaptive capacity. The key determining factors in the ranking are poverty, population pattern, development, natural resource management, agriculture dependency and conflicts, adaptive capacity (Maplecroft, 2014). The climate change impacts make women and children more vulnerable since they suffer from gender-specific vulnerability (Jones, 2010; P. Pokharel, 2012; Terry, 2009). This is due to their dependency on natural resources for their livelihoods, relatively limited access to resources and resulting poverty, and discriminatory socio-cultural norms such as gendered division of labour, limited access to decision-making and limited physical mobility (Terry, 2009).

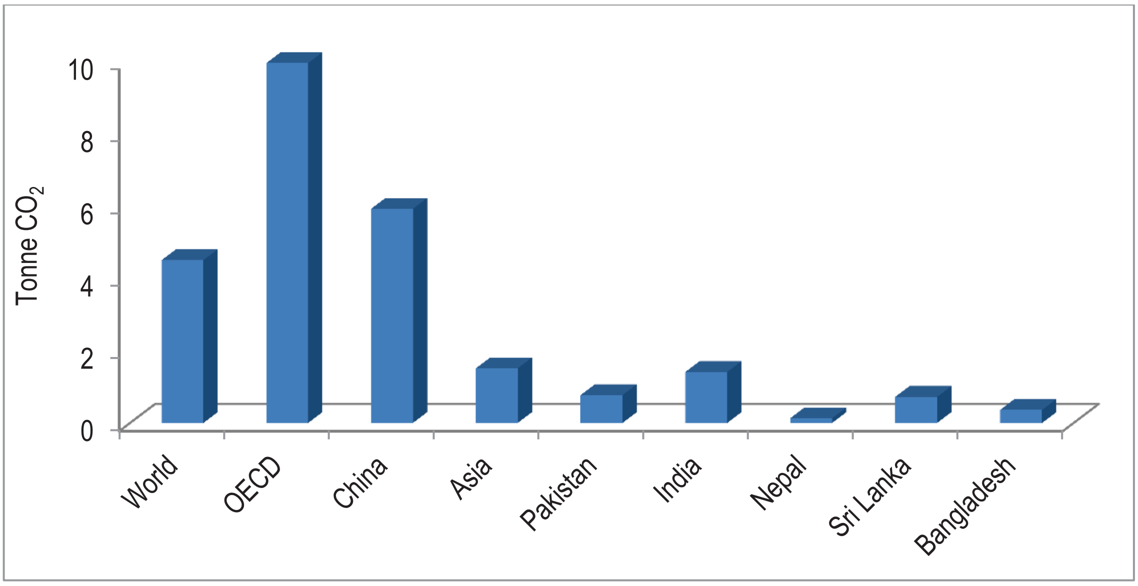

Figure 3.4: Comparison of Nepal's per capita CO_2 emission from fuel combustion with selected Asian countries, OECD and globally

Source: IEA (2013)

The majority of GHG emissions in Nepal are derived from the unsustainable use of firewood for household energy applications and petroleum fuels for the transport and industrial sectors (WECS, 2010). Traditional biomass fuels and petroleum fuels have a high carbon content and are not environmentally-friendly as they emit high amounts of GHGs. Net CO_2 emission due to energy use in different sectors in Nepal was 3.86 million tonnes in 2003, while it was 0.78 million tonnes in 1981, with an average annual

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[25] The UNFCCC (1992) has defined climate change as "a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time period."

growth rate of 7.5% for the same period (Pokharel, 2007b). The WECS (2010) estimated that GHG emissions from energy use in Nepal increased by about 48% from 4.1 million tCO_2e in 1995/96 to 6.1 million tCO_2e in 2008/09. Use of biomass in the rural areas and use of kerosene and LPG in urban areas have contributed to the residential sector becoming the largest contributor of GHG emissions in 2008/09 (54.9%), followed by the transport sector (25.1%), industrial sector (12.6%), agriculture sector (4.2%) and commercial sector (3.2%) (CES, 2013; WECS, 2010). The CES (2013) predicted that the per capita GHG emissions increase from 200 $kgCO_2e$ in 2005 to 240 $kgCO_2e$ in 2030.

Globally, climate change and mitigation issues have been receiving increased attention and Nepal is also no exception. Nepal has also ratified the Kyoto Protocol from the UNFCCC, which considers justifiable use of resources to limit or reduce the emission of gases that contribute to the global warming (MoPE, 2004). It has also committed to be involved in global emission reduction targets in many international forums and formulated a national policy through a national adaptation programme of action (NAPA), a local adaptation plan for action (LAPA) and nationally appropriate mitigation actions (NAMA) (D. Devkota, 2012; MoPE, 2004). Reducing emissions from deforestation and forest degradation (REDD) is an instrument aimed at reducing deforestation in Nepal (ClimateAction, 2015; Dangi, 2012). Nepal can benefit from the provisions of the CDM under the Kyoto Protocol. Funding can be generated though the GEF and carbon trading in the international market as well (G. Nepal, 2012).

Nepal has adopted development and promotion of environmentally-friendly energy technologies based on local resources such as biogas, solar, micro-hydro, improved cooking stoves as a strategy to managing climate change. Total GHG emission avoidance from the development of RETs was estimated at 542,000 tCO_2e in 2005, which is about a 6.5% reduction of the total national GHG emissions (Shakya & Shrestha, 2006). Nepal is strengthening its institutional capacity and securing more funding on climate adaptation, resilience and renewable energy development programmes (Joshi, 2012). A study by CES (2013) revealed that about 4.17 million tCO_2e can be mitigated by deploying RETs in Nepal, and biogas has the potential to mitigate about half of it by replacing traditional woody fuels.

3.7 Biogas Development in Nepal

3.7.1 History of biogas development

The history of biogas development in Nepal began in 1955 (Table 3.8). Biogas plant was experimented and demonstrated in Nepal for the first time in 1955, but the installation at household level started from 1974 when the Department of Agriculture supported installation of 250 biogas plants, providing interest-free loans to the farmers (P. Lamichhane, 2010; G. Nepal, 2008). Later, the Agricultural Development Bank Nepal (ADB/N) started providing soft loans (6% interest rate) to farmers for biogas construction. In 1990, the GGC modified fixed-dome model (GGC-2047) was taken as the standard biogas model for Nepal (BSP-Nepal, 2009a; G. Nepal, 2008). Installation of biogas plants accelerated after the establishment of the Biogas Support Programme-Nepal (BSP-Nepal) in 1992. The funding supported was provided by the Directorate General for International Corporation (DGIC) of the Netherland Government through the Netherland Development Organization in Nepal (SNV/N) (BSP-Nepal, 2009a; G. Nepal, 2008). The Government of Nepal (GoN) and the Kreditanstalt fuer Wiederaufbau (KfW) of Germany also started funding the BSP-Nepal from 1997 (BSP-Nepal, 2009a). During the two decades history of biogas development in Nepal, its success is being replicated in other Asian and African countries (see Section 2.6.2).

Table 3.7: The chronology of biogas development in Nepal

Year	Biogas development-related activity
1955	Biogas plant first experimented and demonstrated in Nepal by father Soubolle of the St. Xavier's School, Godawari, Nepal.
1968	The Khadi Village Industry Commission (KVIC) of India constructed a 250cft biogas system at an exhibition in Kathmandu.
1974	Government of Nepal, Department of Agriculture implemented 250 plants with interest free loan provision.
1975/76 (Agriculture Year)	Promotion of domestic biogas (cattle dung) was initiated by Nepal government under the Department of Agriculture and 199 plants constructed in that year.
1977	A Joint Organisation, Gobar Gas and Agriculture Equipment Development Pvt. Ltd (GGC) was established as a joint venture among ADB/N, UMN and Nepal Fuel Corporation. The ADB/N provided soft loan to users at 6% interest rate for biogas construction
1980	The GGC modified the Chinese fixed-dome model to suit the local conditions.
1990	The modified fixed-dome model (GGC-2047) was taken as a standard model.
1992	Biogas Support Programme-Nepal (BSP-Nepal) was established as an independent organisation to implement biogas programme in Nepal by SNV/Nepal

Year	Biogas development-related activity
	with funding from the Dutch Government.
1993 – 1997	Phase II: The BSP-Nepal was taking a lead role in biogas programme development and implementation.
1997 – 2003	Phase III: KfW and Government of Nepal also started funding to the BSP-Nepal.
2003 – 2010	National Biogas Programme Phase IV was implemented by the BSP-Nepal.
2010 – 2015	National Biogas Progamme Phase V with an ambitious target of 300,000 biogas plants (275,000 household and 25,000 institutional/community).

Source: BSP-Nepal (2009a), Lamichhane (2010), (AEPC, 2013a), BISCONS (2009)

3.7.2 Present status of biogas production

Biogas is one of the promising renewable energy sources in Nepal. According to the BSP-Nepal (2009a), total biogas potential households in Nepal are estimated at about 1.93 million, out of which 57% are expected in the Terai, 37% in the Hill and the remaining 6% in the Mountain (Table 3.9). The trend of biogas plant construction so far is encouraging (Figure 3.5); more than 330,000 biogas plants have already been constructed by 2014 (BSP-Nepal, 2015), of which 96% are in operation (BSP-Nepal, 2009a). Although almost all the districts in Nepal now have access to biogas systems; this represents only about 17% of the total potential. Biogas plants with sizes 4, 6, 8 and 10 m^3 are installed at the household-level, and 15 and 20 m^3 at the institutional level (BSP-Nepal, 2009b).

Table 3.8: Geographical region-wise biogas potentiality and % of biogas plants constructed by 2014

Region	Potential biogas households	Number of biogas plants constructed	% of total potential
Mountain	123,900	2,050	1.6
Hill	723,600	165,698	22.9
Terai	1,089,000	162,839	14.9
Total	1,937,000	330,587	17.1

Source: BSP-Nepal (2009a, 2015)

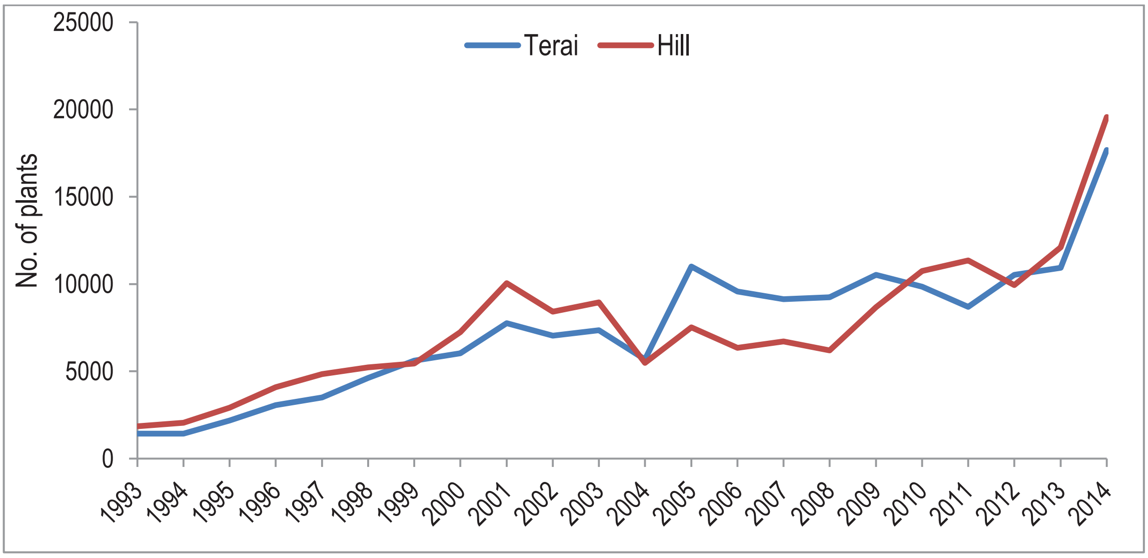

Figure 3.5: Trend of biogas plant installation in the Terai and Hill region

Source: BSP-Nepal (2015)

About 89 biogas construction companies and 16 biogas appliances manufacturing workshops are developed and qualified, and 163 micro-finance institutions received wholesale loans from AEPC's Biogas Credit Fund (BSP-Nepal, 2012b). Similarly, a comprehensive quality standards and quality control system is developed. A total of about 1.4 million persons are directly benefitted by biogas plants in Nepal, including 11,000 persons who got work in this sector (BSP-Nepal, 2012b).

3.7.3 National policies and institutional arrangements for biogas development

Overall, government policies which have acknowledged the important role of biogas in securing household energy requirements and mitigating environmental degradation in Nepal are supportive of the promotion of biogas technology (Shakya & Shrestha, 2006) (see Section 3.5). The Seventh 5-Year Plan (1985-1990) and the Perspective Energy Plan (1991-2017) acknowledged biogas development as an integral part of rural development activities (NPC, 1991). The Renewable Energy Perspective Plan of Nepal, 2002-2020 has envisaged the development of the biogas sector from a technical, financial and socio-economic sustainability perspective (BSP-Nepal, 2000a). The Tenth 5-Year Plan (2002-2007) specifically identified target for the installation of additional 200,000 biogas plants during the plan period (NPC, 2002). In order to accelerate the adoption of biogas technology, various other policies related to renewable energy subsidy were formulated and implemented (AEPC, 2000b; MSTE, 2013b).

The *National Energy Strategy Paper 2010,* a national energy policy document, acknowledged the role of biogas in making consumption of biomass energy resources more sustainable and in reducing dependence of imported fossil fuels (WECS, 2010). *The Three Year Interim Plan of Nepal (2007-2010)* prioritised the installation of biogas systems as:

> "Considering increasing the popularity of the biogas plants due to its benefits to the rural households in terms of the availability of clean cooking fuel, and digested slurry, which has established beneficial effects in enhancing agricultural productivity in environmental conservation, biogas development programme will be expanded. During the plan period, total of 100,000 biogas plants have been proposed to be developed, including 99,950 family size biogas plants and 50 community/institutional plants. Additional financial support will be provided in order to increase the accessibility of poor and disadvantaged households to biogas technology and the development of small size plants shall be given priority besides undertaking research for the development of appropriate plants for upper mountainous regions and ways and means of reducing the cost of plant development" (NPC, 2007, p. 440).

The past *Three Year Plan (2011-2013)* targeted installation of 90,000 household level biogas plants (NPC, 2011), while the current *Thirteenth Plan (2014-2016)* have also prioritised biogas programme with a construction target of 80,000 domestic plants during the plan period (NPC, 2014b).

The Ministry of Energy is mainly responsible for formulation, implementation and monitoring and evaluation of policies, plans and programmes for production, conservation, regulation and utilisation of energy in Nepal (BSP-Nepal, 2012b). Institutional arrangements for Energy Supply in Nepal involves six different ministries: 1) Ministry of Energy; 2) Ministry of Forest and Soil Conservation; 3) Ministry of Agriculture and Co-operatives; 4) Ministry of Commerce and Supplies, 5) Ministry of Environment; and 6) Ministry of Industry. Other major stakeholders of biogas programme in Nepal include the beneficiaries, the BSP-Nepal, the Netherlands Development Organization in Nepal (SNV), International Cooperation of the Netherlands (DGIS), Kreditanstalt fur Wiederaufbau of Germany (KfW), Alternative Energy Promotion Centre (AEPC), Nepal Biogas Promotion Association (NBPA), biogas companies (BCs), Banks and Microfinance Institutions (MFIs), Agriculture Development Bank (ADB), National Cooperative Federation of Nepal (NCF/N), local non-government organizations (NGOs) and rural development agencies (Figure 3.6) (BSP-Nepal, 2012b, 2013b).

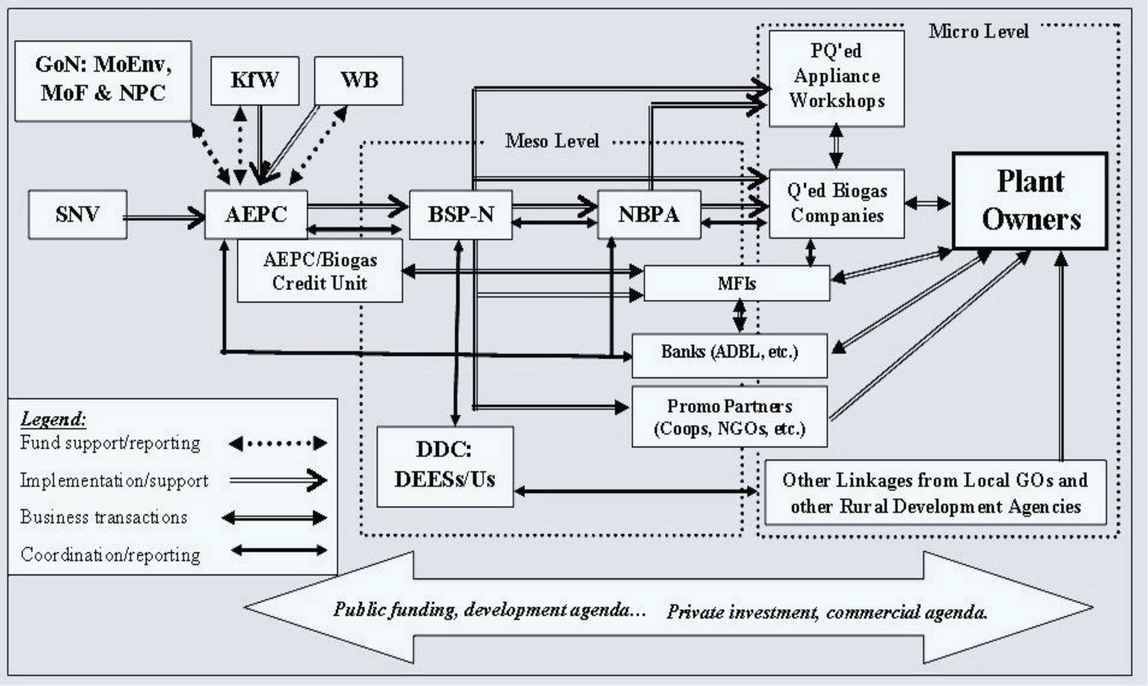

Figure 3.6: Institutional setup of biogas programme in Nepal

Source: BSP-Nepal (2013b)

The DDCs and VDCs are the main actors at the local level. They are slowly becoming aware of the benefits of biogas, but their action for the development of the biogas sector was initially limited. However, the situation is changing. *District Energy and Environment Units* (DEEUs) have been recently established in DDCs (AEPC, 2013c). Further, the World Bank (WB) and the UNDP support the DEEUs in 40 DDCs. These units and sections established with support from AEPC have three main objectives: (1) coordination, at the district level, of the different actors (NGOs, Banks/MFIs and private companies); (2) promotion of renewable energy technologies including biogas; and (3) monitoring of the renewable energy programmes at the local level (AEPC, 2013c; BSP-Nepal, 2012b).

3.7.4 Success factors of biogas development

Supportive government policy

The Nepal government has a strong commitment to promoting biogas technology through formulating supportive policies and targets, provision of interest-free loans, and subsidies (Bajgain & Shakya, 2005; BSP-Nepal, 2009a) (Section 3.7.3). The government has also exempted the Value Added Tax (VAT) on biogas equipment and construction accessories (N. Dhakal, 2014).

Long-term donor support and commitment

An important success factor for biogas development in Nepal is the dedicated vision and commitment of the principal donor, the DGIS, through the SNV/BSP-Nepal initiated in 1992. The SNV/BSP-Nepal worked closely with private biogas companies, manufacturers and NGOs to successfully promote biogas technology, encouraging technical, financial and institutional capacity building at all levels (Bajgain & Shakya, 2005; BSP-Nepal, 2009a; SNV, 2010).

Subsidy support

Subsidy support for making installation of biogas affordable to poor households is another important success factor. Amigun and von Blottnitz (2010) have acknowledged that a simple, transparent and sustained subsidy policy in Nepal is instrumental in increasing the adoption of biogas systems. The subsidy is provided towards the initial construction costs of biogas plants. The Nepal government and the German government through the KfW and DGIS provide the support for subsidies (BSP-Nepal, 2009a).

Table 3.9: Subsidy for domestic biogas plants (in NRs)

Region	2007-2013			After 2013			
	2, 4 & 6 m^3	8 m^3	Additional subsidy	2 m^3	4 m^3	6 m^3	8 m^3
Terai districts (20)	9,700	9,000	2,000	16,0000 (2,000)	20,000 (2,500)	24,000 (3,000)	25,000
Hill districts (40)	12,700	12,000	2,500	20,000 (2,000)	25,000 (2,500)	30,000 (3,000)	35,000
Mountain districts (15)	18,700	18,000	3,500	25,000 (3,000)	30,000 (3,500)	35,000 (4,000)	40,000

Note: 1 US$ = 95.30 Nepali rupees

Figures in parenthesis are the additional subsidy for the households with single women, backward, disaster victim, conflict affected, poor and endangered ethnic groups

Source: BSP-Nepal (2012b); MSTE (2013b)

The Nepal government revises the subsidy policy from time-to-time and it was recently revised in 2013, due to the increasing cost of biogas plant installation (MSTE, 2013b). There was a flat subsidy of Nepalese Rupees (NRs) 6,000 for all sizes in the Terai and NRs 9,000 in the Hill/Mountain until 2006, which was revised to make more practical in terms of remoteness and size of the biogas digester and made provision for additional subsidy for the poor groups (BSP-Nepal, 2012b) (Table 3.9). The subsidy structure from 2007-2013 was such that it provided more subsidies to smaller plants, which has encouraged households to install more appropriate smaller plants. The BSP-Nepal quoted cost of a 6 m^3 biogas plant installation in a hill district is above NRs 76,000 (BSP-Nepal, 2012a), of which subsidy covers only about 40%. In order to make biogas systems affordable to poor households, they are encouraged to contribute their own labour and provide local construction materials, which removes more than 30% of the total installation costs (BSP-Nepal, 2009a; MSTE, 2013b; SNV, 2010).

Besides making biogas plants more affordable to poor households through supporting the costs of construction, the subsidy is also used to ensure installation of good quality plants to the farmers. The subsidy plays an important role to enforce strong quality control measures. The participating biogas companies will only receive the subsidy payments when they meet the quality standards set by the SNV/BSP-Nepal (Bajgain & Shakya, 2005; BSP-Nepal, 2009a; SNV, 2010). This has also encouraged entry of commercial companies to produce quality products, and provided them with incentives for high quality installations (Amigun & von Blottnitz, 2010).

Without the subsidy, the rural households would not have sufficient incentives to adopt the biogas systems (MSTE, 2013b). Most households have a perception that the price of fuelwood is at or near zero as they do not purchase fuelwood directly, resulting in their perceived financial internal rate of return (FIRR) as negative (Bajgain & Shakya, 2005; Mendis & van Nes, 1999a). This justifies subsidy support to promote biogas technology in rural households. The subsidy provision can be justified from the carbon credit earning potential of a biogas system as well (Somanathan, Bluffstone, & Toman, 2014) (see Section 8.5.3).

Technical support for institutional strengthening, research and development

The foundation of successful promotion of biogas technology in Nepal is the technical assistance to the GGC to improve the quality of construction equipment/materials and reduce costs through research and development support (Karki et al., 2005). The SNV/BSP-Nepal strategically developed and promoted a standard technology – the GGC-2047 model fixed-dome digester with toilet attachment option, which is comparatively easier and cheaper to construct as well as more practical for increasing biogas production and quality control than the conventional fixed-dome Chinese model (Bajgain & Shakya, 2005; Karki et al., 2005). Such support not only improved the quality of biogas systems, but also helped to increase the affordability by the rural poor population through reduced costs (Bajgain & Shakya, 2005). The SNV/BSP-Nepal also works in close partnerships with biogas consumers, construction companies, banks and MFIs, NGOs and relevant government line agencies (Bajgain & Shakya, 2005; BSP-Nepal, 2009a; SNV, 2010).

Credit support for financing biogas systems

Households who do not have money to pay upfront cost for the biogas plants after the subsidy are offered credit support through banks/MFIs. Such provision of loan support has made biogas installation quite attractive to the construction companies as well as to the potential households. Even the commercial banks feel comfortable to provide loans for biogas since repayment of loans in this sector is higher than other sector loans (Karki et al., 2005). The average loan repayment period in Nepal ranges from 5-7 years (Karki et al., 2005). Devkota (2001) claimed that application of bio-slurry to replace chemical fertiliser can return biogas investment cost in 3-4 years.

Delivery of quality products and design standards

Strict enforcement of carefully defined quality and design standards is another important factor for the successful promotion of biogas technology in Nepal (SNV, 2010). Maintaining the quality and standards set by the SNV/BSP-Nepal are parts of agreements between the SNV/BSP-Nepal and the participating construction companies. A total of 73 quality standards related to design, size, construction materials, construction of digester (including inlet, dome, outlet, compost pits, toilet attachment), appliances and fittings, training of masons, and after sales services are developed and maintained, which is instrumental in achieving the high ratio (95-98%) of successfully operating systems (Bajgain & Shakya, 2005; BSP-Nepal, 2009a; SNV, 2010). Imposing penalties for non-compliance observed during inspection of the installed systems is a measure to enforce the quality standards. In addition, an effective after sales programme, including a one-year guarantee on pipes, fittings and appliances, and three years' guarantee on the structure of the plant further ensure the success of biogas technology in Nepal (Bajgain & Shakya, 2005; BSP-Nepal, 2009a).

3.7.5 Challenges of biogas promotion in Nepal

Reaching to the poor and remote rural population

So far, the biogas programme has extended mostly to comparatively easy and accessible areas, and economically better-off users who have sufficient landholding and cattle head (Bajgain & Shakya, 2005; BSP-Nepal, 2009a; SNV, 2010). Reaching the poor population in remote areas is still a hindrance due to the increased cost, which is also compounded by the low willingness of biogas companies to extend their services due to the limited profit margins (Bajgain & Shakya, 2005; SNV, 2010). Many potential households are not able to afford the initial cash payments, nor do they have access to financing to make these payments due to the lack of collateral, which is a prerequisite by the banks for sanctioning the loans (Bajgain & Shakya, 2005; Karki et al., 2005). Therefore, there is a need for research on developing a low cost design to increase the adoption of biogas systems in remote areas. Alternatively, new financing solutions, such as an increase in subsidy, that address the initial cost constraints must be developed for wider application of the technology. Innovative financing measures as well as continuation of the subsidy supports could develop a market in those areas.

Promoting biogas in cold climate or at higher altitude

A significant proportion of rural population (about 27%) live in areas above 2,000m (Bajgain & Shakya, 2005; CBS, 2012a). In cold climates or at higher altitudes, the biogas technology is not feasible due to considerable reduction in gas production because of low temperature (see Section 2.2.1). Even in the areas below 2,000m, biogas production cannot cover the energy demand of the household in the winter season. Although various physical, chemical and biological attempts were made to increase the gas production in cold climates (Karki et al., 2005), the suggested methods are cumbersome, sophisticated and expensive from a Nepalese perspective. This is a subject of global concern, and needs a real breakthrough (Karki et al., 2005) and further research (Gautam et al., 2009) to overcome this problem.

Reducing and eliminating the subsidy

The Nepal government’s subsidy policy for biogas, if reduced or eliminated in the future, would have a direct impact on biogas development. It would reduce the number of households who can afford new biogas systems, while it would also take away the incentive for biogas companies to maintain their quality (Bajgain & Shakya, 2005; SNV, 2010). As the issue of reducing or eliminating the subsidy is associated with the sustainability of the biogas programme, and several economic, social and environmental benefits that result from the use of biogas, it should be carefully evaluated (SNV, 2010). Nepal can learn from China's experience where the biogas dissemination rate was considerably decreased when the subsidy was reduced from covering two-thirds to one-third of the initial cost of the digester (Daxiong et al., 1990). Moreover, the estimated value of national and global environmental benefits that result from the use of biogas alone can justify the continuation of the subsidy (see Section 8.5.3). The value of the global environmental benefits that could be derived in the future from the sale of carbon emission reductions of the programme through the CDM could be utilised for further development of the biogas sector in Nepal, including providing subsidy to biogas system installation (Bajgain & Shakya, 2005; BSP-Nepal, 2014; SNV, 2010; Somanathan et al., 2014).

CHAPTER FOUR

RESEARCH METHODOLOGY

4.1 Introduction

This chapter outlines the methodological approach to undertaking this research, aiming to evaluate biogas production efficiency and utilisation in Nepal, and looks at how the end uses of biogas can be made more efficient. The methodological approach adopted is a mixed method incorporating quantitative and qualitative methods of data collection and analysis. In this chapter, conceptual framework, research process, selection of study area, ethical consideration, data collection methods and analytical approach are discussed. The procedures used to ensure the quality of the research are summarised towards the end of this chapter.

4.2 Conceptual Framework

Getting access to affordable and reliable energy resources which bring about socio-economic development and have less adverse impacts on the environment and health is crucial for improving the social conditions of the poor. Therefore, developing and promoting socially acceptable, economically viable, technically feasible and environmental friendly renewable energy sources is a need of the present world in order to ensure energy access for all, provide energy security, mitigate GHG emissions and improve the social conditions of the poor. Unless these issues are addressed, sustainable energy development will not be possible. The review of the literature has demonstrated that biogas could be an option for sustainable energy development in rural areas (Section 2.4), and addresses most of these issues. However, construction of a biogas plant is worthwhile only if biogas production can cover the energy demand of the household and it is cost-effective compared with the previous non-use of biogas.

The conceptual framework in this study therefore assumes that a positive biogas balance secures an affordable energy supply to the rural households with a minimal impact on the environment (Figure 4.1). In the case of negative energy balance, optimising biogas production could solve the problem. Four different options could be considered for increased biogas production, namely, installation of bigger digesters; increasing digester temperature, particularly during cold seasons; rearing more livestock to produce the required dung; and co-digestion of crop residue with dung for improved gas production efficiency. However, bigger digesters, digester heating and rearing more livestock increases the social and economic cost of energy, and hence may not be suitable options. On the other hand, biogas production through co-digestion of mixed feedstocks improves biogas production efficiency and reduces the social and economic cost of energy, thus helping to get better energy security and lower environmental emissions.

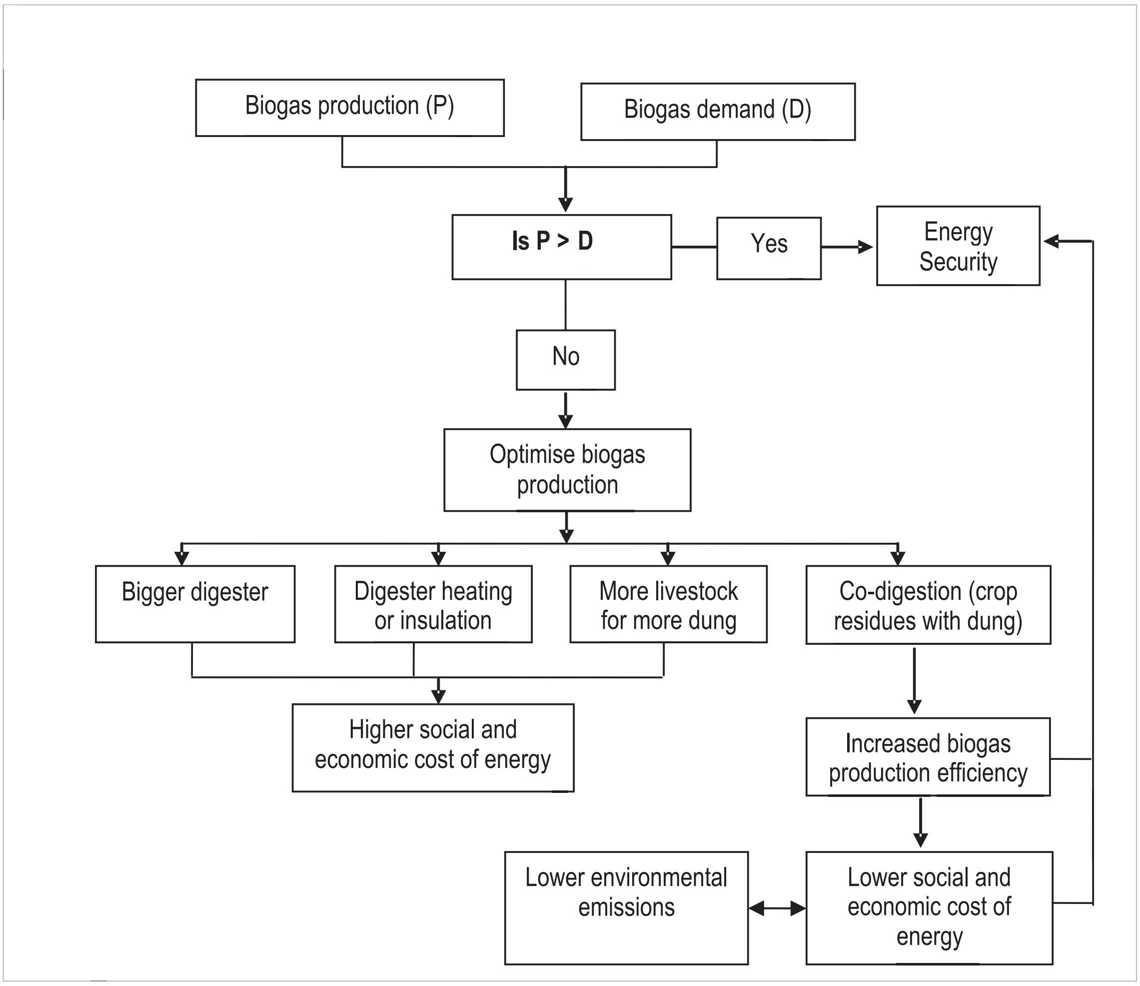

Figure 4.1: Conceptual framework: optimising biogas production for energy security

However, technical analysis of how much biogas production can be increased through co-digestion, and what proportion of different feedstock is suitable for this needs to be examined. Financial analysis of biogas systems with respect to the total energy cost before and after co-digestion, including carbon trading and social cost, enables evaluating whether co-digestion is a cost-effective energy option. In addition, analysis of the potential of biogas co-digestion technology in reducing the consumption of traditional biomass fuels and the corresponding environmental emissions demonstrates the importance of domestic biogas systems as a simple, reliable, clean and cost-effective solution to provide energy security to rural households in Nepal.

4.3 Research Process

The research process includes four main steps: i) Research Design; ii) Data Collection; iii) Data Analysis; and iv) Reflection or Result Interpretation (Flick, 2015; Glesne, 2016; Grbich, 2012; Kumar, 2011; O'Leary, 2013; Punch, 2005) (Figure 4.2). Research design includes many processes, especially: identifying research problems; setting research aims and objectives; developing a conceptual framework; developing a research plan with do-able and pragmatic research questions; and analysing the appropriate research methodology to address the research questions (Flick, 2015; Glesne, 2016; Grbich, 2012; O'Leary, 2013). Ethical consideration, sampling design and a detailed description about data collection procedures are important to be mentioned in the research design process (Glesne, 2016). Selection of study area and participants are also importantly considered to reduce any bias due to the researcher's relationship (Glesne, 2016). In the case of using a mixed method approach, additional aspects are to be considered beforehand like: at what phase the mixed approach is applied; what type of sampling approach is used; how to manage data; and what strategy is used to interpret the results (Grbich, 2012).

In this study, the research aims, objectives and hypothesis were developed in the research design phase through a review of the literature, which guided the development of a conceptual framework and selection of the study area. The data collection protocol was designed as guided by the research aims and objectives, which then defined the data analysis approaches. Findings from the data analysis were discussed in relation to the existing body of literature and the conclusion and policy implications are described. The review of the literature was a continuous iterative process throughout the research.

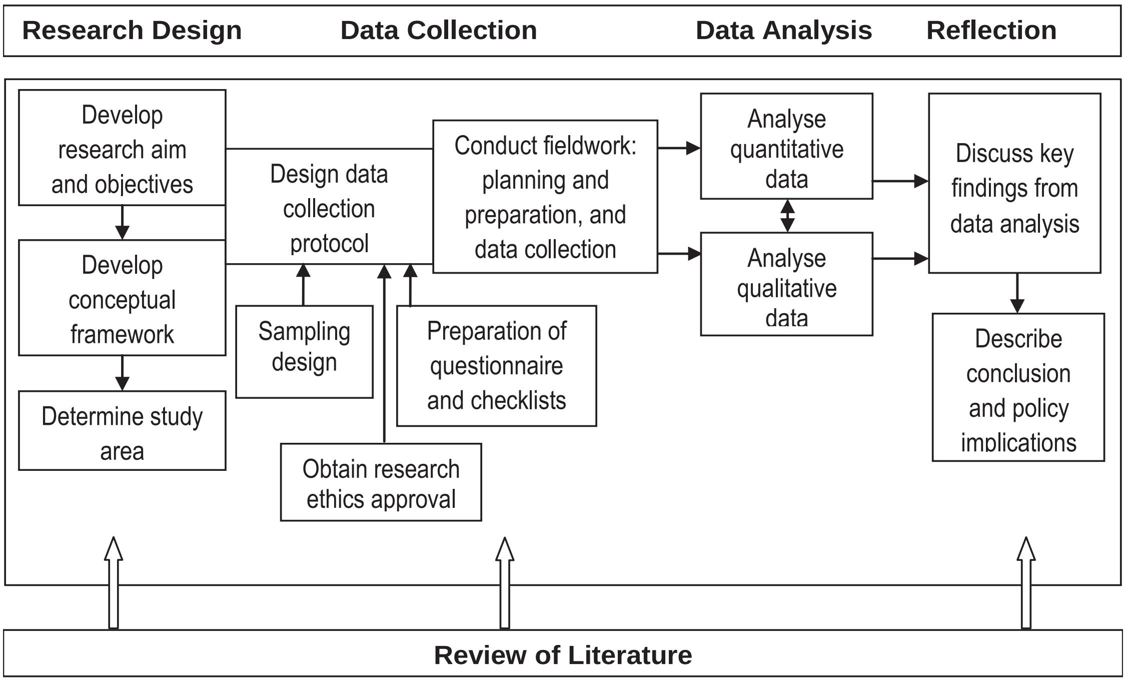

Figure 4.2: Research process adapted in this study

(Adapted from Bajracharya, 2008; Cepeda & Martin, 2005; Kumar, 2011; Punch, 2005)

4.4 Selection and Description of Study Area

The selection of the study area was guided by the research question. Accessibility of data relevant to answering the research question was a consideration for study area selection (Silverman, 2005). Similarly, location in terms of people, communities and organisation having the high potential to provide learning, and convenience in terms of logistics and responses, were also considered (Gummesson, 2000). The resources needed to spend time in the field for the process of data collection also had a bearing on site selection. Two districts of Nepal, namely, Lamjung from the Hill region which extends up to the High Himalayas and Chitwan from the Terai region were selected for this study (Figure 4.3). The selected districts represent the two distinct regions in terms of biogas production which depend upon temperature, energy use practices, fuel costs, availability of feedstock, subsidy policy and remoteness. Both districts have more than a 20-year history of biogas installation (BSP-Nepal, 2011). Another reason for selecting these districts is that they were accessible and convenient for the researcher since she had prior working experience in the region. Surveying more districts would have had obvious value, but the resources available to do this research did not allow for this. However, since Nepal comprises several similar districts to those studied in terms of biogas plant installation and use practices, the overall findings can also be generalised to the wider country context.

4.4.1 Chitwan district

Chitwan district lies in the Central Development Region of Nepal. It is located between 83°55' to 84°48’ east longitude and 27°21' to 27°52' north latitude, and covers an area of 2,218 sq. km (DDC, 2008). It is situated in the inner Terai valley (90%) and Mahabharat[26] and Churia range (10%) with a tropical to sub-tropical climate. Its altitude varies from 144 metres to 1,876 metres. Average maximum and minimum temperatures are 34.9°C in June and 8.1°C in January, respectively. The mean annual rainfall is 2,214 mm, more than 80% of which occurs during the monsoon season (June to September) (DDC, 2008). The Chitwan National Park, a World Heritage Site, is located in this district. Politically, Chitwan district is divided into two municipalities and 37 Village Development Committees.

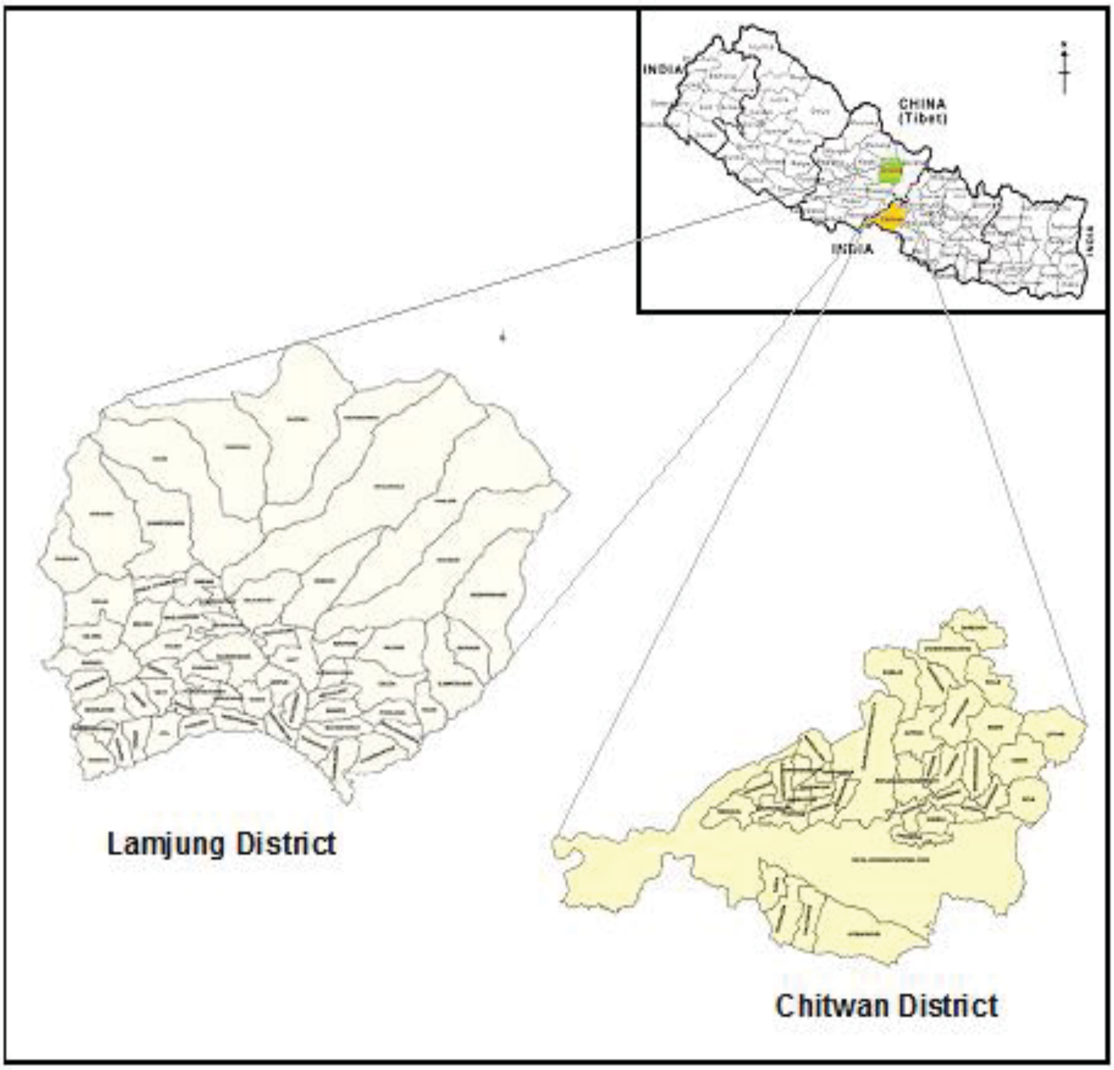

Figure 4.3: Map of Nepal showing the two study districts

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[26] Mahabharat range is a major east-west mountain range with elevations 1,500 to 2,700 metres along the crest, paralleling the Himalayas in the north and the Churia range in the south. The Churia corresponds to the outermost range of the Himalayas and rises steeply from the Tarai plains along its northern border.

The total population of the district is 579,984 (male 48.1% and female 51.9%) with an average household size of 4.38 and population density of 261 households per sq. km. (CBS, 2012a). The district is a multi-caste society. People of different caste/ethnic groups, such as *Brahmin, Chhetri, Newar, Gurung, Magar* and some other socially disadvantaged groups, such as occupational castes (e.g., *Kami, Damai, Sarki), Chepang, Tharu, Majhi, Darai, Kumal,* reside in the district. The average literacy rate in the district is 77% (male 84%, female 70%), which is higher than the national average literacy rate of 70% (CBS, 2012a). The main occupation of the people in the district is agriculture, while other occupations include service in government and non-governmental organisations (NGOs), teaching, business and production labour (CBS, 2012a). The main crops cultivated are rice, wheat, corn, soybeans, mustard and other leguminous crops, and cash crops, such as vegetables. The average number of livestock raised by a household is 0.84 buffaloes, 0.68 cows/bullocks, 1.39 goats, 0.07 pigs and 35.7 chickens (MoAC, 2011).

4.4.2 Lamjung district

Lamjung district, located between 28^0 03’ to 28^0 30’ north latitude and 84^0 11’ to 84^0 38’ east longitude, lies in the Western Development Region of Nepal. The total area of the district is 1,692 sq. km and its altitude varies from 793 metres to 8,162 metres. It is situated in the Middle Hill (42.5%), High Hill (39.2%) and High Mountain regions (18.3%) (CBS, 2007). The district has sub-tropical, alpine and tundra climates, with an average rainfall of 2,944 mm with a maximum average temperature of 26.7^0C and a minimum average temperature of 14.1^0C. The main Himalayas situated in the district are Manaslu (8,162m), Annapurna (7,939m), Himalchuli (7,647m), Manaslu South (7,637m), Lamjungchuli (6,988m) and Bouddha Himal (6,974m) (CBS, 2012a). Lamjung district is divided into 61 Village Development Committees.

The total population is 167,724 (male 45.3% and female 54.7%) with an average household size of 3.99 and population density of 99 households per sq. km. (CBS, 2012a). As in Chitwan district, people in Lamjung district belong to different caste/ethnic groups, such as *Brahmin, Chhetri, Gurung, Newar* and some other occupational castes, such as *Kami, Damai, Sarki*. The average literacy rate in the district is 71.5% (male 80%, female 63%), slightly lower than that of Chitwan district, but slightly higher than the national average of 69.9% (CBS, 2012a).The main occupation of the people in the district is agriculture. Other occupations include jobs in government and NGOs, teachers, business and production/agricultural labour (CBS, 2012a). The main crops cultivated are rice, corn, mustard, wheat, soybean and other leguminous crops, and vegetables. The average number of livestock raised by a household is 1.4 buffaloes, 0.8 cows/bullocks, 2.28 goats, 0.45 sheep and 3.9 chickens (MoAC, 2011).

4.4.3 Energy use pattern in Chitwan and Lamjung

Fuelwood is the major source of energy used for cooking and heating in both districts (Table 4.1). About half (49.1%) of the total households in Chitwan district use fuelwood as the major source of fuel for cooking, followed by LPG (39%). Biogas is the third major source for cooking with about 9.2% of the total households in Chitwan district using it. Kerosene, cow dung and electricity are used for cooking by only 0.75%, 0.16% and 0.18% of the total households, respectively (CBS, 2012a). Similarly, about 86% of the total households' main source of lighting is electricity. Solar power and kerosene are used by 5.6% and 0.54% of the total households, respectively. Very few households (0.25%) use biogas for lighting (CBS, 2012a), and none of the surveyed households reported using biogas for lighting.

Table 4.1: Energy sources in Chitwan and Lamjung Districts

(% of total households)

Energy sources	Chitwan		Lamjung	
	Cooking	Lighting	Cooking	Lighting
Fuelwood	49.1	-	70	-
LPG	39	-	19	-
Biogas	9.2	0.25	10	0.26
Electricity	0.18	86	0.13	76.8
Kerosene	0.75	0.54	0.4	14.6
Cow dung	0.16	-	0.14	-
Solar power	-	5.6	-	6.6

Source: CBS (2012a)

About 70% of the total households in Lamjung use fuelwood as their major source of energy for cooking followed by LPG (19%) (Table 4.1). Biogas is the third major source with about 10% of the total households in Lamjung using biogas for cooking. Kerosene, cow dung and electricity are used for cooking by only 0.4%, 0.14% and 0.13% of the total households, respectively (CBS, 2012a). Similarly, more than three-quarters (76.8%) of the total households' main source of lighting is electricity. Kerosene and solar power are used by 14.6% and 6.6% of the total households, respectively. Only a few households (0.26%) use biogas for lighting (CBS, 2012a).

Installation of biogas plants in both the districts was started from 1992/93. The total number of biogas plants installed by 2014 in Lamjung and Chitwan was 9,623 and 17,798, respectively (Table 4.2). However, the total number of plants installed at the time of field survey, which were considered for energy consumption and GHG analysis in Chapter 8, was 8,179 in Lamjung and 15,042 in Chitwan (BSP-Nepal, 2013a).

Table 4.2: Total number of biogas plants installed in the study districts

District	Total number of households	Potential number of households suitable for biogas	Total number of biogas plants installed by 2014
Lamjung	42,048	14,246	9,623
Chitwan	132,345	57,115	17,798

Source: CBS (2012a); BSP-Nepal (2015)

The number of annual biogas plant installations in the districts has been relatively steady over the past decade after increasing in the 1990s (Figure 4.4). The demand for biogas plant construction remains encouraging, with more than 400 biogas plants installed in Lamjung district, while more than 800 biogas plants were constructed in Chitwan district in 2014 (BSP-Nepal, 2015). However, both districts showed a general decline in biogas plant installation from 2011.

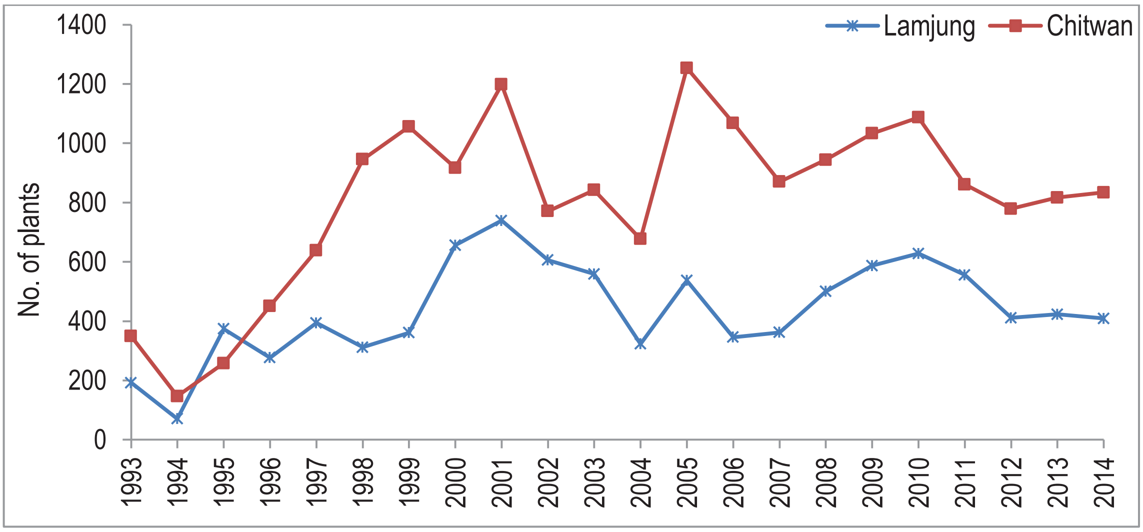

Figure 4.4: Trend of annual biogas plant installation in Lamjung and Chitwan districts

4.5 Review of Research Methods

Quantitative method

The quantitative method is a deductive type which includes mostly closed-ended objective questionnaires to collect static or numerical data that is used in statistical analysis for hypothesis testing and outcome confirmation (Edmonds & Kennedy, 2013; O'Leary, 2013). Researchers can use multiple sources of data from multiple sites or locations in purposively selected samples to maximise variations and variables to confirm findings with validity and reliability (S.B Merriam, 2002). Quantitative researchers can use computer programs, relevant models or software for statistical data analysis with a clear understanding about: how to manage data; identifying variables; the role and function of descriptive statistics; appropriate use of statistical tests; and effective data presentation skill and capacity (O'Leary, 2013). Quantitative research is essential for providing a broad base of insight into which a strong voice or robust outcome could be recommended (S.B Merriam, 2002). However, knowledge might be too abstract or general for direct application of the quantitative outcomes to specific local situations, contexts or individuals unless a qualitative approach is also used for clear interpretation (Flick, 2015).

Qualitative method

The qualitative research, on the other hand, is inductive (Edmonds & Kennedy, 2013), exploratory and investigative (S.B Merriam, 2002) in nature. It includes a holistic view, with the structure impacting on the context settings such as policies, culture, context and situation (Grbich, 2012). Qualitative research is used to get meaning and understanding by exploring and interpreting complex data from sources such as interviews, group discussions, observations and document review without the use of quantification (O'Leary, 2013). However, the qualitative researcher needs to be mindful of how their epistemological view shapes and influences the research conducted, because personnel characteristics such as status, ethnicity, age and gender impact on how participants respond in research settings (O'Reilly & Kiyimba, 2015). Hence, the researcher needs to maintain transparency through clearly separating evidence from interpretation and reflexivity in reporting research methods (O'Reilly & Kiyimba, 2015) where reflexivity is the process of being self-aware of how these factors influence participants' responses. The important aspects to be considered in qualitative research are: validity and reliability, which can be addressed through using strategies like triangulation; the researcher's position or reflexivity, variation in sampling like location, groups of people, time; and providing a detailed description about the research process

(S.B Merriam, 2002). Qualitative data analysis (QDA) is mostly thematic, rather than statistical (O'Leary, 2013), which can be done either using computer program software or a manual method (Gilbert, 2002; Grbich, 2012; Jason & Glenwick, 2012; O'Leary, 2004, 2005, 2013). It depends on how to best fit the approach with research questions, sets of data and the aims of the research project without losing sight of the context (Grbich, 2012). In-depth exploration under a qualitative framework will help best answer the research questions (O'Leary, 2013). However, the findings from qualitative research alone are often not conclusive and cannot automatically be used to make generalisations (Edmonds & Kennedy, 2013).

Mixed method

Using both a qualitative and quantitative approach in a single study is a mixed method approach (Edmonds & Kennedy, 2013). It is necessary to use a mixed method approach when neither method alone is adequate to address research questions (Creswell & Clark, 2007; Edmonds & Kennedy, 2013; O'Leary, 2013). This method is becoming more popular in social science research to get a synergetic outcome as it is not simply an A+B operation of adding a qualitative to a quantitative method and vice versa, but it is an important third paradigm (Denscombe, 2008; Jason & Glenwick, 2012) or a hybrid approach. It capitalised on the best of both methods and overcame many of their shortcomings when handled well (O'Leary, 2013). As it allows for the use of both inductive and deductive reasoning, it builds a broader picture by adding depth and insights. However, researchers can use different research protocols in different phases: research design; data collection; data analysis and/or outcome interpretation, so one method can be used to tailor and support the other. Moreover, using a mixed method approach offers more than one way of looking at a situation, hence it increases the researcher's confidence in the findings (Dixon-Woods, Agarwal, Young, Jones, & Sutton, 2004). It adds precision to 'words' through the inclusion of numbers and statistics, and it facilitates capturing varied perspectives through the inclusion of dialogue, narratives and pictures (O'Leary, 2013) to strong outcome interpretation (Flick, 2015). Additional reasons for using a mixed method approach in social-type research are: participant’s selection without any bias; faithful and accurate; and fosters data outcomes that increase the effectiveness of social programs (Collins, Onwuegbuzie, & Sutton, 2006). However, a mixed method approach offers the promise of the best of both methodological traditions but not without substantial challenges, which are mainly: timing; priority to either method; and function or purpose of the research (Creswell & Clark, 2007). Theoretical challenges in a mixed method approach is incommensurability versus compatibility of quantitative and qualitative elements within a single research study (O'Reilly & Kiyimba, 2015). However, according to the fundamental principle of the mixed method, the researcher should use mixed methods to imply complementary strengths and non-overlapping weaknesses (S.B Merriam, 2002). Most importantly, a mixed method approach provides both confirmatory and qualitative findings that allow triangulation for validity and reliability and thus it provides stronger and more valid influences for generalisation (Edmonds & Kennedy, 2013; S.B Merriam, 2002; O'Leary, 2013).

4.6 Design Data Collection Protocol

In a mixed method approach, the data collection method includes collection of both qualitative and quantitative-type primary and secondary data. The qualitative data collection and quantitative data collection process can run parallel or sequentially (Edmonds & Kennedy, 2013), depending on the nature of the study or level of data requirement to address research questions, but it has to be clearly described during the research design, planning and preparation phase. In social-type research, the data collection process involves mainly: sampling or representativeness, ethical consideration, surveys/interviews, observations, discussions, document reviews and content analysis (Flick, 2015; O'Leary, 2004, 2013). In general, the primary data collection process includes surveys, interviews and observations while the secondary data collection process includes a review of previous published literature and documents. However, there are some limitations in the data collection process, in either method such as any bias, language barriers, and the researcher's position in relation to impression/influences. These issues should be addressed carefully to get more valid, reliable/trustworthy and data accuracy (Flick, 2015). The use of mixed methods provides a more complete and comprehensive understanding of the context or setting in which people behave and minimises the potential for biased interpretations made by the researcher if only one method is used. The data collection process in this study was divided into two phases: planning and preparation phase; and data collection phase (Figure 4.5).

4.6.1 Selection of research method

A research approach combining quantitative and qualitative principles is selected in this research, which involves the collection, analysis and integration of quantitative and qualitative methods and data. The focus for data collection was on domestic biogas production and utilisation. Both quantitative and qualitative data were collected from the field. A mixed methods approach was used since it improves the credibility of the findings when information from different data sources converges. Quantitative data were necessary to analyse changes in energy use patterns after the use of biogas; to examine demand and consumption patterns of biogas; to assess the potential for improving biogas production efficiency; and to analyse impacts of biogas on social, economic and GHG emission reduction. Likewise, qualitative information was required to understand the institutional settings, policies and strategies to increase biogas production efficiency; and opportunities and constraints for replication of biogas technology to provide benefits to poor households. The quantitative data is based on a community survey of biogas user households, while the qualitative information was collected through interviews with key informants and documents analysis. The data collection procedure was guided by the conceptual framework (Section 4.2).

The biogas user household was the lowest unit of sampling and, hence, the unit of data sources for the analysis. In order to collect data effectively, the data collection protocol was made flexible to adapt to the field situation (O'Leary, 2004; Silverman, 2005). Table 4.3 summarises the sampling and data collection techniques used to collect data from the field. The main methods through which data were collected were household surveys, interviews, observations, informal discussions and analysis of documents. The biogas households and key informants were two main categories of respondents. A circular systematic sampling method was used to determine survey households (see Section 4.6.1). In this method, the end of a list in selecting the sample is connected to the beginning of the list after exhausting the list during the first cycle, making a circular pattern in selecting the sample (Ahmed, 2009; Daniel, 2012). This method provides better random distribution than simple random sampling when the frame is ordered, and is easy to implement (Ahmed, 2009).

4.6.2 Selection of participants

A purposive sampling was used to select the participants for key informant interviews. A purposive sampling is a non-probability sampling technique used to serve a specific purpose (Neuman, 2006). In this method, participants are deliberately sought according to information required by the study. This method is useful where sampling for proportionality is not an objective and when a few people have the expertise in the subject matter under study (Morse, 2004). The researcher chose the samples (key informants) based on who she thought would be suitable to achieve the objectives of the study.

Table 4.3: Sampling and data collection techniques

Categories of respondents	Sampling technique	Data collection technique
Biogas households	Circular systematic sampling	Interview, informal discussion, observation
Key informants	Purposive sampling	Interview, informal discussion

4.6.3 Preparation for fieldwork

In the fieldwork planning and preparation phase, after first arriving in Nepal, the researcher held meetings with the Director, Assistant Director and Treasurer of the BSP-Nepal to brief them about the research project in order to obtain their comments on the project and seek their suggestions and support on how the fieldwork could be better organised. The BSP-Nepal, which provided the biogas user household database for selecting the surveyed households, is a professional organisation responsible for implementation of the biogas programme that accredits the work of private companies. It provides training to users and biogas companies, ensures quality and long-term reliability of biogas plants, and manages the programme of subsidies to assist users with the purchase of plants (BSP-Nepal, 2012).

Personnel from the BSP-Nepal acknowledged the research concept and showed their commitment to providing the necessary support during data collection, and afterwards if required. In the meeting it was also suggested that the researcher hold meetings with district-based biogas construction companies, which are the ‘executive arm’ of the programme for installing and maintaining the biogas plants with field-based staff (BSP-Nepal, 2012), and ask for their assistance during fieldwork. The BSP-Nepal also provided the contact information of the relevant district-based biogas companies and communicated with the companies about this research project requesting that they provide support during the fieldwork.

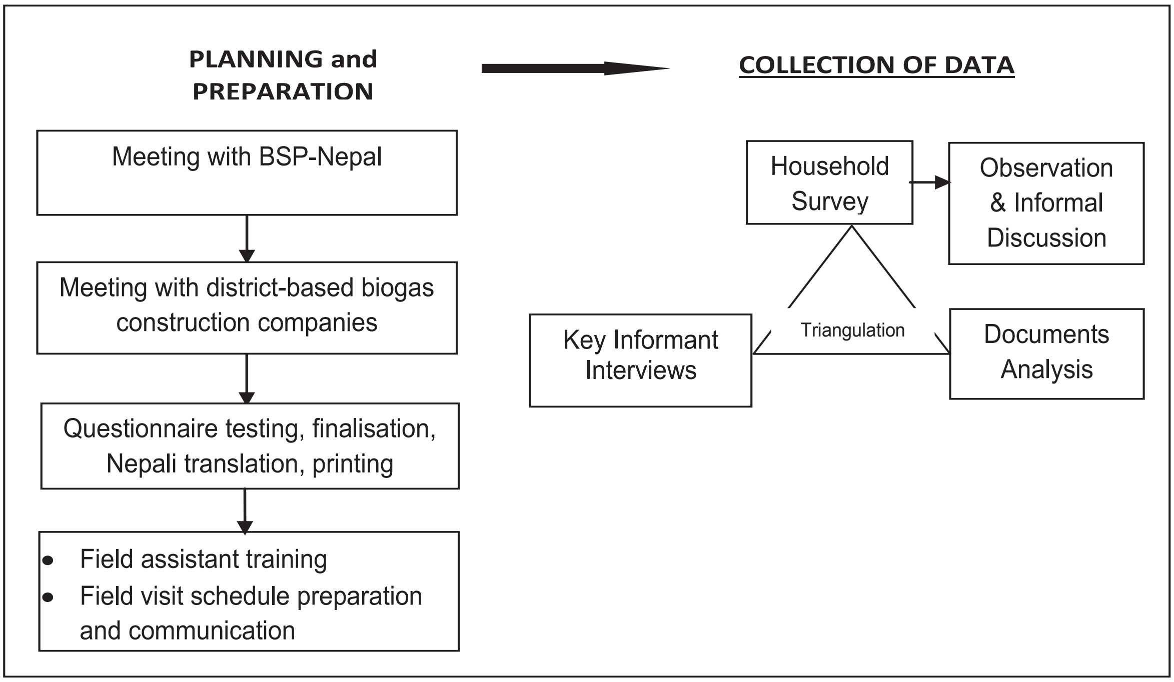

Figure 4.5: Data collection process and methods

Meetings were held individually with the managers and field officers in charge of biogas construction companies in the respective districts (Table 4.4), who assured the researcher of their full cooperation and support during the collection of data. Two consecutive meetings with the companies prepared the detailed fieldwork plan/schedule, and the companies instructed their staff accordingly so as to assist the researcher in data collection in their respective duty areas.

Table 4.4: List of people met with during fieldwork planning and preparation

Reference	Position	Organisation	Date
FPP-1	Assistant Director	BSP-Nepal	May 2012
FPP-2	Director	BSP-Nepal	May 2012
FPP-3	Admin & Finance Manager	BSP-Nepal	May 2012
FPP-4	Technical Officer	BSP-Nepal	May 2012
FPP-5	Field Officer	BSP-Nepal	May 2012
FPP-6	Branch Manager	Rastriya Gobar Gas Nirmal tatha Sewa Pvt. Ltd., Regional Office, Dumre, Tanahun	June 2012
FPP-7	Branch Manager	Rastriya Gobar Gas Nirmal tatha Sewa Pvt. Ltd., Chitwan	June 2012
FPP-8	Manager	Janata Urja Bikas Company, Chitwan	June 2012
FPP-9	Manager	Marsyangdi Gobar Gas Company, Lamjung	June 2012
FPP-10	Director	Lamjung Gobar Gas Company, Lamjung	June 2012

At the meetings, it was also suggested that a field assistant was taken while visiting the field in order to avoid the risk of being harmed, particularly considering the fragile security situation in the post-conflict political state, as well as to get help in the collection of data. Four locally-based assistants, two in each district, were identified in consultation with the respective companies and trained to assist in data collection (Table 4.5). The assistants were field officers from the local biogas companies, who had been involved in promotion and construction of biogas technology in the districts for more than 10 years. They were trained individually by the researcher on the data collection process/methods, including filling out the survey forms. The researcher was accompanied by a field assistant during household surveys. The field assistants provided administrative support, such as arranging and communicating the dates for data collection, bridging between the researcher and the respondents to make the respondents feel comfortable in providing information, and also recording the data on a questionnaire sheet, jointly with the researcher. A series of interviews and informal discussions were carried out to collect data, which are discussed in the following sections. The schedule of the field visit is presented in Annex 2.

Table 4.5: List of field assistants

Reference	Position	Organisation	Date
FA-1	Field Officer	Rastriya Gobar Gas Company, Chitwan	June 2012
FA-2	Field Officer	Janata Urja Bikas Company, Chitwan	June 2012
FA-3	Field Officer	Rastriya Gobar Gas Company, Lamjung	June 2012
FA-4	Field Officer	Rastriya Gobar Gas Company, Bhorletar, Lamjung	June 2012

4.6.4. Sample size and sampling design

Probability techniques were applied to determine the sample size and sampling design for household surveys in order to generate reliable data with minimum errors. It allowed every household in the database of all households with biogas available from BSP-Nepal an equal chance to be selected. The statistical outcomes from a probability sampling are also suitable to be generalised to the entire population (Edmonds & Kennedy, 2013). The following formula was applied to obtain an estimated sample size in each study district (Acharya, Aryal, & Shrestha, 2011):

$$n = \frac{Nz^2\, p(1-p)}{Nd^2 + z^2 p(1-p)} \qquad \text{Equation 4.1}$$

where,

n = Sample size

N = Total population size

z = Confidence level (at 96% level, $z = 1.96$)

p = Proportion of samples on population estimate (95%)

d = margin of error (+/- 3.4%, expressed as a proportion, i.e., 0.034)

The original sample size given by the above equation was 155 in Lamjung district and 156 in Chitwan district, but it was increased to account for contingencies and fixed at 157 for both districts. In order to have a sufficient number of households in case substitutes were needed, first the design-adjusted sample size (n_1) was determined after allowing for 50% extra households ($n_1 = n + 0.5n$). The biogas user household database prepared by the BSP-Nepal was provided for each of the two selected districts and used as the sampling frame for selecting the sample households (see Annex 3 for an example of the database).

A circular systematic sampling method[27] was used to select the survey households. For each district, the total number of biogas households (N) was then divided by the sample size (n_1) to obtain the interval (*i*). A random number (k) was then chosen between 1 and N for each district, which was selected as the first sample household. The second sample household was $(k+i)^{th}$ household on the list, the third sample household was $(k+2i)^{th}$ household, the fourth sample household was $(k+3i)^{th}$ household, continuing in a circle to the point where the initial selection was made. This resulted in a total of 236 sample households, as 'i' was set to allow for a sample size 'n' that is 50% larger than the actual number of sample size required if everyone responded. The actual households to be surveyed were determined choosing two households from the list of the sample households and leaving the third one out as an alternative household. When a survey household was unavailable, the alternative household was chosen instead, being the one nearest in the list rather than the nearest in physical location in order to avoid bias. The list of the sampled households is presented in Annex 4.

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[27] The systematic sampling scheme made use of the complete list of all biogas households available in each district from BSP-Nepal. The list was endorsed before sample selection, so that the systematic sample is effectively a simple random sample without replacement at household level, which allows statistical analysis without the use of complex survey design software.

4.7 Ethical Considerations

Research ethics were very important to this research as it involved interactions with people in their environment. The Massey University Human Ethics Committee (MUHEC) Code of Ethical Conduct for Research was followed when undertaking the survey. First, the researcher read the MUHEC's Code of Ethical Conduct for Research, and discussed the ethical issues of this research project with her supervisors. These issues included selection of participants, informed consent, privacy and confidentiality, potential harm, data management, access to (and use of) information, potential conflicts, use of assistants, cultural considerations and gender considerations. In order to undertake an ethical analysis of this project, the Screening Questionnaire was completed, which identified this project as a low-risk project. As the nature of the harm of this research is no more than is normally encountered in daily life, the low-risk notification approval process was determined and the MUHEC-low risk notification guidelines were followed. The ethics report prepared for this research was reviewed and approved by the MUHEC. The detailed documents of major ethical processes are presented in Annex 1.

The researcher followed three principles to ensure the research was ethical. First, the participants in this research were provided with the required information about the researcher and this research prior to data collection. The participants were provided with an Information Sheet which gave the researcher's introduction; project description and invitation to participate; participant identification and selection criteria; project procedures, including time involved; data management; and a statement of a participant's right to decline to participation. The information sheet also included the contact details of the researcher and supervisors for the participants, if they had any questions about the project.

The second principle followed was that participants provided information voluntarily. Participants were invited to participate in the research and their informed consent was obtained on a form, including the title of the research and the time period for retaining the signed form (a minimum of five years from the research completion date). It also included the participant's statement agreeing to participate in the research and the participant's full name, signature and date.

The third principle employed was the privacy and confidentiality consideration. A signed confidentiality agreement was obtained from the field assistants (see Section 4.6 for information on field assistants), who helped while collecting household survey data that contained personal information. This confidentiality agreement covers an agreement to not disclose, retain or copy any information.

4.8 Data Collection

There are some limitations in both qualitative and quantitative research approaches (Flick, 2015). A mixed method can capitalise the strengths of both methods, increase the dimensions of understanding and corroboration (Johnson, Onwuegbuzie, & Turner, 2007) and compensate the limitations (Bryman, 2008), however, some issues need to be addressed properly to get a more robust and less ambiguous outcome. Data transformation design allows the researcher to collect qualitative and quantitative data, either sequentially or concurrently, but qualitative data can be managed and coded first to support subsequent QDA (Edmonds & Kennedy, 2013). In addition, the important limitations in the data collection process by using either method lie in: a) sampling or representativeness; b) standardised survey; c) structured observations; d) quantitative content analysis; e) analysing secondary data; and f) making conclusions (Flick, 2015).
In this study, both quantitative and qualitative data were collected by using the same data collection protocol/phenomenon which are described below in detail.

4.8.1. Household survey

Household surveys has become a key and among the most flexible method of data collection in social research (Neuman, 2006; O'Leary, 2004). It is often a structured way to collect information. A survey can be defined as an information collection process by asking a range of individuals the same questions related to their characteristics, attributes, way of living or their opinions to generate standardised, empirical data (O'Leary, 2004). A survey is useful to collect standardised information from a large number of individuals when independent opinions and responses are required (Neuman, 2006). The aim of the survey in this research was to assess the potential for improving biogas production efficiency by collecting household-level information on a range of topics concerning socio-economic characteristics, energy use patterns before and after biogas plant installation, demand and consumption patterns of biogas to identify biogas deficit and how the users cope with low biogas production, and availability of different types and quantity of feedstock. This survey also aimed to gather information for the comparative analysis of the cost of energy before and after the use of biogas, and examine the potential of biogas to reduce energy consumption and associated environmental emissions.

Considering the wide range of information to be collected through this survey, this study was targeted to the decision-maker, speaking on behalf of the entire household, and a female member managing the household energy system, together, as respondents for the survey (Figure 4.6). The prevailing socio-economic cultural settings of Nepal gives decision-making power and control to the head of the household, and this is generally a male who makes the majority of the household's decisions (Shrestha, Shrestha, & Shrestha, 2004). However, females are very much involved in managing the household energy systems and are the ones who are directly affected by the household energy crisis (Katuwal & Bohara, 2009; Mahat, 2003). Hence their representation and opinion in these surveys was considered vital. It would be very difficult to extract the information if the surveys were not considered from a gendered perspective. The surveys took place at the respondents' houses.

Figure 4.6: A household survey in Lamjung district

A household survey questionnaire, most of which were closed-ended, was prepared and used to extract information from the respondents. O'Leary (2004) argues that closed-ended questions are pre-categorised and have greater precision, uniformity, are easier to recall for the respondents, and easier for coding and analysis. The questionnaire was also discussed with the Director, Assistant Director and Treasurer of the BSP-Nepal, who were happy about the contents of the questionnaire. The draft questionnaire was also tested/piloted in four households during the planning/preparation phase before conducting the actual survey, in order to identify any missing information in the questionnaire and/or potential difficulties that might be encountered while answering the questions. Pre-testing of a questionnaire is important in planning a good survey, as identification of questionnaire problems and much of the accuracy and interpretability of the survey results lies on this pre-testing; if avoided, it may lead to loss of vital information (Fink, 2009; Scheuren, 2004). Pre-testing of the questionnaire is useful to ensure that each question measures what it is supposed to measure, and all of the questions are understood and interpreted in the same way by all respondents (Salant & Dillman, 1994). The questionnaire was tested against time taken, pacing, recording/note-taking, objectivity, conversational flow, ambiguities and quality of data generated (O'Leary, 2004), and interviewees' feedback on difficulties encountered or anything else they wanted to discuss were analysed. The respondents provided positive feedback on interview time taken, pacing, objectivity and conversational flow. However, the pre-testing with one-on-one interviews identified duplication in the understanding and interpretation of two questions related to energy use patterns and biogas availability, and a few formatting concerns in terms of recording/note-taking. These problems were rectified to produce a final questionnaire (Annex 5). The questionnaire was then translated into Nepali language for the convenience of the respondents, and the required number of questionnaires was printed.

The survey was facilitated by the researcher. The field assistants assisted the researcher in recording, particularly, the answers to the open-ended questions during the surveys. The interview was started in an informal way to establish rapport, gain trust and create a conducive environment to open and honest communication (O'Leary, 2004). The respondents were first introduced to the researcher, and given an explanation of the research aims and objectives. The ethical principles were outlined, fieldwork processes were stated and the importance of the respondents' information to this research was described. The researcher then asked the respondents for their agreement to be interviewed for this study. The survey proceeded only when the respondents agreed to be interviewed, although none showed their disagreement. The respondents were also given a copy of the questionnaire to read, if they wished. In order to create a transparent environment for the survey, notes were taken in the Nepali language, the respondents' native language. For those who could not read, both the questionnaire and notes were clearly read out to them. Towards the end of each survey, a brief summary of the interview was presented in order to ensure that the views of the respondents were accurately recorded and consent to use the information for this research was reaffirmed.

This household survey collected a range of information, which included:

- Socio-economic information, for example, ethnicity, family size, type/number of livestock, land-holding, occupation/income source and distance to forest for sourcing fuelwood;
- Energy use patterns before and after biogas was introduced, for example, access to electricity, type and quantity of energy used for cooking and lighting, and daily energy consumption patterns;
- Specifications of the biogas plant installed, e.g., plant size and age, use of biogas, number of biogas stoves/lights, digester heating system, toilet attachment;
- Availability of feedstock, e.g., daily requirement and availability of dung for both summer and winter seasons, use and availability of other organic material as feedstock, present use of agricultural residues and implications of agricultural residues on previous or other potential uses if used as feedstock;
- Anticipated biogas demand and actual availability, surplus/deficit status, and measures to increase biogas production;
- Economic evaluation of biogas and alternative energy systems
- Role of biogas in reducing women’s workload.

In order to measure the changes in energy use patterns due to the installation of a biogas plant, the respondents were asked about the energy sources they used for cooking and lighting before and after the installation of biogas for both the winter and summer seasons. Daily biogas demand and biogas availability for cooking and lighting for both seasons were extracted from the respondents in order to examine the demand and consumption pattern of biogas and to analyse how the users cope when lower gas production occurs. Likewise, the respondents were asked to report the type and quantity of animal dung available for feeding into the digester daily and whether they were using any other organic materials as feedstock. The aim was to explore if insufficient availability of feedstock is a major factor for lower biogas gas production. Similarly, information on the economic aspects of biogas and alternative energy systems, particularly solar lighting and solar cooking, was collected to look at the potential of other energy sources in meeting the energy demand that could not be met with the biogas. The information collected during the survey was also verified with the household profile made available by the respective biogas construction companies, and any inconsistency detected was corrected by consulting the respective households. After the completion of the survey, the filed impressions and initial findings were shared with the experts from the BSP-Nepal and the biogas construction companies.

Due to the nature of the data to be collected (e.g., seasonal variation in biogas production and consumption and feedstock availability), the household surveys were conducted in two different seasons, summer (June – August) and winter (December – February). As biogas production and use depends also on temperature, that is, farmers experienced low biogas production during winter or in cold climate regions, it was important to look at biogas demand and availability in both the seasons separately. The questionnaire was also designed accordingly to record the information specific to both the seasons (Annex 5). The same respondents in the first visit (summer) were spoken with during the second visit (winter). A third visit was also made to a few households where the same respondents were not available for the survey during the second visit. Questions not specific to any season (e.g., household characteristics, specifications of biogas plants installed, changes in energy use pattern after biogas, economic evaluation of biogas system, changes in women's time allocation and workload on household activities after biogas) and summer-specific questions (related to feedstock availability, biogas demand and availability in summer) were asked during the first visit. Only winter-specific questions were specifically asked during the second visit. The field assistants arranged the dates for the surveys in consultation with the participant households. The average time taken for the interview was about 1.2 hours in the first visit and 30 minutes in the second visit. The data collected were carefully checked, coded and transferred into a spreadsheet.

The fieldwork took longer than expected due to the remoteness of the sampled households, rainy season (June/July), due to flooding and blocked roads, and peak crop (paddy) planting season making people busy in the field (see Annex 2). The field work was again slowed down due to farmers' unavailability during the peak crop harvesting season (November/December). Furthermore, the unstable political situation that gave rise to frequent strikes/protests (organised by various political parties and/or student unions) also affected the fieldwork initially.

4.8.2 Interviews with key informants

Key informant interviews consisted of an in-depth interview with a person or group who were believed to have the most knowledge of the issue, organisation or subject matter under study (Parsons, 2008). This method can be useful when a study requires in-depth, qualitative information that cannot be collected from survey respondents or documents/records. The outcomes of such interviews can be used for triangulation and to supplement survey findings while interpreting survey results. Because key informants are selected purposively, it is important to include a mix of persons to be interviewed in order to reflect all possible aspects of the study (O'Haire et al., 2011; Parsons, 2008).

Information was collected from 21 key informants from 18 organisations, experts in the field of RETs and domestic biogas, in order to understand the context of overall RETs, development and replication of biogas technology, and the roles and strategies of implementation agencies to replicate the technologies so as to provide benefits to the poor rural households. Informants thus included personnel from relevant organisations, both at the central and field-level, such as BSP-Nepal, relevant government departments, donor agencies, biogas plant construction companies, relevant financial institutions and I/NGOs, who had a good understanding about and experiences in the biogas sector. The selection of the interviewees was guided by the researcher's prior knowledge about the organisations and in consultation with the BSP-Nepal. The researcher arranged the dates for the interviews, and the appointments were made by telephone, email or through a personal visit. The relevant organisations and the number of key informants interviewed from each organisation are listed in Annex 6.

The key informants were first informed about the research project, including a short outline of introduction, the research aims and objectives, research ethical issues and fieldwork processes, and their agreement obtained to give interviews for this study. The researcher facilitated these interviews using a semi-structured checklist as a guideline. Separate sets of checklists were prepared for central-level and field-level organisations and other renewable energy system installation companies (Annex 7). However, the order and mode of asking the questions was varied for each informant, depending on their organisation and position. At the end of each interview, a brief summary of the interview was presented in order to ensure that the views of the interviewee were accurately recorded. The interviews were conducted over the period of the fieldwork. The list of key informants interviewed is presented in Annex 8**.**

4.8.3 Observations

Another important qualitative data collection method applied to this study was direct field observations. Schutt (2006) and Lindsay (1997) have described field observations as more natural than interviews to understand people's behaviour and the process. This method can be useful for a holistic interpretation of the situation under study when combined with interviews and document analysis (Sharan B. Merriam, 1998). In this study, an unstructured observation method was used to observe and record information without predetermined observation schedules or checklists (O'Leary, 2004).

Although no structured template or checklist was used to record field observations, detailed notes about the relevant activities were taken. The observation technique provided an opportunity to observe the activities reported during household surveys, such as size/weight of fuelwood (generally expressed in terms of backload equivalent to 30 kg), energy use (e.g., biogas, fuelwood, LPG) and cooking practices, types and quantity of animal dung and agricultural residues available and used, biogas digester feeding processes/practices and activities from utilisation of saved time after use of biogas (Figure 4.7 a). Information from these observations supplemented the data collected in the household surveys, and was also used to triangulate findings from the interviews and document reviews.

Figure 4.7: (a) Field observation (b) Informal discussion with local women

4.8.4 Informal discussions

Informal discussion is another important tool for data collection in social research (O'Leary, 2004). Informal discussion, which is often unstructured, is a casual form of data collection that relies on the social interaction between the researcher and informants to dig out information (Minichiello, Aroni, Timewell, & Alexander, 1990). Punch (2005) has described informal discussion as a part of the ongoing fieldwork observation to understand people’s social realities. In this study, informal discussions were held with the biogas plant construction field technicians, local social-political leaders, environment-focused local NGO representatives, and both biogas and non-biogas households to understand their impressions of biogas technology, and the problems and constraints of biogas installation and operation in rural households. A 'conversation with purpose' approach was used in the discussions (Figure 4.7 b). Such discussions provided the researcher with an opportunity to interact with non-biogas households (not otherwise included in this study), in order to understand why the farmers were not interested in constructing biogas plants. These discussions also helped identify what problems biogas households were facing in getting the full benefit from this technology. Such discussions also helped to understand the relationship between the biogas users and the service providers (biogas companies) if the users were happy with the services provided by the companies.

The researcher also attended a national-level seminar and a discussion programme[28] on the role of renewable energy in the current energy crisis in Nepal. This gave her a clear insight about the energy status at the local and national level, and the future strategies including the potential role of the biogas sector. The expressions and views of the participants during such discussions were recorded as field notes in their own words and were verified with them at the end of the discussions. Information from such informal discussions also contributed to the research findings.

4.8.5 Document analysis

Interviews alone were not sufficient to provide the necessary information to explain the organisational processes and performances of biogas technology development. Documents can also provide useful information. O'Leary (2004) refers to document analysis as a primary source of research data that involves the collection, review, interrogation and analysis of various forms of texts. This method is relatively inexpensive, and is a good source of background information that may bring up issues not noted by other means (CDC, 2009). In this research, policy documents relevant to biogas development in Nepal provided useful information on current policies and strategies for the development and replication of biogas technology to provide benefits to the poor through rural energy security. The major policy documents reviewed, but not limited to, were: *Three Year Plan (2011-2013); The Perspective Energy Plan (1991–2017); Renewable Energy Perspective Plan (2002-2020); Rural Energy Policy, 2006; Policy for Renewable (Rural) Energy, 2009; Subsidy Policy for Renewable*

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[28] The program was organised by the AEPC from 20-26 January 2013 in Kathmandu. The main objectives of the program were to **create awareness among the general public about RETs as effective energy alternatives in order to address the energy crisis existed in Nepal, and sensitise policy-makers for improvement in the energy policies, and encourage private sectors to invest in the renewable energy sector. Personnel from renewable energy-related government agencies and NGOs and the general public participated in the program.**

Energy, 2012; Biogas Credit Fund Operating Guidelines, 2011. Documents collected from BSP-Nepal, relevant government and donor agencies, and NGOs provided useful preliminary information for understanding their roles and performances, and opportunities and constraints in implementing a successful biogas programme.

4.9 Data Analysis and Interpretation

An effective data analysis process involves managing the raw data, systematically coding and entering the data, engaging in the process of quantitative and qualitative analysis, interpreting meaning, and drawing relevant and logical conclusions, while keeping a focus on the research questions, aims and objectives (O'Leary, 2004, 2013). The purpose of coding in quantitative data analysis is to organise the data by reducing it into a measurable form of variables and categories using numbers that are understandable by computer programmes (Bourque, 2004; Richards, 2014). The process of data analysis should move between the data and the research question, aims and objectives and theoretical underpinnings to make it critical, reflexive and iterative (Kumar, 2011; Neuman, 2006; O'Leary, 2004). In the mixed method approach it is often emphasised to use the QDA approach where qualitative data are numerically coded first and then supported by statistical analysis (Jason & Glenwik, 2012). Such a technique is emerging because data from each method are analysed in their own tradition, but the results from each are brought together during interpretations of the overall findings (Onweugbujie & Combs, 2010).

In this study, both quantitative and qualitative methods were used to analyse the data. After the completion of the household survey and interviews, all the data were checked to ensure that they were legible and complete. The survey answers were then coded numerically and entered systematically into a spreadsheet. A schematic diagram of the overall project analysis is presented in Figure 4.8**.** The analytical approaches employed in this study are described in the following section.

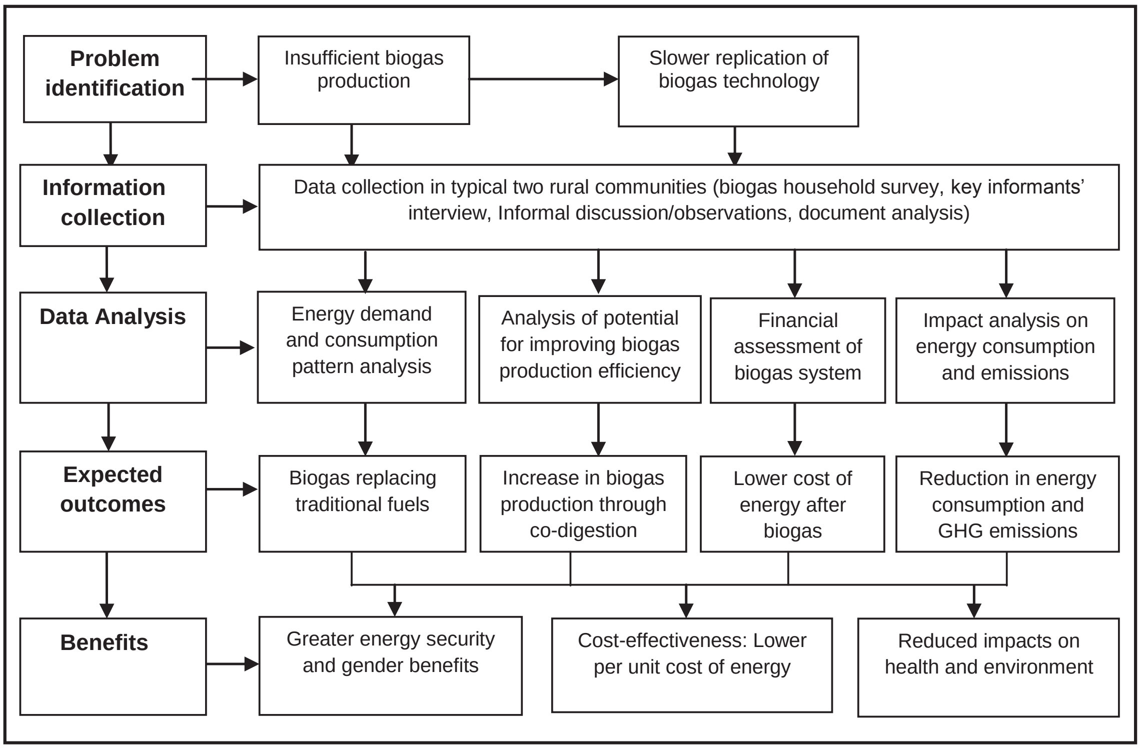

Figure 4.8: A schematic diagram of overall project analysis

4.9.1 Quantitative data analysis

Quantitative data analysis includes the use of a computer program, software and models which consume skill, time and cost. Hence, before the start of quantitative data analysis, the researcher should revisit the hypothesis, research questions, aims and objectives to assess precision, predictivity and to be aware of how much effect will occur if any methodological shortcomings appear (O'Leary, 2013). The researcher is like an instrument for data collection and analysis, hence the quality of the result depends on the researcher's data management performance, understanding of variables and an appropriate use of statistical tests (O'Leary, 2013). However, results should be presented in a systematic and logical fashion so that the research questions could be addressed consistently and increase the reader's understanding.

The quantitative data analysis approach in this study involved: (i) analysis of household characteristics and energy use patterns; (ii) assessment of the potential for improving biogas production efficiency; (iii) financial assessment of biogas systems; and (iv) impact analysis on energy consumption and corresponding environmental emissions.

Household characteristics and energy use pattern analysis

Descriptive statistics were used to analyse the characteristics of the surveyed households. This included the socio-economic characteristics of the households in terms of existing practices of biogas production and utilisation, such as energy use practices, size and age of biogas plants installed, use of biogas, feedstock availability, and reduction in women's workload. Basic statistical tools, such as frequency distribution, mean, standard deviation and range were used to analyse the data. A comprehensive analysis of household energy consumption patterns for cooking before the use of biogas, and changes in the consumption and quantity of fuels after the use of biogas, were also analysed in order to examine the role of biogas in replacing conventional fuel sources. Analysing the changes in energy use patterns after the use of biogas is important for measuring the potential and real benefits from biogas systems. The data was analysed using the Microsoft Excel and Statistical Package for Social Sciences (SPSS), and the results were summarised and presented descriptively using tables or charts. Such analysis was also used to interpret the results of the quantitative outcomes.

In order to identify the daily biogas deficit, and examine how the users coped with lower gas production, the demand and consumption patterns of biogas were analysed both for the summer and winter seasons. Although it was difficult to measure the actual daily biogas demand, the average daily biogas demand was measured by multiplying gas consumption rate of the stove (R) with average daily required operating time (T) (Equation 4.1) (Werner, Stöhr, & Hees, 1989). It is assumed that the stoves were used at their full capacity (based on the respondents' responses), and the gas consumption rate of the standard biogas stove at full capacity is $0.4m^3$/hour (BSP-Nepal, 2012). The actual daily biogas consumption was calculated by multiplying the gas consumption rate of the appliances (R) with the daily actual operating time (t) (Equation 4.2). The average daily biogas demand and consumption was recorded for major uses of biogas[29], e.g., cooking two meals, breakfast and snacks, based on the respondents' daily practice. The responses were also verified by the researcher herself in a few households during observation/informal discussion. The difference between the demand and consumption gives the biogas deficit (Equation 4.3). The use of other energy sources to cope with the biogas deficit was then analysed.

Average daily biogas demand (D) = $R_1T_1 + R_2T_2 + \ldots\ldots\ldots + R_nT_n$ (Equation 4.1)

Actual daily biogas consumption (C) = $R_1t_1 + R_2t_2 + \ldots\ldots\ldots + R_nt_n$ (Equation 4.2)

Daily biogas deficit = $D - C$ (Equation 4.3)

(Biogas is surplus, if $C > D$)

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[29] None of the surveyed households used biogas for lighting, hence the use of biogas for lighting is not considered here.

where,

$R_1, R_2, \ldots, R_n$ are the consumption rate of the appliances 1, 2, …., n;

$T_1, T_2, \ldots, T_n$ are the required operating time of the appliances; and

$t_1, t_2, \ldots, t_n$ are the actual operating time of the appliances.

Measuring biogas production efficiency

In order to evaluate the performance of the biogas plants under study, the efficiency of the biogas plants was calculated. The efficiency of a biogas plant is defined as the ratio of output to input, where feedstock added to the digester is considered as input and gas produced from anaerobic digestion is the output (Equation 4.4) (Ghimire, 2005; Postel, Schumacher, & Liebetrau, 2012). The efficiency was calculated in terms of theoretical biogas production based on: (i) plant size (feeding of prescribed quantity of feedstock); and (ii) actual daily feeding. It was considered for this calculation that one kg of dung produces 40 litres (0.04 m^3) of biogas (BSP-Nepal, 2012; Ghimire, 2005; Werner, et al., 1989). The actual biogas output was calculated based on the gas being used per day, considering that a biogas stove burn in full capacity consumes 400 litres (0.4 m^3) of gas per hour[30] (BSP-Nepal, 2012).

$$\text{Efficiency (\%)} = \frac{\text{Actual biogas production (output)}}{\text{Theoretical gas production based on feedstock input}} \times 100 \qquad \text{(Equation 4.4)}$$

In order to assess the potential for improving the biogas production efficiency, this study considered co-digestion of agricultural residues with animal dung as a way to enhance biogas yield and supplement feedstock deficit experienced in the biogas households. Biogas production from manure-only digestion as practised in Nepal has a relatively low gas yield (IEA Bioenergy, 2005) and was not sufficient to meet the energy demand for cooking. The possibility of using other organic wastes, such as agricultural residues as co-substrate, could improve biogas production efficiency and provide a viable option fulfilling the energy demand (Jingura & Matengaifa, 2009; Lungkhimba, et al., 2011). The literature suggests that co-digestion can increase biogas yield by 50-200% more than single feedstock digestion, depending on the operating condition and co-substrate used (Alvarez, et al., 2010; Amon et al., 2006) by providing an opportunity to optimise biogas production by improving nutrient balance from a variety of substrates (e.g., Alvarez, Mace, & Llabres, 2000; Jingura & Matengaifa, 2009; Poschl, et al., 2010; Rao & Braral, 2011). In this study, three different methods of methane yield prediction, namely, (a) elemental composition analysis; (b) chemical oxygen

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[30] GGC 2047 biogas stove is designed to consume 400 litres of gas per hour (BSP-Nepal, 2012).

demand (COD) stabilisation; and (c) organic composition analysis were used to estimate biogas yields from individual feedstocks (dung, crop residues and human excreta) and different proportions of co-digestion mixtures as co-substrates (Hansen, 2005; Labatut & Scott, 2008; Shanmugan & Horan, 2009; Tchobanoglous, Burton, & Stensel, 2003). The yields were then compared to estimated increases in biogas production as a result of co-digestion. VMP was calculated to predict how much methane could be produced per day. The methods are described in detail in Chapter 6.

Financial assessment of biogas system

Co-digestion of crop residues to supplement feedstock deficit and improve biogas production efficiency might incur additional cost. Therefore, a financial assessment of a biogas system was conducted in order to ensure that biogas production is a viable and affordable option, even after the co-digestion, in terms of total annual cost of energy compared to the cost before biogas or without co-digestion. The basic underlying assumption of financial assessment is that households will adopt co-digestion practices if it is cost-effective and at the same time reduces the demand for unsustainable (e.g., fuelwood) and expensive (e.g., LPG) energy sources. The analysis looked at what was the total annual cost of energy before the installation of biogas plants, total existing annual cost of energy after the use of biogas, and the expected total cost of energy after co-digestion of crop residues with dung.

In this study, all the costs were valued from the user’s point of view, because the costs depend upon the use of inputs and outputs by a particular user. The evaluation was carried out assuming that all capital costs for the systems were expended in the first year, while the operation and maintenance costs were constant over the life of the system. The results of the assessment are presented in Chapter 7.

Impact of biogas on energy consumption and associated emissions

In order to ensure that biogas is a cheap, efficient and adequate source of renewable energy to provide energy security for rural households in Nepal, it is important to look at the impact of biogas use on energy demand and its environmental dimensions. A comprehensive analysis was made of the potential of biogas to reduce energy demand and environmental emissions using the LEAP model under different technical and policy scenarios. LEAP, a widely-used modelling tool for the study of integrated energy policy analysis and climate change mitigation assessment, was selected as the most suitable model for this study from among the existing similar models (see Chapter 8). Four different scenarios were generated based on energy use information and related policy conditions such as biogas and subsidy policy: reference or business-as-usual, improved production efficiency, increased subsidy, and integrated scenario (with cumulative effect of improved biogas production and increased subsidy scenarios) to examine how much conventional fuels, particularly fuelwood and corresponding emissions, could be reduced under different scenarios. The analysis was also focused on the potential of biogas to reduce non-energy emissions and save social costs, including externality costs and carbon credit earning. Details of policy options/conditions and various assumptions for the scenario generation and the empirical results of the LEAP model are described in Chapter 8.

4.9.2 Qualitative data analysis to support quantitatve findings

Schutt (2012) has described QDA as one of the methods to analyse textual/descriptive data/information, which helps researchers to generate linkages between concepts and experiences described in the data and check whether the concepts and interpretations are reflected in the process. Dey (1993) has defined it as an iterative process of describing, classifying and inter-connecting data. It involves interaction between the original data and its conceptualisation, abstraction and interpretation (Spencer, Ritchie, & O'Connor, 2003). According to Patton (2002), qualitative analysis transforms data into findings without any formula. O’Leary (2004, 2013) also defines five steps in QDA as: a) organise raw data; b) enter and code the data; c) search for meaning through data analysis; d) interpret meaning; and e) draw conclusion, where it involves three repeated processes of critically reading, result interpreting and reaching understandings (Dey, 1993). QDA can be done either by applying manual method or by using computer software (Flick, 2015; Gilbert, 2002; O'Leary, 2005, 2013).

The use of quantitative data analysis software (QDAs) may not be appropriate for each and every project; it depends on the nature of the project. ATLAS.ti, MAXQDA, Nvivo and QDA Minor are some commonly used QDAs. QDAa may be used more for a narrative approach, while segregating the data into themes and patterns. Sometimes coding and manipulating the segregated data would be dangerous if it loses sight of the context. The use of QDAs makes the analysis faster, accurate and less tedious. However, if the database is not large, and the researcher does not have any plan to re-use that type of software in future, the manual method can be used (Gilbert, 2002; O’Leary, 2013).

In the manual method, traditionally sticky notes are used, a marker etc, to file, cut and manage the data, but the use of computer programs (rather than using software) like

Word and Excel spreadsheets, is an easy method of data management which helps to reduce data volume, retain data records and provide a new view of the data until it is totally understood (Richards, 2014). The manual method involves: a line-by-line examination of all data sources; undertaking a systematic drilling of raw data to build categories of understanding; reducing data volume; setting it into various themes and highlights; and getting engaged with data analysis. A line-by-line exploration of the data source can be done in several ways: by focusing on the keywords and narratives that were used; concepts that were discussed; linguistic devices (like proverbs and quotations) that were expressed by the respondents; and non-verbal cues (like body language) that were observed by the researcher for a meaningful understanding of the context (O'Leary, 2013) that increases data reliability, familiarity and trustworthiness (Glesne, 2016). Coding in qualitative data analysis is a grouping and labeling of data in the process of making it more manageable to display and answer the research questions more effectively. Textual or narrative data, after coding and interpretations, are used for thematic analysis while respondents' quotations and pictures support the result interpretation. Coding can also be done either with or without thematic analysis (Grbich, 2012). However, analysis of the data should fit with research questions, the methodology, sets of data and any theoretical predispositions.

Qualitative data often contains unique information sources like visual, textual or respondents' language cues, which are otherwise not captured in the quantitative study components. The language translation/conversion methods must be sensitive to these issues so that the distinctive perspectives captured through qualitative means are not lost. Hence, the right interpretation can be assured through a member check and/or by using multiple data sources for theoretical triangulations (Jason & Glenwick, 2012).

The QDAS was not used in this study because the original field notes were in Nepali and the software has no facility for this language. However, the information collected from the key informant interviews, observations and informal discussions were analysed using the manual QDA technique. During this process some information were coded by using spreadsheet, some were presented in narrative descriptions, while some were put *as it is* in their quotation, but all process was done to support quantitative data analysis and findings. For example, the information about the reasons behind lower biogas production was used for statistical descriptive analysis, the impact of subsidy policy in biogas production rate was used to assess the GHG emission rate in different scenarios and benefits of biogas to reduce women's hardship and hunger is presented as it is in their own words. For this, the first step was for the researcher to thoroughly read the field notes and make brief notes or comments in the margin about the key patterns, themes and issues in the data while staying focused on research questions and objectives. The researcher read and re-read the data in-depth for a better understanding of the data. The meanings and connections between the themes were established, which were then linked to the survey findings.

Translation of the Nepali words from the field notes into English, and maintaining the original meanings and the integrity of each respondent's responses in the translation might be a challenge (Temple & Young, 2004), but it was addressed carefully. The researcher's position was from the similar Nepali community with a Nepali mother tongue. Also, the technical support staff from BSP-Nepal helped during the member check process. Some level of interpretation based on the researcher's understanding was also involved in the translation in order to maintain the original meanings in the translation. The data analysis was focused not only on what the respondents said, but also the way and context in which it was said. Hence, the researcher went through the original field notes (in Nepali), then the translated notes in order to capture the local context for a better understanding and interpretation of what they really meant.

4.10 Quality of the Research

Conducting research is a highly complex process; indicators for good research could ensure the quality of the research. O'Leary (2004) and S.B Merriam (2002) suggested some strategies for promoting data validity and reliability: a) triangulation for internal validity; b) member check; c) reflexivity; d) adequate engagement in data collection and analysis; d) rich and thick description to contextualise the study; and e) address any ethical issues for external validity or generalisation. This study followed those strategies in all research process from research design and data collection to data analysis and result reflection process, which is described below, to maintain the quality of this research.

In research design**,** the data collection techniques and processes, and analytical models and methods, were described in detail. In this research, data collection methods were developed conscientiously, and were flexible to the field situations. For example, a mixed method approach of data collection was designed and used during fieldwork. Another important indicator for good research is dependability, which refers to the consistent, logical, systematic, well-documented methodological protocols that are designed to account for research subjectivities (O'Leary, 2004, 2013). Such a systematic and well-designed methodological approach helped to minimise any subjectivities, and the pre-understanding of the research area on the part of the researcher to ensure the quality of the research (Grbich, 2012; O'Reilly & Kiyimba, 2015).

During sampling design, the research area and participants should be selected appropriately so that the response rate could be high, positive and consistent. During the standardised survey, the limitation may occur when respondent answers are out of anticipation; subjective data is out of range, and there are problems in communication, language expression, translation and data verification (Flick, 2015). So flexibility is also important in social research (Collins, et al., 2006), but without any effect on data compatibility (Flick, 2015). Similarly, a pre-structured mindset may influence the researcher to be less focused on important issues, in particular context during observation. Document review and use of secondary database should be done carefully so that the content fits within the research aims and objectives. Finally, at the end of data collection process, the researcher, as an interviewer, should re-check the data accuracy by sharing/repeating the brief outcome with the interviewee, which is also called 'member check' (Glesne, 2016). This may take extra time, but it is a good strategy to increase confidence about data validity and reliability (S.B. Merriam, 2002).

The team members from different backgrounds who have competencies to enable communication can support the researcher to make an interview environment more comfortable in case of the particular socio-cultural settings of the sample community (O'Reilly & Kiyimba, 2015). This is because communication is important for the data interpretation and in terms of how the audience will engage with the text. However, personal influences and any intentional/unintentional biases should be avoided, and ethical aspects should be considered carefully, hence neutrality is important (O'Leary, 2013).

In this study, the response rate from the sampled household was very good. None of the sampled households declined to be interviewed, although few households were not available to be interviewed at the first visit, so they were visited two to three times to complete the survey. However, 8 households in Lamjung and 20 households in Chitwan district were replaced by the households from the additional list, because they had either migrated from that location or the biogas plants were no longer in operation in those households.

The researcher had sought support from BSP-Nepal during the data collection process from the planning and preparation phase to the data collection phase. BSP-Nepal was chosen as a first point of contact to get support from to undertake the field work in Nepal. BSP-Nepal helped the researcher provide a biogas household database that was used as a sampling frame for selecting respondent households for the survey. Its suggestions and support on how the fieldwork could be better organised was important for the successful implementation of data collection work. BSP-Nepal also coordinated and communicated with the district-based biogas companies and relevant organisations to provide support during the fieldwork. Since BSP-Nepal appreciated the research proposal as a relevant and necessary work for the development of biogas sector in Nepal and the organisation was not involved in data collection, there was no possibility of potential bias or conflict of interest. There was no influence of BSP-Nepal on the way the data was extracted or the content of the data collected, because all the respondents were selected randomly from a list of biogas households prior to the Nepal visit, and all data collection (both quantitative and qualitative) was carried out by the researcher herself. Except from their coordination and supportive role, BSP-Nepal's involvement in the research was as the respondents during the key informant interviews. The data collected was further triangulated, cross-checked and verified with government agencies, biogas companies, relevant local NGOs and user households during the formal and informal discussions and key informant interviews in order to enhance the validity of the data and avoid any bias.

In this study, the raw data were in the form of survey questionnaires' answers and field notes, and attempts were made to record the exact words of the respondents, which were confirmed by presenting a brief summary of the interview towards the end of the survey. In this study, the findings and conclusions were not influenced by the researcher's emotions, personal prejudice or subjectivities. The research fairly represented the perspectives of different people of the community in the findings. The researcher's position as a Nepali female from a similar community, who has an in-depth understanding of the socio-economic-cultural context of the area, also had positive influences on ensuring the quality of the research. The researcher's understanding of the respondents' language and awareness about their customs and traditions helped to build trust with the respondents and made a conducive environment for communication, providing insights that could be reflected in the translation and interpretation of data. The respondents' feedback obtained at the end of the interviews/discussions also contributed to maximise the accuracy of the data recorded. Sufficient time was also spent in the field to obtain a detailed understanding of the research context and collection of data.

Moreover, a systematic, rigorous and comprehensive data analysis was carried out using simple and effective analytical methods to come to credible conclusions. The data/information were read again and again and understood comprehensively, and interpreted using the respondents' quotations as evidence. The researcher had discussed the data with supervisors and colleagues and went through a series of questioning, clarifying and discussing, which helped minimise the researcher's bias while interpreting the data and losing the reflection of context while translating the data into English (Bajracharya, 2008). This further helped in ensuring the data accuracy for data analysis.

Neutrality is one of the indicators for good research, which refers to the issues of subjectivity to keep findings and conclusions free from bias. A researcher's subjective positioning in relation to his/her research topic or objectives makes objectivity problematic and sometimes unachievable. A good research thus requires the researcher to reflect on his/her own subjective and personal positioning in the research process to avoid biases in conclusions (O'Leary, 2004, 2013) without any negative influences (Flick, 2015). Validity and authenticity are another set of indicators linked to capturing the truth and generalising the findings (S.B Merriam, 2002; O'Leary, 2004). Validity relates from the research methods to the findings and conclusions. Internal validity is related to the validity of the measurement itself through triangulation, while external validity indicates the ability to generalise the findings of the research (O'Leary, 2013; Punch, 2005). Likewise, the indicator of authenticity is concerned with the potential for multiple and alternate realities. In research, there should be links between the conceptual framework, research questions, and findings, and rigour and reflexive practices are necessary to assure that conclusions are justified, credible and trustworthy (O'Leary, 2004).

In order to provide better evidence to explain the data, a combination of different types of data collection methods and set of data sources were employed in this study, which also drew evidence for findings and conclusions. These multiple sources of evidence were also used to triangulate data collected from different methods. The researcher made the methods employed in the study transparent to the stakeholders, which increased the accountability of the researcher as described by various scholars (Gray, 2009; Kumar, 2011; Schutt, 2012) and contributed to the quality of the research.

Transferability can be another useful indicator for research where generalising the significance of findings to larger population or within other contexts is applicable. It highlights that researchers have provided a detailed description of the research context and methods in order to made the lesson learned applicable in alternative settings or across populations (O'Leary, 2004, 2013). A detailed description of the research context (Chapter 1, 3 and 5), and data collection and analytical methods (Chapter 4), were provided in this research. Appropriate sampling strategies, ensuring both adequate and broad representation, were employed to ensure generalisation of the findings and the lesson learned across populations. Findings from the data analysis were discussed in relation to the existing body of literature to determine to what degree the findings were applicable across populations or in alternative settings (Chapter 9). The researcher had the opportunity to present the preliminary findings of this research to the scientific community[31], which provided a forum to discuss and evaluate them from a large number of perspectives. This strengthened the researcher's confidence in her research findings, and motivated her to go back to the data in order to integrate the diverse views, adding to the quality of the research (Hycne, 1999; Jason & Glenwick, 2012). The researcher also presented the study's final conclusions in international conferences[32] and achieved a broader vision and networking with the relevant communities that will be helpful to appropriately apply and disseminate the findings in the days to come.

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[31] a) The New Zealand Climate Change Conference 2013, 4-5 June 2013, Palmerston North; b) Massey University Three Minutes Thesis Presentation, 16 August 2013; c) Postgraduate PhD Pecha – Kucha Talk, 6 June 2014, Massey University, Palmerston North; d) IEEE Postgraduate Presentations, 18 September 2014, Victoria University of Wellington; e) Annual Doctoral Students' Symposium 2014, 28-29 October 2014, PSA, Massey University, Palmerston North.; f) IEEE Postgraduate Presentations, 20 October, 2015, Massey University, Palmerston North; and g) Appropriate Technology Workshop 2015, Massey University , Palmerston North.

[32] a) Bioenergy Australia Conference, 2015 (Nov 30 - Dec 2), Launceston, Tasmania, Australia; b) Tenth International Conference on Sensing Technology (ICST, 2015), (Dec 8-10) , Auckland, New Zealand

CHAPTER FIVE

SOCIO-ECONOMIC IMPACTS OF BIOGAS AND CHANGES IN ENERGY USE PATTERNS

5.1 Introduction

In this chapter, the findings of the descriptive statistics are discussed. Descriptive statistics were used to analyse the characteristics of the surveyed households and household energy use patterns. A description of socio-economic characteristics of biogas user households is reported first. Information on installation and operation of biogas plants and feedstock availability in the households are then reported. It then analyses the impacts of biogas systems on time allocation and workload reduction of household members, followed by the analysis of changes in household energy use patterns after the use of biogas. Finally, this chapter concludes with the analysis of existing biogas demand and consumption to identify the daily biogas deficit and examine how the users cope with lower gas production.

5.2 Socio-Economic Characteristics of Biogas User Households

A biogas user household has been taken as the unit of data collection and analysis. A brief description of the characteristics of these households can be helpful to understand socio-economic conditions of biogas users, and to explain how these characteristics influence the production and use of biogas.

5.2.1 Caste group distribution

Ethnic distribution of households using biogas as an alternative source of energy is helpful to assess the affordability and access of different caste groups to biogas technology. The respondents were categorised into three broad caste groups as recognised by the Government of Nepal: the high castes including *Brahmins*, *Chhetries* and *Thakuris;* the *Janajatis* including forty-five ethnic groups; and the lower castes, or *Dalits,* including Kami, Damai, Sarki; and other ethnic groups who suffer most through discrimination based on this hierarchical Hindu caste system (CBS, 2011a). According to the Nepal Living Standards Survey 2010/2011, Dalits have the highest poverty level and smallest landholdings among the ethnic groups (CBS, 2011b).

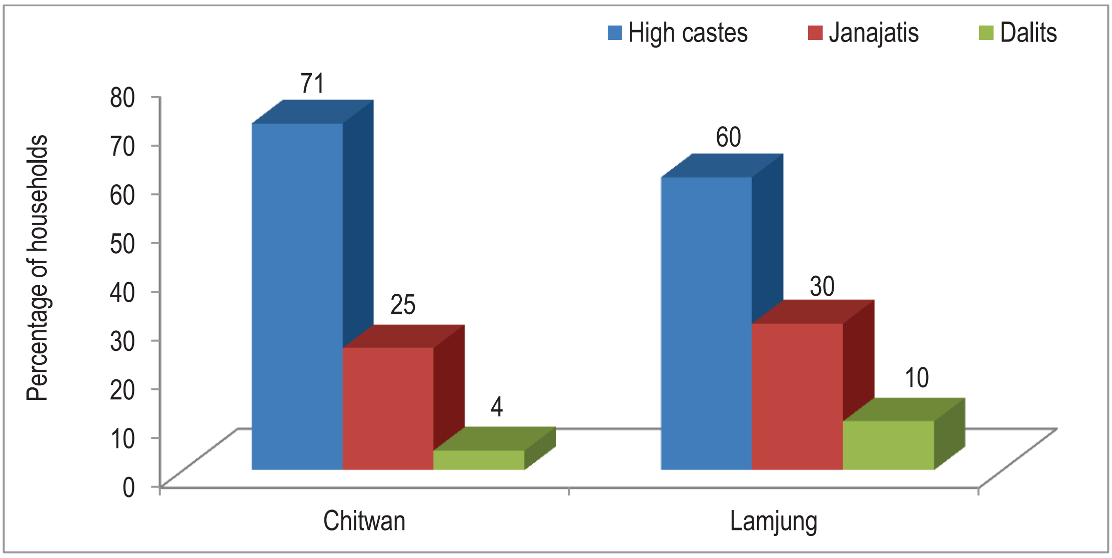

Figure 5.1: Distribution of households by caste groups

Source: Field Survey 2012

The majority of the biogas households (65%) under study were from the high castes, followed by Janajatis (28%) and Dalits (7%) (Figure 5.1). Although the proportion of higher caste households was slightly higher in Chitwan district (71%) than in Lamjung district (60%), and the number of Janajati (30%) and Dalit (10%) households were higher in Lamjung district, the differences were not statistically significant at the 5% level (Chi-square 6.36 at 2 d.f., p-value 0.42). This result could not be compared with national data, since district level information on caste group distribution is not published in the census reports. This finding indicated that, in terms of absolute numbers, Dalits and Janajatis, who are generally poor, have less access to biogas technology compared with higher caste households. Proportions within each caste could not however be compared, again because the relevant districts' data is not available.

5.2.2 Family size

The family size of the respondent households ranged between 1-11 members with an overall average family size of 5.01, which is slightly higher than the national average of 4.88 (CBS, 2012a). The average family size of the surveyed households in Chitwan district was 5.4, higher than both the national average and the district average of 4.38. Similarly, the average family size in Lamjung district was 4.6, lower than the national average, but higher than the district average of 3.99 (CBS, 2012a).

The highest proportion of households in both the districts had a family size of five members, followed by a family size of four and six (Table 5.1). Only seven households in Chitwan and six households in Lamjung had a family size of more than eight members. One household in Chitwan and three households in Lamjung reported only one family member. The link between family size and biogas operation is described later in Section 5.3.1.

In terms of ethnic groups, a higher number of households in all the caste groups had a family size between four to six (Table 5.1). None of the Dalits in Chitwan and Janajatis in Lamjung had more than eight members. Although there was a statistically significant difference at 5% level in the family size between the two districts (Chi-square 22.22 at 8 d.f., p-value 0.0045), with Lamjung tending to have smaller households than households with biogas, there was no significant difference of the family size for different caste groups within either district.

Table 5.1: District-wise distribution of family size by caste groups

(Unit: No. of households)

Caste groups	Family size									Total
	1	2	3	4	5	6	7	8	>8	
Chitwan										
High castes	1 (1)	5 (4.5)	6 (5)	19 (17)	32 (29)	25(22)	8 (7)	11(10)	5 (4.5)	112(100)
Janajatis	0	1 (3)	3 (7)	12 (31)	8 (21)	5 (13)	6 (15)	2 (5)	2 (5)	39 (100)
Dalits	0	0	0	1 (17)	2 (34)	1 (17)	1 (17)	1 (17)	0	6 (100)
Total	*1(0.6)*	*6 (4)*	*9 (6)*	*32 (20)*	*42 (26)*	*31(20)*	*15(10)*	*14 (9)*	*7 (4.4)*	*157(100)*
Lamjung										
High castes	3 (3)	9 (10)	17(18)	17 (18)	23 (25)	17(18)	2 (2)	1 (1)	5 (5)	94(100)
Janajatis	0	6 (12)	7(15)	12 (25)	8 (17)	8 (17)	4 (8)	3 (6)	0	48 (100)
Dalits	0	0	3(20)	4 (26)	5 (33)	0	1 (7)	1 (7)	1 (7)	15 (100)
Total	*3 (2)*	*15(10)*	*27(17)*	*33 (21)*	*36 (23)*	*25(16)*	*7 (4)*	*5 (3)*	*6 (4)*	*157(100)*

Note: Chi-square values: Chitwan – 10.28 (16 df), p-value = 0.85; Lamjung – 18.41 (16 df), p-value = 0.30.
Figures in parenthesis are row percentages.

Source: Field Survey, 2012

A Chi-square test at a 5% significance level was employed to compare the survey data with the Nepal Census 2011 data (Table 5.2). The test showed statistically significant difference between the survey data and census data, with households with biogas tending to be larger than the other households in both the districts.

Table 5.2: Comparison of 2011 census data and survey data on family size

Family Size	No. of households			
	Chitwan		Lamjung	
	2011 Census	Survey	2011 Census	Survey
1	6,298 (4.8)	1 (0.6)	3,187 (7.6)	3 (1.9)
2	16,804 (12.7)	6 (3.8)	6,801 (16.2)	15 (9.6)
3	25,496 (19.2)	9 (5.7)	8,538 (20.3)	27 (17.2)
4	31,215 (23.6)	32 (20.4)	8,888 (21.1)	33 (21.0)
5	22,821 (17.2)	42 (26.8)	6,763 (16.1)	36 (22.9)
6	14,371 (10.8)	31 (19.7)	4,238 (10.1)	25 (15.9)
7	6,723 (5.1)	15 (9.6)	1,788 (4.2)	7 (4.5)
8	3,701 (2.8)	14 (8.9)	989 (2.4)	5 (3.2)
> 8	5,033 (3.8)	7 (4.5)	887 (2.1)	6 (3.8)
Chi-squared value	78.067 at 8 d.f., p-value = 1.20E-13		24.232 at 8 d.f., p-value = 0.002	

Note: Chi-square test for comparing survey results with known census proportions.
Figures in parenthesis are percentage of households.

Source: CBS (2012a) and Field Survey (2012).

5.2.3 Occupation

Nepal is predominantly an agrarian country. Agriculture was reported as the main occupation and primary source of income by 92% biogas households under study, and a secondary source of income for the remaining 8% of households (Table 5.3). Slightly higher numbers of households (97%) in Lamjung reported agriculture as the main source of income compared with Chitwan (86%). Agriculture, which mostly includes crop farming and livestock activities, produces food and income for the rural households. About 16% of households reported service and pension as the second major source of income. Money sent home by migrants constituted the third largest financial inflow to the biogas households; at least one member of 9% of households was living outside the country with a cash earning job. More households (16%) generated income from remittances in Lamjung district than in Chitwan district (2%). Similarly, 8% of households in Chitwan and 6% in Lamjung were involved in business, particularly owning retail shops and restaurants. Since households with agriculture as a secondary source of income also installed biogas plants, this indicated that occupation did not have much influence in decisions about installation of biogas plants. The relationship between socio-economic status and size of biogas plant is described later in Section 5.3.2.

Table 5.3: Occupation of the household members

Occupation	Number of households		
	Chitwan	Lamjung	Total
Agriculture	135 (86)	153 (97)	288 (92)
Service/Pension	26 (17)	26 (16)	52 (16)
Remittance	3 (2)	26 (16)	29 (9)
Business	13 (8)	10 (6)	23 (7)

Note: Figures in parenthesis are percentage of households.
Households may have reported more than one occupation.
Source: Field Survey, 2012

In terms of caste groups, above 90% of households within each caste group practised agriculture as the main source of income (Table 5.4). Fourteen percent of households within higher castes (16% in Chitwan and 12% in Lamjung) and 14% of households within Janajatis (11% in Chitwan and 15% in Lamjung) earned income from jobs/pension. Only two *Dalit* households, one household each in both the districts reported their income from the same. *Dalit*s in Nepal have lower access to job opportunities due to their low level of education, poverty and a discriminatory social system against the lower caste people (Section 3.2.5). Poverty and ever-increasing unemployment problems in the country have forced the youths to migrate to overseas in order to earn money for their family living. The proportion of higher castes (7%) earning such remittances was lower than that of Janajatis (10%) and Dalits (24%). However, the Chi-square test at a 5% level of significance shows that there is no significant difference in occupation among different caste groups in either district.

Table 5.4: District-wise distribution of occupation by caste groups

Caste groups	Agriculture	Service/Pension	Business	Remittance	Total	Chi-square
Chitwan District						
High castes	94 (75)	20 (16)	10 (8)	1 (1)	125 (100)	8.94 (6 df), p-value = 0.2
Janajatis	36 (82)	5 (11)	2 (5)	1 (2)	44 (100	
Dalits	5 (62.5)	1 (12.5)	1 (12.5)	1 (12.5)	8 (100)	
Lamjung District						
High castes	94 (73)	15 (11)	6 (5)	14 (11)	129 (100)	2.61 (6 df), p-value= 0.84
Janajatis	44 (68)	19 (15)	3 (5)	8 (12)	65 (100)	
Dalits	15 (71)	1 (5)	1 (5)	4 (19)	21 (100)	

Note: Figures in parenthesis are row percentage of households
Source: Field Survey, 2012

5.2.4 Landholdings

The size of landholding is one of the main indicators of the socio-economic status of a household. The size of landholding is also linked with the number of livestock owned, which in turn influences the decision of biogas plant installation and the capacity of the plant. The average landholding size in the study area was reported to be 0.60 ha per household, with a minimum of 0.017 and maximum of 3.4 ha. This average landholding size is lower than the national average of 0.8 ha (CBS, 2012a). Only 27% of households had landholdings more than the national average. The standard deviation of 0.43 indicates that the gap between the smaller and bigger landholdings is quite large. Eighty percent of households had a small landholding of less than 1 ha (Table 5.5). About 4% of households had very small holdings (< 0.1 ha), while only 4 households had larger landholdings of 2 ha and above. This indicated that where biogas was installed, they were not necessarily installed in comparatively bigger landholding households.

Table 5.5: Landholding pattern of the surveyed households

Landholding size (ha)	No. of households		
	Chitwan	Lamjung	Total
Under 0.1	7 (5)	6 (4)	13 (4)
0.1 and under 0.5	68 (43)	59 (38)	128 (41)
0.5 and under 1	52 (33)	58 (37)	109 (35)
1 and under 2	27 (17)	33 (21)	60 (19)
2 and above	3 (2)	1 (0.6)	4 (1)

Chi square = 2.64 (4 df), p - value = 0.62 (p > 0.05).
Note: Figures in parenthesis are the percentage of households.
Source: Field Survey, 2012

There is a slight but not significant difference in the average landholding size per household between the two districts. The average landholding size of Chitwan district was 0.59 ha per household, whereas that of Lamjung district was 0.61 ha per household. The Chi-square test at a 5% level of significance shows no significant difference in the distribution of landholdings among the biogas households between the two districts (Table 5.5). The number of households with landholdings of 1 ha or above is slightly higher in Lamjung (22%) than that in Chitwan (19%). Only 25% of households in Chitwan and 29% of households in Lamjung owned land more than the national average size, indicating that while on average households with biogas were larger, they had smaller landholdings than the national average.

The majority of the households within each caste group had a landholding size of less than 1 ha (Table 5.6). About 72%, 75% and 81% of higher caste Janajati and *Dalit* households within the caste groups had landholdings less than the national average landholding size, respectively. Overall, higher caste households have a slightly larger landholding size than other caste groups. About 13% of higher caste households had landholdings more than the national average, whereas only 5% of Janajatis and 1% Dalits were above the national average. The difference between castes is not statistically significant in Chitwan but is so in Lamjung. Interestingly, none of the *Dalit*s owned land of more than 2 ha, while the majority of them (76%) had landholdings less than 0.5 ha, which cannot produce enough food for their families year-round. However, a higher number of Dalit households in Lamjung had larger landholdings than those in Chitwan.

Table 5.6: District-wise distribution of landholdings by caste groups

	No. of households						Chi-square
Caste Group	< 0.1 ha	0.1-0.5 ha	0.51-1 ha	1.01- 2 ha	> 2 ha	Total	
Chitwan District							
High castes	5 (4)	49 (44)	37 (33)	19 (17)	2 (2)	112 (100)	5.84 (8 df), p-value = 0.66
Janajatis	1 (3)	15 (38)	15 (38)	7 (18)	1 (3)	39 (100)	
Dalits	1 (17)	4 (66)	0	1 (17)	0	6 (100)	
Total	7 (5)	68 (43)	52 (33)	27 (17)	3 (2)	157 (100)	
Lamjung District							
High caste	2 (2)	31 (33)	37 (39)	23 (25)	1 (1)	94 (100)	17.65 (8 df), p-value=0.024
Janajatis	1 (2)	20 (42)	19 (40)	8 (16)	0	48 (100)	
Dalits	3 (20)	8 (54)	2 (13)	2 (13)	0	15 (100)	
Total	6 (4)	59 (37.4)	58 (37)	33 (21)	1 (0.6)	157 (100)	

Note: Figures in parenthesis are row percentages.

Source: Field Survey, 2012

Chi-square tests were formally employed to examine if there were any significant differences in the landholdings among the caste groups in the two districts (Table 5.6). The test at a 5% level of significance showed that caste groups had a significant influence on landholdings in Lamjung, but did not have significant influence in Chitwan.

5.2.5 Livestock farming

Raising livestock is a major activity that influences biogas use in Nepal. Households in both the districts reported raising one or more types of livestock. On average, each household raised 1.0 cow/bullock, 1.5 buffaloes, 2.6 goats/sheep, 0.1 pig and 20.7 chickens (Table 5.7). There was significant difference at the 5% level (Chi-square 562.7 at 4 d.f., p-value = 0.000) in the number of livestock raised between two districts, with Chitwan having more cows/bullocks and chickens and Lamjung having more buffaloes and goats/sheep.

Table 5.7: Number of livestock raised in the surveyed households

District	Cow/bullock	Buffalo	Goat/sheep	Pig	Chicken
Chitwan	170 (1.1)	214 (1.4)	281 (1.8)	11 (0.1)	4,671 (29.8)
Lamjung	143 (0.9)	245 (1.6)	538 (3.4)	9 (0.1)	1,829 (11.6)
Overall	313 (1.0)	459 (1.5)	819 (2.6)	20 (0.1)	6,500 (20.7)

Note: Figures in parenthesis are average number of livestock.
Chi-square = 562.7 at 4 d.f., p-value = 0.000.

Source: Field Survey, 2012

The livestock raised in the survey households in both the districts were higher than the national average[33] (except for cows/bullocks and pigs), and the district averages (except for pigs and chickens) (Table 5.8) (MoAC, 2012). This indicated that households with biogas tend to keep higher numbers of livestock, particularly cows/bullocks and buffaloes, than the other households in both the districts even though they generally have less land. A Chi-square test at a 5% significance level also resulted in a statistically significant difference of number of livestock between the national data and the surveyed data in both the districts (Table 5.8).

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[33] The national average was 1.3 cows/bullocks, 0.9 buffaloes, 2.4 goats/sheep, 0.2 pigs and 8.3 chickens (MOAC, 2012).

Table 5.8: Comparison of number of livestock raised in Chitwan and Lamjung

Livestock type	Chitwan		Lamjung	
	National data 2011	Survey	National data 2011	Survey
Cow/bullock	90773 (0.7)	170 (1.1)	32267 (0.8)	143 (0.9)
Buffalo	115609 (0.9)	214 (1.4)	58129 (1.4)	245 (1.6)
Goat/sheep	190775 (1.4)	281 (1.8)	111991 (2.7)	538 (3.4)
Pig	9,824 (0.1)	11 (0.1)	6,544 (0.2)	9 (0.1)
Chicken	5,795,688 (43.8)	4,671 (29.7)	173,172 (4.1)	1829 (11.6)
Chi-squared value	343.26 at 4 d.f., p-value = 4.99E-73		496.04 at 4 d.f., p-value = 4.80E-106	

Note: Chi-square test for one more table, comparing survey results with known census proportions.
Figures in parenthesis are average number of livestock.

Source: MoAC (2012) and Field Survey (2012)

Cows/bullocks, buffaloes, goats/sheep and pigs were kept by 54%, 86%, 67% and 4% of households, respectively (Figure 5.2). A total of 51%, 92% and 76% of households in Lamjung and 58%, 80% and 60% of households in Chitwan had kept cows/bullocks, buffaloes and goats/sheet, respectively. Sheep were mostly raised in Lamjung district because the settlements in colder regions are more suitable for raising sheep. Only 19% of households in Chitwan and 21% in Lamjung raised chickens, but a higher standard deviation of 112.7 indicated a larger gap in the number of chickens raised among the households within districts. However, the Chi-square test at a 5% significance level using the data in Figure 5.2 resulted in no significant difference (Chi-square = 4.13 at 4df, p-value = 0.397) in the number of households raising livestock between the two districts.

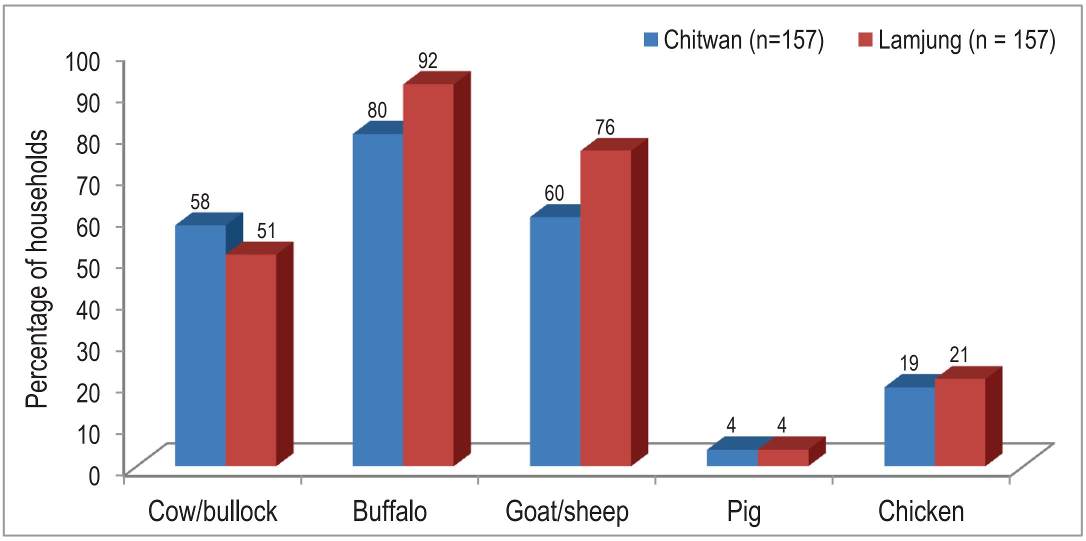

Figure 5.2: Percentage of households raising livestock

Source: Field Survey, 2012

In terms of caste groups, the majority of the households within each caste group raised buffaloes in both the districts, followed by goats/sheep and cows/bullocks (Table 5.9). Pigs were raised only by Dalits and Janajatis in both the districts. Higher caste households did not raise pigs, because a pig is regarded as an untouchable animal to higher caste people.

Table 5.9: Number of households raising livestock by caste groups

Caste Group	Cow/bullock	Buffalo	Goat/sheep	Pig	Chicken
Chitwan					
High castes	67 (60)	88 (79)	62 (55)	0	17 (15)
Janajatis	22 (56)	31 (79)	26 (67)	5 (13)	11 (28)
Dalits	2 (33)	6 (100)	3 (50)	2 (33)	2 (33)
Total	91 (29)	125 (40)	91 (29)	7 (2)	30 (10)
Lamjung					
High castes	46 (49)	87 (93)	74 (79)	0	16 (17)
Janajatis	26 (54)	44 (92)	32 (67)	4 (8)	11 (23)
Dalits	8 (53)	14 (93)	13 (87)	2 (13)	6 (40)
Total	80 (25)	145 (46)	119 (38)	6 (2)	33 (11)

Note: Figures in parenthesis are percentage of households with caste group.

Source: Field Survey, 2012

5.2.6 Distance to forest and market

The average distance to the nearest forests from the households for sourcing fuelwood is 2.6km, with maximum and minimum distances of 13 and 0.1km, respectively (Table 5.10). The average distance to forests is further in Chitwan district (3.5km) than in Lamjung district (1.7km). This shows that significant time was spent on travelling to the forests for fuelwood collection. Similarly, the average distance to the nearest market is 2.5km, with not much difference between the districts. However, this distance is large, particularly in Lamjung district, because farmers had to travel this distance on foot due to the poor transportation services in remote parts of the districts.

Table 5.10: Distance to nearest forests and market

District	Distance to forests (km)			Distance to market (km)		
	Average	Maximum	Minimum	Average	Maximum	Minimum*
Both districts	2.60 (0.18)	13	0.1	2.5 (0.20)	16	0
Chitwan	3.5 (0.22)	13	0.1	2.4 (0.24)	16	0
Lamjung	1.7 (0.07)	4	0.1	2.5 (0.14)	7	0

Note: Figures in parenthesis are standard errors.

* Minimum distance of 0 means few surveyed households were situated within the local market area.

Source: Field Survey, 2012

5.3 Construction and Operation of Biogas Plants

5.3.1 Type and size of biogas plants

All biogas plants sampled for and analysed during the study were the GGC-2047 model plants, a slightly modified fixed-dome design biogas plant adopted from a Chinese model. Only the GGC–2047 design model biogas plants are eligible to receive the subsidy provided by the Government of Nepal under the Biogas Support Programme (Bajgain, 1994; BSP-Nepal, 2012b). Among the 314 biogas plants surveyed, the higher number of plants (61%) were of size 6 m^3, followed by 4 m^3 (20%), 8 m^3 (15.5%) and 10 m^3 (3.5%) (Figure 5.3). Biogas plants of 6 m^3 size were the most popular plants in both the districts. Biogas plants of 8m^3 size were more popular in Chitwan, but 4 m^3 plants were more popular in Lamjung district. Eight of the 11 plants of 10 m^3 were constructed in Chitwan. The Chi-square test at a 5% significance level revealed that there was significant association (Chi-square 33.16 at 3 df, p= 2.9E-07) in the size of the biogas plants installed between the two districts. The size of the biogas plants was reported to be selected by the farmers based on the recommendations from the biogas construction companies, using quantity of feedstock (dung) available, gas requirement for the family and farmer's affordability as the main decision-making criteria.

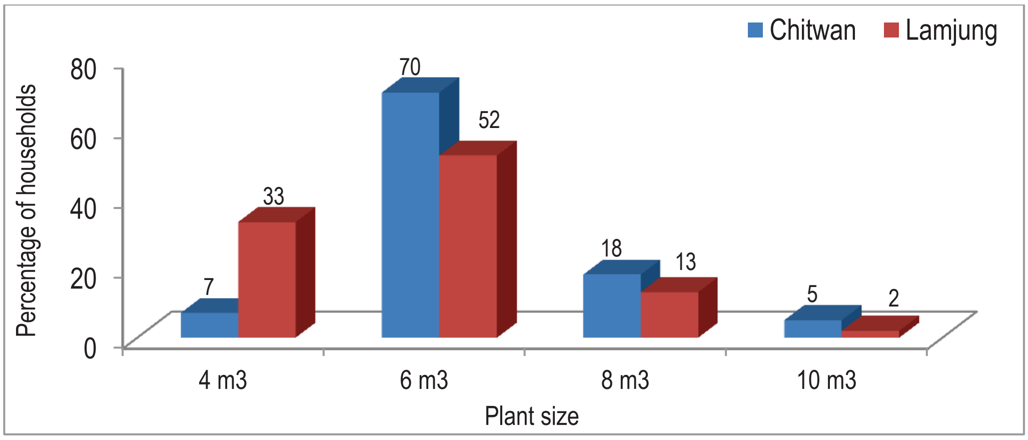

Figure 5.3: Size of biogas plants installed

Source: Field Survey, 2012

As a check on survey representativeness, a Chi-square test at a 5% level of significance was employed to examine if there was any statistically significant difference in the plant size between the surveyed data and the BSP database for the two districts (Table 5.11). The test resulted in no statistically significant difference in the plant size between the surveyed data and the BSP database in both the districts. This indicated that this survey adequately represents the full database of households with respect to biogas plant size in both districts.

Table 5.11: Comparison of biogas plant size

Plant size (m^3)	Chitwan (No. of households)		Lamjung (No. of households)	
	BSP database 2012	Survey	BSP database 2012	Survey
4	867 (7)	11 (7)	2,637 (32)	51 (32)
6	10,740 (71)	110 (70)	4,497 (55)	82 (53)
8	2,479 (16)	28 (18)	866 (11)	21 (13)
10	941 (6)	8 (5)	177 (2)	3 (2)
Chi-squared value	0.97 at 3 d.f., p-value = 0.808		1.42 at 3 d.f., p-value = 0.701	

Note: Figures in parenthesis are percentage of biogas plants.

Source: BSP-Nepal (2012) and Field Survey (2012)

5.3.2 Linkage of plant size with socio-economic variables

The size of the biogas plant was found linked with family size, size of landholdings and number of livestock owned (Table 5.12). Households with 4 m^3 biogas plants had an average family size of 4.3 members and owned an average of 2.2 livestock and 0.43 ha of land. Similarly, households with 6, 8 and 10 m^3 biogas plants had an average family size of 5.1, 5.4 and 5.2 members; kept an average of 2.5, 2.6 and 3.3 livestock; and owned an average of 0.58, 0.79 and 1.01 ha of land, respectively. This indicated that the larger the family size, the larger the size of biogas plant installed. Similarly, households with larger landholdings were found to own more livestock. The number of livestock owned, in turn, largely influenced the decision to install a biogas plant and the size of the plant because of the greater availability of feeding materials for the plant with more livestock owned.

Table 5.12: Linkage of plant size with average family size, livestock and landholding

Plant size	Average family size	Average number of livestock owned[34]		Average landholding size (ha)
		Cow/bullock	Buffalo	
4 m^3	4.3	0.9	1.3	0.43
6 m^3	5.1	1.1	1.4	0.58
8 m^3	5.4	0.8	1.8	0.79
10 m^3	5.2	0.9	2.3	1.01

Source: Field Survey, 2012

Table 5.13 presents the correlation among the five variables presented in Table 5.12. Plant size was highly correlated with the average number of buffalo owned and average landholding size, with coefficients significant at the 5% and 1% level,

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[34] Mostly dung from cows/bullocks and buffalo were used to feed biogas plants.

respectively. This indicates that households with more buffaloes and larger landholdings tend to install bigger size biogas plants. Biogas plant size, however, was not found significantly correlated with family size and average number of cows/bullocks owned, indicating that family size and number of cattle owned might have less influence on users' decisions about the size of the biogas plants.

Table 5.13: Correlation amongst the socio-economic variables

Variables	Plant size	Family size	Cow/bullock	Buffalo	Landholding size
Plant size	1	.802	-.349	.966*	.996**
Family size	.802	1	-.180	.622	.751
Cow/ox	-.349	-.180	1	-.432	-.385
Buffalo	.966*	.622	-.432	1	.984*
Landholding size	.996**	.751	-.385	.984*	1

** Correlation is significant at the 0.01 level (two-tailed).

* Correlation is significant at the 0.05 level (two-tailed).

5.3.3 Age of biogas plants

Construction of biogas plants was started in the surveyed districts from 1994 (BSP-Nepal, 2012). At the time of field survey, the age of biogas plants under study ranged between 2-17 years (Figure 5.4). Overall, 9% of plants were constructed more than 15 years ago (1996 and before) from the time of field survey, and the oldest plants had been in operation since 1995. At the time of survey, 27% of plants were between 11-15 years old, while another 34% of plants were between 6-10 years old. The remaining 25% of plants were relatively new, operating for the last 5 years.

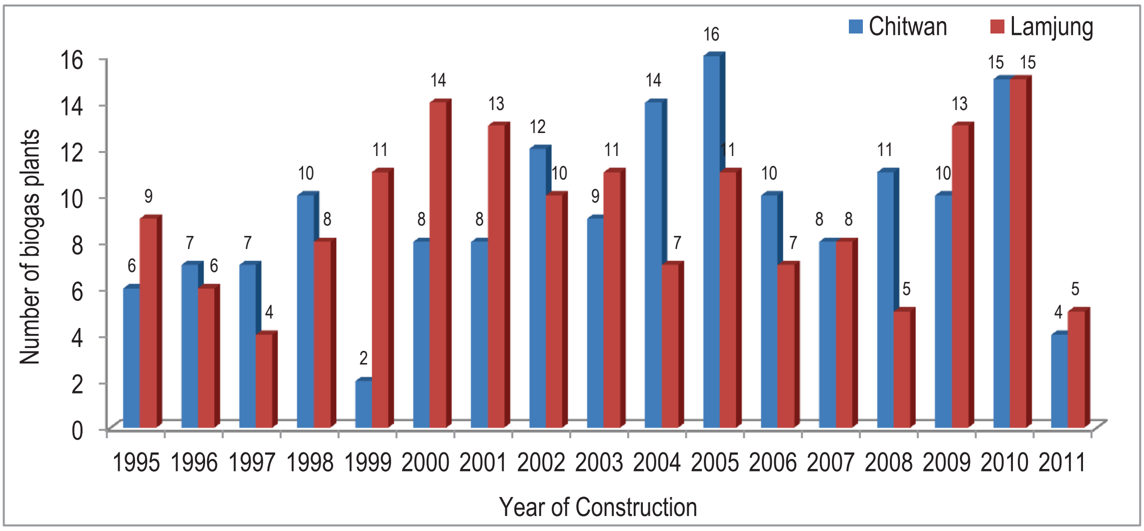

Figure 5.4: Number of biogas plants by year of installation
Source: Field Survey, 2012

In terms of districts, 39% of plants in Chitwan district were 6-10 years old, while another 31% were comparatively new (up to 5 years old) (Figure 5.4). Similarly, 32% plants in Lamjung were between 11-15 years old, whilst 29% of plants were installed in the last 5 years. The Chi-square test result shows that there is no statistically significant difference (Chi-square 4.93 at 3 d.f., p-value = 0.177) in the biogas plants installed in the two districts in terms of their age. However, the test resulted in a statistically significant relationship between the size of the plants and their age in both the districts with larger plants tending to be older (Table 5.14).

Table 5.14: District-wise distribution of biogas plants by plant size and their age

Plant Size	> 15 years	11-15 years	6-10 years	≤ 5 years	Total	Chi-square
Chitwan						
4 m^3	0	2	4	5	11	89.8 (9 df), p-value =1.8E-15
6 m^3	2	15	52	41	110	
8 m^3	5	16	5	2	28	
10 m^3	6	2	0	0	8	
Total	13	35	61	48	157	
Lamjung						
4 m^3	0	4	16	31	51	104.5 (9 df), p-value =1.9E-18
6 m^3	4	33	30	15	82	
8 m^3	8	13	0	0	21	
10 m^3	3	0	0	0	3	
Total	15	50	46	46	157	

Source: Field Survey, 2012

The older plants were bigger in size. The smaller size plants had become more popular in recent years (Table 5.14). All of the 4 m^3 size plants were constructed after 1996, whereas none of the 10 m^3 size plants were constructed after 2002 in both the districts. This indicated that the present demand for biogas is for smaller size plants, mainly because of their low installation costs and less feeding material requirement compared to the bigger plants. Hence, the current subsidy policy should be more focused on favouring smaller size plants, e.g., 4 m^3 and 6 m^3, in order to enhance wider replication of, and provide access to, biogas technology among the households with lower socio-economic status and less land.

5.3.4 Differences in biogas production with the age of the plant

This study attempted to evaluate the difference in production of biogas with age of the plant on the basis of the responses of respective users. The respondents were asked and encouraged to recall[35] whether they experienced any difference in gas production with the age of the plants. The age of plants was found linked with the production of biogas. Users, in general, experienced lower gas production when the biogas plants got older. Lower gas production with age of the plant was reported in 33% of biogas plants (Table 5.15). A higher proportion of biogas plants, and particularly the bigger size plants, in Lamjung (43%) suffered from lower gas production with age. The Chi-square test at a 5% significant level also showed a significant difference in biogas output with plant age between the two districts, mainly because of Chitwan having a warmer climate favourable to biogas production and better fed plants than in Lamjung. Lower gas production with age of the plants was reported in 41% of plants older than 10 years and 37% of plants of 6-10 years old. It is interesting to note, however, that lower gas production was also reported in 19 relatively new biogas plants that were less than 5 years old.

Table 5.15: No. of households experiencing lower gas production with plant age

District	Lower gas production with plant age			Chi-square
	Yes	No	Total	
Chitwan	37 (24)	120 (76)	157 (100)	13.75 at 1 df, p-value = 0.0002
Lamjung	68 (43)	89 (57)	157 (100)	
Total	105 (33)	209 (67)	314 (100)	

Note: Figures in parenthesis are row percentage of biogas plants.

Source: Field Survey, 2012

Users reported that biogas was sufficient for cooking when the plants were new, but biogas output decreased over time with age of the plant, making a biogas deficit. Still the users were not quite sure whether the lower gas production was a result of older plants or other factors were responsible. However, biogas production should not have decreased with the age of a plant, provided the plant had no technical problems (e.g., leakage) and had been fed with the required amount of feedstock regularly (P. Lamichhane, Deputy Director, BSP-Nepal, personal communication, 18 October 2012). One most obvious reasons for the lower gas production with age of the plants as observed in a few biogas households could be the lack of regular prescribed feeding practices for the biogas plants (see Section 5.3.6). When the plants were new, farmers were excited and fed the plants daily with the prescribed amount of dung, but as the plants got older, farmers lost their excitement and were not so careful about prescribed

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[35] The answer from a household was also compared with other household's answers to assure the user's memory that helped to get more accuracy.

feeding of the plants, which resulted in lower gas production. Another reason for lower gas availability could be technical problems, such as gas leakage from pipe or valve. These problems are discussed later in this chapter.

5.3.5 Use of biogas

Biogas is well suited as a source of energy within many areas from cooking, heating to power generation and vehicle fuel. In Nepal it is used only for cooking, space heating and lighting. However, biogas was used only for cooking in the surveyed households. Lighting was not a preferred choice, first because 83% of households had access to electricity for lighting at the time of biogas plant installation. Second, there was insufficient availability of biogas even for cooking. Besides, additional installation costs of the lamps and users' poor impression about the performance of the lamps were reported as other major reasons for not installing the biogas lamp. One household in Lamjung district reported installation of a biogas lamp, but never used it for more than about a week due to its poor performance (i.e., gas mantles were easily worn out with frequent fluctuation of biogas pressure) during the first few days of its use.

All households were using the GGC-2047 stove design approved by the BSP-Nepal as the standard biogas stove (Figure 5.5). The stove has only one burner of size 200mm with burner clearance strictly between 25-30 mm to ensure efficient heating performance of the stove (BSP-Nepal, 2002). Only one stove was installed in 83% of households, while the other 17% of households used two stoves. Although use of two stoves could be convenient for cooking, the additional cost incurred and the need for more biogas were the major factors for not having two stoves.

Figure 5.5: GGC-2047 model biogas stove

Source: BSP-Nepal (2002)

5.3.6 Biogas plant feeding

Feeding materials produced and fed into the digester

The quantity of biogas production depends upon the right amount of feeding material added to the digester daily, provided the plant does not have any technical problems. Livestock dung, human excreta, goat/sheep manure, poultry droppings and kitchen wastes were the major feeding materials produced that were suitable to feed into the biogas digester. The daily dung produced in a biogas household was estimated for each district in which daily fresh dung produced by each livestock type from four households in each districts was collected and weighted during the pre-testing of the questionnaire. The average was then taken as standard and multiplied by the total number of livestock in each category and added to estimate the total quantity of dung produced by a household. The average quantity of dung produced in a day by an adult cow/bullock and buffalo as measured during the field surveys was calculated to be 9.2 and 13.4 kg in Chitwan and 8.1 and 12 kg in Lamjung, respectively. The difference in dung production between the districts was due to the livestock size, feeding practices and climate; Chitwan having comparatively bigger size (hybrid) livestock, fully stall-feeding practices and warm climate.

The overall average feeding materials produced by a biogas household from all the sources was 32 kg/day, with little difference between summer and winter (Table 5.16). On average, only 0.5 kg/day per household was less in winter. The overall average daily production of cow/bullock dung, buffalo dung and other materials (that includes goat/sheep manure, pig manure, poultry droppings, human excreta, animal urine and kitchen wastes) per household was 8.8, 18.7, and 4.5 kg, respectively (Table 5.16). Cow/bullock and buffalo dung was reported to be the main feeding material fed into the digester in both the districts. The average feeding materials produced in Chitwan and Lamjung districts were 32.2 kg and 31.7 kg, respectively (Table 5.16). The average daily quantity of cow/ox dung, buffalo dung and other feedstock produced in Chitwan district was 10.1, 18.2 and 3.9 kg, respectively, while that in Lamjung district was 7.4, 19.3 and 5 kg, respectively (Table 5.16).

Table 5.16: Average quantity of feeding material produced and fed into digester

Plant size	Average feedstock produced daily (kg/household)				Average feedstock fed daily (kg/plant)			
	Cow/ox dung	Buffalo dung	Other#	Total	Cow/ox dung	Buffalo dung	Other#	Total
Chitwan	10.1	18.2	3.9	32.2	9.7	17.5	2.4	29.6
Lamjung	7.4	19.3	5	31.7	6.2	14.7	2.7	23.6
Overall Total	8.8	18.7	4.5	32.0	8.0	16.1	2.5	26.6

Note: There was no difference in the quantity of feedstock produced and fed during summer and winter, except for an additional 0.5 kg/day per household buffalo dung produced in summer.

Other includes goat/sheep manure, poultry droppings, human excreta** and kitchen wastes.

** The weight of human excreta is assumed as 0.40 kg production per adult per day (Karki et al., 2005).

Source: Field Survey, 2012

Interestingly, not all the feeding materials produced by the biogas households were fed into the digester, which had resulted in a higher number of underfed plants. The overall average quantity of feedstock fed into the biogas digester from all sources was 26.6 kg/day per household, which is 83% of the total feeding materials produced (Table 5.16). Thus, the average digester feeding rate was 5 kg/m^3 size against the BSP-Nepal prescribed feeding rate of 6 kg/m^3 size. Although 67% of households raised goats/sheep and 20% of households kept poultry, none of them used goat/sheep manure and poultry droppings as feedstock. Goat manure and poultry droppings were considered as the best source of manure and hence were directly applied to the field. Human excreta were also used to feed biogas plants in 90% of households. In terms of districts, the daily average quantity of feeding materials fed into the digesters was 29.6 kg (92% of total daily available materials) in Chitwan and 23.6 kg (74% of total daily available feeding materials) in Lamjung (Table 5.16).

The households with bigger plants produced higher amounts of daily feedstock (Table 5.17). The average daily feedstock produced in the households with 4 m^3 size plants was 27.4 kg, whereas that in the households with 10 m^3 size plants was 43.8 kg. This, when compared with the daily prescribed feedstock input requirement, shows that only biogas plants of 4 m^3 size had sufficient feedstock produced to meet the daily requirement. However, the average quantity of feedstock fed was lower than the daily prescribed quantity, even in the 4 m^3 size plants. This clearly indicates that all sizes of biogas plants are underfed.

Table 5.17: Average feeding materials produced and fed into the digester

Plant size	Average feedstock produced (kg/household/day)				Average feedstock fed (kg/plant/day)				Daily feedstock requirement (kg)*
	Cow dung	Buffalo dung	Other#	Total	Cow dung	Buffalo dung	Other#	Total	
4 m^3	7.5	16.2	3.7	27.4	6.6	13.3	2.3	22.2 (2.8)	24
6 m^3	9.9	18.1	3.9	31.8	8.7	15.7	2.5	26.9 (0.8)	36
8 m^3	7.0	21.8	5.0	33.8	6.9	19.2	2.9	29.0 (1.8)	48
10 m^3	7.8	30.5	4.4	42.8	6.5	25.7	2.7	34.9 (4.3)	60

Note: Figures in parenthesis are standard errors.

Other includes goat/sheep manure, poultry droppings, human excreta, animal urine and kitchen wastes.

* Prescribed by the BSP-Nepal for the GGC-2047 model plant.

Source: Field Survey, 2012

In order to check if there was any statistically significant difference between the average quantity of feedstock fed and the prescribed quantity of feedstock input requirement, the standard errors (SE) of average quantity of feedstock fed with respect to plant size were estimated and compared with the daily prescribed feedstock requirement. The prescribed daily feedstock requirement for 4 m^3 plants was within the range of average daily feedstock fed ± 2*SE, indicating that there was no statistically significant difference (at 5% level of significance) between the average quantity of feedstock fed into the digester and the prescribed quantity of feedstock input requirement. However, the prescribed daily feedstock requirements for other size plants (6, 8 and 10 m^3) were not within the range of average daily feedstock fed ± 2*SE, which shows that there was statistically significant difference (at 5% level of significance) between the average quantity of feedstock fed into the digester and the prescribed quantity of feedstock input requirement, and more feedstock was needed.

Table 5.18 shows that 26% of households produced no more than 20 kg feeding materials per day, including animal dung (cow/bullock, buffalo), goat/sheep manure, poultry droppings, human excreta and kitchen wastes. More households in Lamjung produced less than 20 kg/day feeding materials per household. Similarly, 29% of households produced feeding materials between 21-30 kg/day per household. More than 50 kg feeding materials/day per household was available in 10% of households in Chitwan and 11% in Lamjung, whereas 15% of households in Chitwan and 17% in Lamjung produced feeding materials between 41-50 kg/day per household. However, the Chi-square test at a 5% significance level showed no significant difference in the number of households producing different amounts of feeding materials between the two districts (Table 5.18), which indicates that patterns of feedstock usage were similar in the two districts.

Table 5.18: Average amount of feedstock per household by district (wet weight)

District	No. of households				
	>20 kg/day	20-30 kg/day	30-40 kg/day	40-50 kg/day	>50 kg/day
Chitwan	35 (22)	47 (30)	37 (23)	23 (15)	15 (10)
Lamjung	48 (30)	45 (29)	21 (13)	26 (17)	17 (11)
Total	83 (26)	92 (29)	58 (19)	49 (16)	32 (10)

Note: Chi-square value = 6.8 (4 df), p-value = 0.146.

Source: Field Survey, 2012

Eighteen households who produced more than 20 kg of feeding materials per day did not feed all the available materials into the digester. Only 30% of households who produced more than 50 kg feeding materials per day fed the plants with the total quantity produced. The remainder of the feeding materials, particularly dung, was used for making farm yard manure, which is prepared mostly in open heaps (Figure 5.6), and was the major source of fertiliser for the majority of the rural households. It was observed from the field that the households did not feed all available dung into the digesters considering that it would considerably decrease the quantity of farm yard manure. However, the respondents did not recall/report any difference in quantity of feeding materials fed into biogas plants between summer and winter.

Figure 5.6: Livestock dung was used for making compost

In terms of daily prescribed feedstock input requirement, only 23% of households in Chitwan and 19% in Lamjung produced surplus dung to feed into the biogas plants (Table 5.19). Only six households (four in Chitwan and two in Lamjung) reported producing the amount of feeding material equal to the daily prescribed feedstock input requirement. The remaining 75% of households in Chitwan and 80% in Lamjung had a shortage of feeding materials. The majority of the households in both the districts had a daily feedstock shortage of up to 20 kg, while about 5% of households in either district had a daily shortage of above 30 kg (Table 5.19). Because of the feedstock shortage, 17% of biogas plants were fed once in two days, which might have also contributed to the lower gas production. Chi-square tests (at a 5% level) were carried out to test the significant difference in the number of households with feedstock shortage between the two districts, and that within the districts using the data in Table 5.19. The results showed that there is no significant difference (Chi-square = 1.47 at 3 df, p-value = 0.688) in the number of households with feedstock shortage between the two districts. Similarly, the test resulted in no statistically significant difference in feedstock shortage (Chi-square = 7.11 at 3 d.f., p-value = 0.068), but showed a statistically significant difference in feedstock surplus (Chi-square = 8.25 at 3 d.f., p = 0.041) within the districts.

Table 5.19: Households with feeding material shortages or surplus by district

Amount of feedstock (kg/day)	No. of households with feedstock shortage		No. of households with feedstock surplus	
	Chitwan	Lamjung	Chitwan	Lamjung
≤ 20	91 (58)	90 (57)	35 (22)	28 (18)
20 - 30	19 (12)	28 (18)	1 (0.6)	1 (0.6)
30 - 40	6 (4)	7 (4.4)	0	0
> 40	1 (0.6)	1 (0.6)	0	0
Total	117 (75)	126 (80)	36 (23)	29 (19)

Note: Figures in parenthesis are percentages.

Source: Field Survey, 2012

The number of biogas plants receiving less than 80% of the daily feedstock requirement, which is generally considered as under-fed plants, was significantly high (61%) (Table 5.20). About 56% of plants in Chitwan and 66% of plants in Lamjung were fed less than 80% of the daily feedstock requirement. A total of 9% biogas plants in Chitwan and 15% in Lamjung received considerably less feedstock, even less than 40% of the daily prescribed quantity. This was because of the reduced number of livestock raised as a result of decline in household labour due to out-migration of youth overseas or to urban areas for study or job seeking, and other socio-economic conditions that resulted in owning less livestock. A considerable number of biogas plants (23%), despite having sufficient production of dung, were also under-fed.

Table 5.20: No. of plants fed with proportion of the daily prescribed requirement

Plant size (m^3)	Proportion of daily prescribed feedstock input requirement						Chi-square
	Up to 40%	40-60%	60-80%	80-100%	> 100%	Total	
Chitwan							
4	0	2 (18)	2 (18)	2 (18)	5 (46)	11 (100)	13.86 at 12 df, p-value = 0.309
6	7 (6)	22 (20)	31 (28)	25 (23)	25 (23)	110 (100)	
8	7 (25)	5 (18)	7 (25)	5 (18)	4 (14)	28 (100)	
10	1 (12.5)	2 (25)	2 (25)	1 (12.5)	2 (25)	8 (100)	
Total	15 (9)	31 (20)	42 (27)	33 (21)	36 (23)	157 (100)	
Lamjung							
4	1 (2)	14 (27)	8 (16)	9 (18)	19 (37)	51 (100)	40.87 at 12 df, p-value = 0.000
6	16 (20)	14 (17)	29 (35)	14 (17)	9 (11)	82 (100)	
8	5 (24)	9 (42)	5 (24)	1 (5)	1 (5)	21 (100)	
10	2 (67)	1 (33)	0	0	0	3 (100)	
Total	24 (15)	38 (24)	42 (27)	24 (15)	29 (19)	157 (100)	

Note: Figures in parenthesis are the row percentages.

Source: Field Survey, 2012

It is interesting to note that 21% of plants (23% in Chitwan and 19% in Lamjung) were over-fed, receiving more than the daily prescribed input required. A higher proportion of smaller sized plants were fed more than the required quantity of dung compared with bigger sized plants. However, feeding of extra dung does not necessarily increase biogas production than the plant's full capacity. Instead the production could be decreased as the size of the gasholder reduces due to the extra slurry's uplift pressure (Figure 2.8). A Chi-square test at a 5% level of significance was employed to examine if there is any statistical significant difference in digester feeding in terms of plant size. The test resulted in a statistically significant difference in Lamjung (Chi-square = 40.87 at 12 d.f., p = 0.000), but not in Chitwan (Chi-square = 13.86 at 12 d.f., p = 0.309) (Table 5.20). Generally, larger plants were more likely to be under-resourced in terms of feedstock input requirements.

Water-dung ratio

One of the factors for creating conducive environment for micro-organisms inside the digesters to produce biogas is an appropriate water-dung ratio. A water-dung ratio of 1:1 (equal volume of dung and water) is considered appropriate for optimum biogas production (Bajgain, 1994; Karki et al., 2005). A higher water-dung ratio reduces the effective volume of the digester by the settling of solid particles on the floor, creating a dead volume, whereas a lower water-dung ratio eventually blocks gas flow produced inside the digester by forming scum on the top of slurry layer (P. C. Ghimire, 2005). Results show that 97% of plants in Chitwan and 95% in Lamjung had a dung-water ratio of 1:1, which means that these plants received an equal amount of dung and water. Similarly, 3% plants in Chitwan and 4% in Lamjung received less water than dung, while two plants in Lamjung received more water than dung. However, the Chi-square test did not result in significant difference (Chi-square = 2.36 at 4 d.f., p-value = 0.67) in water-dung ratio between the two districts. The test however is affected by the small number of high or low water-dung ratio.

Human excreta feeding

The concept of connecting household toilets to biogas digesters was an acceptable and common practice in the study area. Almost 90% of households attached their toilets to the biogas digesters. All households but one in Lamjung, and 80% of households in Chitwan had attached toilets to their biogas plants. There were numerous benefits reported of linking toilets to the biogas digester. First, human excreta that were causing a serious threat to human health and sanitation of the surroundings were converted to biogas. Second, there was no need to construct a septic tank, which saved the cost of its construction and cleaning/maintenance. However, despite the benefits, 9% of households were found to be reluctant to link toilets to the biogas digesters for a number of socio-cultural reasons, whereas two households reported that they already had a toilet and did not need the second one. Using biogas from toilet-attached plant for cooking remained very much a taboo to those 9% of households. The major reasons for such reluctance were: biogas from such a source was considered to be un-sacred, objection from the elderly members, and hesitation to handle the bio-slurry from latrine-attached plants. An elderly woman from a household with a toilet not-attached biogas plant in Chitwan district described biogas from a toilet attached plant as a “dirty gas” and said:

> “How can I cook in such dirty gas? Burning such gas in kitchen is not hygienic and is un-sacred. Besides, no one will be ready to carry and apply the manure from toilet-attached plant to the farms. I do not allow connecting toilet to biogas plant while I live”.

5.3.7 Availability of other organic materials to fulfill the feedstock deficit

It is understood from the above discussions that feeding materials were not sufficient to the majority of the biogas plants under study. Information on availability of other organic materials to be used as feedstock was collected from the respondents in order to assess their potential to fulfil the feeding material shortages and at the same time to improve biogas production efficiency through co-digestion of these materials with dung. Almost all the households, except 13% in Chitwan and 3% in Lamjung, who were using small amount of food wastes (about 0.5-1.0 kg/day per household) as feedstock, showed a lack of awareness about using organic materials other than dung, such as agricultural residues, as feedstock. Similarly, the practice of storing feedstock (dung) was not observed in any of the households; any surplus dung was used for making compost.

The literature suggests that crop residues have a large potential as a bioenergy feedstock due to their nutrient and carbon characteristics values (Moller et al., 2004; Tripathi, Iyer, Kandpal, & Singh, 1998). Using agricultural residues as feedstock for co-digestion with animal dung has a good potential in the country (Lungkhimba et al., 2011). In Nepal, crop residues, such as rice straw, corn stover, wheat straw and leguminous plant straw, are widely used as livestock feed to compensate for animal feed shortages, due to the drastic reduction in grazing areas and with tree felling (Suttie, 2000). Besides this, agricultural residues are also used to make compost where availability of livestock feed is not a problem. The data shows that all the households, except one in Chitwan who rented out the land and received only grains, produced agricultural residues. Not all the households produced all types of crop residues, but all of them produced rice straw. The average annual quantity of rice straw produced per household was 1,952 kg (standard deviation 1404), which ranged from a minimum of 150 kg to a maximum of 10 tonnes/year (Table 5.21). Similarly, 88% of households produced corn stover, 11% produced wheat straw and 14% produced other crop residues including finger-millet straw and leguminous plant straw; the average quantities produced were 1,095, 31.4 and 303 kg/year per household, respectively.

Table 5.21: Quantity of agricultural residues produced by a household

Crop residues	No. of households	Average (kg/year)	Minimum (kg/year)	Maximum (kg/year)	Standard deviation	Major uses
Rice straw	313 (99.7)	1,952	150	10,000	1,404	Animal feed
Corn stover	275 (88)	1,095	110	5,000	1,087	Animal feed, energy, composting
Wheat straw	35 (11)	31.4	110	770	102.8	Animal feed, composting
Other	43 (14)	303	180	7300	963.3	Animal feed, composting

Note: Figures in parenthesis are percentages.

Source: Field Survey, 2012

More households in Lamjung produced rice straw and corn stover, while more households in Chitwan produced wheat straw and other agricultural residues, particularly soybean and mustard straw (Table 5.22). Wheat and other crop residues were produced in only one household in Chitwan and three households in Lamjung. The Chi-square test at a 5% significance level shows a significant difference in the number of households (Chi-squared value 64.71 at 3 df, p-value 5.8E-14) between the two districts with more households in Chitwan producing more wheat straw and other agricultural residues and more households in Lamjung producing more corn stover because of the favourable climate.

Table 5.22: Number of households producing agricultural residues

District	No. of households				Average quantity produced (kg/household/year)			
	Rice straw	Corn stover	Wheat straw	Others	Rice straw	Corn stover	Wheat straw	Others
Chitwan	156	123	34	41	1663 (0.25)	947 (0.21)	60.3 (0.03)	545 (0.27)
Lamjung	157	152	1	3	2241 (0.34)	1460 (0.24)	2.2 (0.01)	61 (0.09)
Total	313	275	35	44	3904 (0.30)	2407 (0.17)	62.5 (0.01)	606 (0.05)
Chi-square = 64.71 at 3 d.f., p = 5.8E-14								

Note: Figures in parenthesis are standard errors.

Source: Field Survey, 2012

Figure 5.7 shows the distribution of agricultural residues produced in the surveyed households. The households who produced the top 50% of the crop residues are represented by everything above the median. Households who produced the top 25% of crop residues are shown by the top whisker. Similarly, households who produced less than 50% of the crop residues are represented by everything below the median, and those who produced the lower 25% of crop residues are shown by the bottom whisker. In both the districts, except for wheat straw, which has a comparatively short box plot indicating lower difference in the quantity produced among the households, the long upper whisker shows that the quantity of crop residues produced varies among the households.

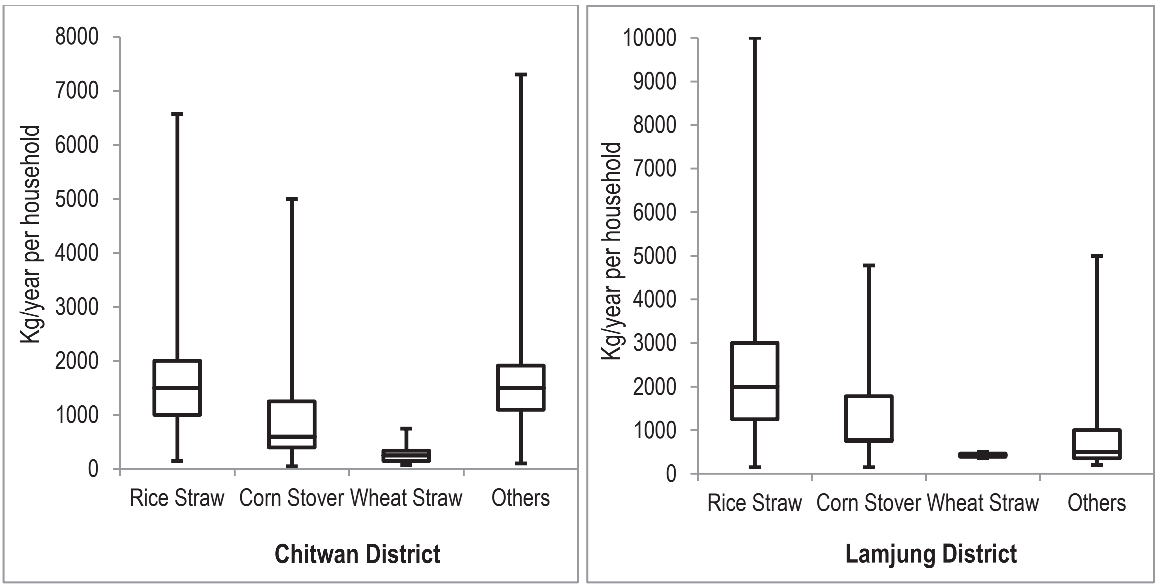

Figure 5.7: Distribution of agricultural residues produced in the surveyed households

Source: Field Survey, 2012

In terms of present uses of agricultural residues, rice straw was used mainly as animal feed (Figure 5.8). This was a major staple feed, particularly during the dry season of about 6 to 7 months, when there was green forage/fodder shortage. Similarly, corn stover was used as a major source of animal feed by all the producing households to supplement rice straw or fodder. The dried stover was also found used as an energy source for cooking animal feed in 4.5% of households, while 5% of households used it for making compost heaps with animal dung. Although none of the surveyed households reported burning of corn stover in field for manuring, the practice was observed during the field work in Lamjung district (Figure 5.9).

Figure 5.8: Traditional method of rice straw storage

Figure 5.9: Corn stover burnt in the field for manuring

Wheat straw is another agricultural residue produced by 11% of households, of which 91% and 31% of households used it for livestock feeding and making compost, respectively. Wheat straw was chopped into smaller pieces, soaked in water and fed to livestock. Households who had sufficient fodder, rice straw and/or corn stover to feed their livestock used wheat straw for making compost stacking it with animal dung. Other crop residues such as finger-millet and leguminous plant straw were also used to feed animals and make compost. However, none of the households were found using agricultural residues as feedstock to produce biogas. First, there was a lack of promotion about the use of other organic materials as feedstock. Most of the respondents were unaware of the potential use of agricultural residues as feedstock. Second, farmers preferred to make compost out of surplus organic materials to fulfil manure deficit from using dung to produce biogas.

The respondents had mixed responses when asked whether there would be any implication on previous or other potential uses of agricultural residues if they were used as feedstock. Respondents expressed that livestock feed was directly correlated with the amount of dung produced; hence changes in the feed would have direct implications on biogas production (Table 5.23). Around 23% of households in Chitwan and 19% in Lamjung with surplus dung production did not see any need for changing the existing use practices of agricultural residue, but would consider using it as biogas feedstock if its use increased biogas production significantly. About 61% of households in Chitwan and 59% in Lamjung, which produced a relatively less amount of livestock feed with respect to the number of livestock raised, responded that use of agricultural residues for purposes other than animal feed would have implication on livestock productivity, including dung production. They were required to provide alternatives to agricultural residues to meet their demand for animal feed if they were to use the residues as feedstock. However, 10% of households in Chitwan and 21% in Lamjung, who had sufficient alternative livestock feed and used agricultural residues as an energy source or for making compost, would not have any implication from using it as biogas feedstock on their present or future use. A Chi-square test at a 5% level of significance showed a significant difference (Chi-squared value 57.67 at 4 df, p- value 8.94E-12) in the implications of using agricultural residues as biogas feedstock between the two districts, mainly due to higher availability of animal feed in Lamjung.

Table 5.23: Implications of using agricultural residues as biogas feedstock

Implications reported	Chitwan	Lamjung	Total
Will have shortage of animal feed if utilised for biogas, so cannot afford/manage	41 (26)	19 (12)	60 (19)
Will have shortage of animal feed, but can be managed by cultivating forage if its use as feedstock increases biogas yield	55 (35)	74 (47)	129 (41)
Can be managed, as we have sufficient/surplus animal feed	16 (10)	33 (21)	49 (16)
Have sufficient dung or enough biogas, so no need to change the present use of agricultural residues	36 (23)	29 (19)	65 (21)
Residues other than rice straw can be used as feedstock	9 (6)	2 (1)	11 (3)
Total	157 (100)	157 (100)	314 (100)

Note: Figures in parenthesis are the percentages

Source: Field Survey, 2012

5.3.8 Systems of biogas digester heating or insulation

The literatures suggest that low temperature results in decreased gas yields (Balasubramaniyam et al., 2008; FAO/CMS, 1996). Heating or insulating biogas digesters during low temperature could increase biogas yield. This study also indicated a lower biogas production during winter (see Section 5.6). Therefore, the respondents were asked if they had practised any system of digester heating or insulation during cold weather. Most of the households (96%) reported that they did not practise any heating system nor they knew much about it. The remaining households (4%), all from Chitwan district, put compost piles above the digester to maintain temperature during cold weather, yet they suffered from lower gas production during winter. For a few households who had some knowledge about it, the higher cost of energy prevented them from adopting this system. The energy they would have to spend on heating the digester or the cost spend for insulation could be sufficient to fulfil the energy gap due to biogas deficit as a result of low gas production when the temperature is low.

5.3.9 Technical problems in biogas operation

Operation of biogas plants in the study area was not free from technical problems, which were also considered a contributing factor for insufficient gas availability. Although the majority of the households (69%) did not experience any technical problems in operation, 31% of households reported that they had at least one technical problem in biogas plant operation in almost every year since the installation. More biogas plants in Chitwan suffered from technical problems such as gas leakage and blockage (Table 5.24), which has also resulted in a statistically significant difference in technical problems in biogas plant operation between the two districts.

Table 5.24: Number of biogas plants with technical problems in operation

District	Pipe leakage		Pipe blockage		Main valve leakage	
	Yes	No	Yes	No	Yes	No
Chitwan	53 (34)	104 (66)	43 (27)	114 (73)	11 (7)	146 (93)
Lamjung	18 (12)	139 (88)	10 (6)	147 (94)	17 (11)	140 (89)
Chi-squared value	22.29		24.71		1.41	
Degree of freedom	1		1		1	
p-value	2.30E-06		6.60E-07		0.234	

Note: Figures in parenthesis are percentages.

Source: Field Survey, 2012

A total of 34% of households in Chitwan and 12% in Lamjung reported gas leakage through the pipeline, whereas 27% of households in Chitwan and 6% in Lamjung suffered from gas pipe blockages, which mainly included slurry in the pipelines and clogging of pipe with condensed water (Table 5.24). The problem of main valve leakages was reported in 7% of households in Chitwan and 11% in Lamjung. About 53% of the households reported more than one problem. About 6% of the plants, which were comparatively new, i.e., constructed within the last 5 years, also experienced technical problems. The Chi-square test at a 5% significance level showed a statistically significant difference in the pipe leakage and pipe blockage problems between the two districts, mainly because the problem of pipe leakages and blockages occurred more in Chitwan district. However, there was no significant difference in the biogas plants with main valve leakage problem between the two districts.

Although the problems, when reported, were fixed by the respective biogas companies under their after-sale-service provision (free of charge if within the warranty period of 3 years), the problems were not often reported unless they grew bigger. The users reported that they themselves tried to fix small problems to avoid the costs of hiring biogas technicians.

5.4 Impacts on Time Allocation and Workload Reduction

The study attempted to assess impacts of biogas on saving time in daily household activities including cooking (Section 5.4.1), cleaning utensils (Section 5.4.2), livestock caring (Section 5.4.3), fetching water (Section 5.4.4), collection of fuelwood (Section

5.4.5), biogas plant feeding (Section 5.4.6), and reducing the workload of its users. The respondents were asked whether they had experienced any difference in time allocation on these activities before and after the use of biogas. Since the households did not keep any record of time allocation on these activities, the time allocation before biogas was recalled from memory of the household members with the aid of the researcher.

It was found that biogas plants have positive impacts on saving time and reducing the workload of users in daily household activities. Overall, a household spent 15.9 hours (SE = 0.18), combined total of all household members, on these activities before the installation of the biogas plant (Table 5.25), ranging between 8.5-28 hours/day per household. The time spent on those activities reduced to 11.1 hours (SE = 0.03) after the installation of biogas plant, with a maximum and minimum combined reduced time of 4.5-18.5 hours/day per household. This indicates that a household saved an average of 4.8 hours/day (SE = 0.13), and hence experienced decreased workload after the use of biogas. The workloads of all family members including adult males, adult females and children[36] decreased after the installation of biogas plants, though adult females benefitted the most. On average, the daily time saved per household for adult females was 3.2 hours, whereas that for adult males and children was 1.1 and 0.5 hours, respectively (Table 5.25).

Table 5.25: Average time allocation of a biogas household on household activities

Household member	Before biogas (hours/day)	After biogas (hours/day)	Time saved (hours/day)
Adult male	4.4 (0.10)	3.3 (0.09)	1.1 (0.08)
Adult female	10.6 (0.13)	7.4 (0.09)	3.2 (0.11)
Child	0.9 (0.08)	0.4 (0.05)	0.5 (0.06)
Total	15.9 (0.18)	11.1 (0.03)	4.8 (0.13)

Note: Figures in parenthesis are standard errors.

Source: Field Survey, 2012

In terms of districts, time saved was slightly higher in Lamjung (36 minutes for adult female and 6 minutes for adult male) than that in Chitwan (Table 5.26). This is mainly because the hilly terrain of Lamjung means more time spent walking for fuelwood and water collection. Children saved more time in Chitwan, and more were sent to school

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[36] Aged between 5-16 years of both sex.

due to the reduced time requirement after the installation of biogas plants, which is the indirect educational benefit of the biogas technology.

Table 5.26: Average time allocation of household members by district

Time allocation	Chitwan (hours/day per household)			Lamjung (hours/day per household)		
	Adult male	Adult female	Child	Adult male	Adult female	Child
Before biogas	4.4 (0.15)	10.6 (0.20)	1.3 (0.13)	4.3 (0.15)	10.6 (0.18)	0.4 (0.06)
After biogas	3.4 (0.14)	7.7 (0.13)	0.7 (0.09)	3.2 (0.12)	7.1 (0.13)	0.1 (0.03)
Time saved	1.0 (0.11)	2.9 (0.18)	0.6 (0.13)	1.1 (0.11)	3.5 (0.12)	0.3 (0.05)

Note: Figures in parenthesis are standard errors.

Source: Field Survey, 2012

The distribution of time allocation on biogas related household activities before and after the installation of biogas plants in Chitwan and Lamjung is illustrated in Figure 5.10. The overall patterns of time allocation before and after the use of biogas in the districts are similar. However, the uneven size of the box plot after the use of biogas in Chitwan and before the use of biogas in Lamjung shows more variation in time allocation at the upper quartiles. The positions of the box plots, i.e., time allocation before the use of biogas being much higher than after the use of biogas, suggests an obvious difference between time allocation in the two periods.

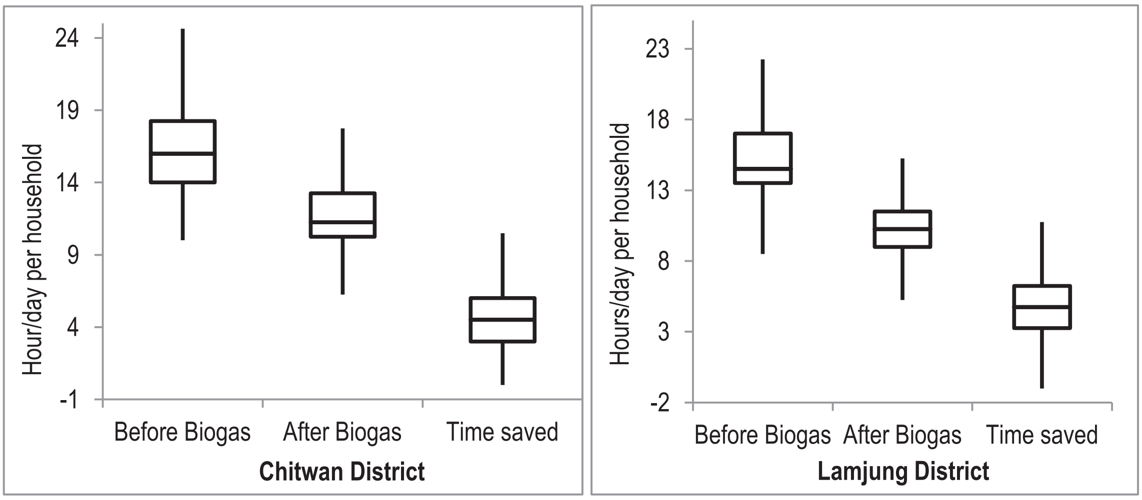

Figure 5.10: Distribution of time allocation before and after biogas

Source: Field Survey, 2012

A paired, two-tailed t-test was used to determine whether there is a statistically significant difference at 5% level of significance between time allocation before and after the installation of biogas in either district. The test resulted in a highly statistical significant difference for both the districts (Chitwan: p-value = 1.125E-60 < 0.05; Lamjung: p-value = 9.53E-59 < 0.05). However, the t-test resulted in no significant difference (p-value = 0.356 > 0.05) between the two districts for the time saved on households activities after the installation of biogas plants.

Almost all the surveyed households, except two, reported daily saving in time after the use of biogas (Table 5.27). The overall minimum and maximum time saved daily was in the range of 30 minutes to just above 13 hours. About 95% of adult females saved time that ranged from 15 minutes to almost 10 hours daily. Similarly, 70% of adult males and 33% of children saved time after the use of biogas. Only one household experienced no change in time allocation before and after the use of biogas. However, time allocation of male members in 15% of households and children in 63% of households were not affected, because the benefit was mainly for the women.

Table 5.27: Overall changes in time allocation in household activities

Household member	No. of households		
	Time increased	No change	Time saved
Male	46 (15)	46 (15)	222 (70)
Female	12 (4)	2 (0.6)	300 (95.4)
Child	11 (4)	199 (63)	104 (33)
Overall	1 (0.3)	1 (0.3)	312 (99.4)

Note: Figures in parenthesis are row percentages.

Source: Field Survey, 2012

Despite time saving at the household level for most of the households, one household reported to have incurred more time for total household activities after the installation of a biogas plant, with an increase of one hour daily. An increase in time allocation for individual household members was also reported in a few other households. Adult males, adult females and children experienced increased time allocation in 15%, 4% and 4% of households, respectively. The daily added time ranged from 15 minutes to 3.25 hours. The major reasons for the added time was reported to be shifting of traditional roles (e.g., cooking, fuelwood collection) from female to male after the use of biogas, and additional time required for the operation of the biogas plant.

In terms of districts, higher numbers of adult females and adult males in Lamjung saved time on household activities after the installation of biogas (Table 5.28). Although the majority of children in both the districts were not affected after the use of biogas in terms of their time allocation, the more children in Chitwan saved time than in

Lamjung. Similarly, more households in Chitwan experienced time added on household activities after the installation of biogas plants.

Table 5.28: Changes in time allocation after the use of biogas by district

Household member	No. of households			Chi-square
	Time added	No change	Time saved	
Chitwan				
Adult male	26 (17)	22 (14)	109 (69)	154.43 at 4 d.f., p-value = 2.3E-32
Adult female	11 (7)	2 (1)	144 (92)	
Child	7 (4)	88 (56)	62 (40)	
Lamjung				
Adult male	20 (13)	24 (15)	113 (72)	240.58 at 4 d.f., p-value = 7.0E-51
Adult female	1 (0.6)	0	156 (99.4)	
Child	4 (2)	111 (71)	42 (27)	

Note: Figures in parenthesis are percentage of households.

Source: Field Survey, 2012

The Chi-square test at a 5% significance level shows a statistically significant difference in changes in time allocation among the family members in both the districts (Table 5.28), with a higher number of female members saving time compared to other members after the installation of biogas plants. This indicated that installation of biogas had a significant positive impact on adult females by reducing their workload. Table 5.29 reports the time saving on individual household activities after the installation of biogas plants, which is explained in the following sections.

Table 5.29: No. of households saving time after the use of biogas

Activities	Chitwan		Lamjung		Chitwan and Lamjung combined	
	No. of households	Time saved (mins/day)	No. of households	Time saved (mins/day)	No. of households	Time saved (mins/day)
Cooking	104 (66)	50 (0.06)*	140 (89)	53 (0.04)*	244 (77)	51.5 (0.04)*
Cleaning pots	121 (77)	47 (0.04)*	122 (78)	32 (0.03)*	243 (77)	39 (0.03)*
Livestock caring	80 (51)	43 (0.07)*	86 (55)	44 (0.07)*	166 (53)	43.5 (0.05)*
Fuelwood collection	154 (98)	123 (0.08)*	155 (99)	127 (0.08)*	309 (98)	125 (0.06)*
Water collection	80 (51)	27 (0.04)*	102 (65)	39 (0.05)*	182 (58)	33 (0.04)*

Note: Figures in parenthesis are percentage of households.
Figures in parenthesis with an asterisk (…)* are the standard errors.

Source: Field Survey, 2012

Box 1: Percentage and standard error for household level variables

The table given below is used to estimate the standard errors for percentages in this study. The table, as provided by Professor Steve Haslett, Massey University, gives the percentage and standard error (SE) for household level variables in each district. The table uses the following formula to calculate the standard errors for a range of proportions p between zero and one; and where percentage = p * 100.

$$SE = [p(1-p)/n]^{1/2}$$

For percentages between those tabulated, the SE can be interpolated and is between the SE value of the percentage that is higher and the percentage that is lower in the table.

Table of percentages and standard error for household level variables

SN	Percentage	SE	SN	Percentage	SE	SN	Percentage	SE
1	0	0.00	15	35	3.81	29	70	3.66
2	2.5	1.25	16	37.5	3.86	30	72.5	3.56
3	5	1.74	17	40	3.91	31	75	3.46
4	7.5	2.10	18	42.5	3.95	32	77.5	3.33
5	10	2.39	19	45	3.97	33	80	3.19
SN	Percentage	SE	SN	Percentage	SE	SN	Percentage	SE
6	12.5	2.64	20	47.5	3.99	34	82.5	3.03
7	15	2.85	21	50	3.99	35	85	2.85
8	17.5	3.03	22	52.5	3.99	36	87.5	2.64
9	20	3.19	23	55	3.97	37	90	2.39
10	22.5	3.33	24	57.5	3.95	38	92.5	2.10
11	25	3.46	25	60	3.91	39	95	1.74
12	27.5	3.56	26	62.5	3.86	40	97.5	1.25
13	30	3.66	27	65	3.81	41	100	0.00
14	32.5	3.74	28	67.5	3.74	Note: n = 157 for each district		

5.4.1 Time saving on cooking

Overall, the average daily time saved by a household on cooking meals and snacks was reported to be 51.5 minutes (SE = 0.037), ranging between 30 minutes to 3 hours (Table 5.29). Saving of time was reported in 66% of households (SE = 3.78)[37] in Chitwan and 89% (SE = 2.49) in Lamjung. The average daily time saving on cooking per household in Chitwan and Lamjung was 50 minutes (SE = 0.06) and 53 minutes

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[37] See Box 1.

(SE = 0.04), respectively. Adult females were mostly benefitted from time saving on cooking after the installation of biogas in both the districts. Use of biogas for cooking did not affect the time allocation of adult males and children in the majority of households in both the districts, because cooking is traditionally a job for female members in rural households. Overall, adult males did not save any time on cooking, while children saved 8 minutes/day per household.

Moreover, cooking in biogas was reported as much easier than fuelwood. One female respondent shared her joy about cooking in biogas:

> "Our social practice is such that we usually eat our meal last and least. Sometimes the quantity left was not enough, but because of the burden to cook food again in fuelwood, we used to eat only the leftovers which might have contributed to nutrition deficiency and associated health problems. But we are no more left hungry after the use of biogas, as we don't feel burden to cook food again and again."

This reflects that the installation of a biogas plant has a positive impact on reducing cooking time, especially of women, and is linked with achieving MDGs 1, 4, 5 and 6 (Section 2.5.1 and 2.5.4).

5.4.2 Time saving on cleaning of cooking pots/utensils

Use of biogas also had a significant impact on saving time, particularly of female members, on cleaning utensils in the absence of black soot that used to be a major problem while cooking food with fuelwood. Overall, saving of time was reported in 78% of households (SE = 3.30), and the average time saved was reported to be 39 minutes/day per household (SE = 0.03), with savings for each household ranging between 15 minutes to 1 hour, depending on types of food cooked and types of pots used (Table 5.29). Saving of time was reported in 77% of households (SE = 3.35) in Chitwan and 78% (SE = 3.30) in Lamjung, and the daily time saved by all members of a household in Chitwan and Lamjung was 47 minutes (SE = 0.04) and 32 minutes (SE = 0.03), respectively. Again as in cooking, female members benefitted the most, as cleaning utensils was also the job that adult females practised traditionally in rural households.

5.4.3 Time saving on livestock caring

Livestock caring was another activity that was impacted after the installation of biogas plants. This included collecting livestock feed, feeding livestock, including grazing and cleaning the livestock shed. Overall, 53% of households (SE = 3.99) experienced saving in time for livestock caring after the installation of biogas plants and the average time saved was 43.5 minutes/day per household (SE = 0.05), which ranged between 30 minutes and 4 hours (Table 5.29). Saving of time was reported in 51% (SE = 3.99) of households in Chitwan and 55% (SE = 3.97) in Lamjung. The average time saved in both the districts was almost equal. The reason for saved time was that farmers stopped taking their livestock to forests/marginal lands for grazing, which was a common practice before the installation of biogas plants, and started stall-feeding in order to produce more dung for biogas production. They used to spend almost half a day grazing their animals before the installation of biogas plants. However, stall-feeding to produce more dung was the reason for added time in eight households. Collecting fodder/grass was more time consuming for them due to the lack of (marginal) land to supply fodder/forage and depended on far-located forests for most of their fodder needs. There was no change in livestock shed cleaning practices and hence no change in time allocated for it in both the districts.

5.4.4 Time saving on fuelwood collection

Fuelwood collection was one of the major household activities impacted after the installation of biogas plants. Fuelwood was reported as the main conventional energy source used in all the biogas households for cooking before the installation of biogas. Fuelwood was collected from the nearby forests and from their own farms/marginal lands. Installation of biogas plants had significantly impacted on time allocated for fuelwood collection. Overall, 98% of households (SE = 1) saved time on fuelwood collection and the time saved was significant, i.e., 125 minutes/day per household (SE = 0.057) (Table 5.29). The average daily time saving per household was 123 minutes (SE = 0.08) in Chitwan and 127 minutes (SE = 0.08) in Lamjung with savings for each household ranging between 15 minutes and 6.5 hours a day.

Female members benefitted the most by saving time on fuelwood collection. The average time saved by an adult female was 68 minutes/day (SE = 0.04) per household. Children’s time allocation for collecting fuelwood in the majority of the households was not affected, because children were involved in collecting fuelwood only in 3% of households (SE = 1.35). None of the households reported added time on collecting fuelwood after the installation of biogas plants. A female respondent expressed how their drudgery was reduced after the use of biogas:

> "We (women) were always responsible for collecting fuelwood for cooking. Male even didn't care from where and how we collected it, and whether that caused any health problem to us, but what they only wanted was their food to be served in time. Biogas has improved the situation, but we are still suffering for not having enough gas."

5.4.5 Time saving on water collection

Feeding of biogas digesters requires additional water, and hence it was assumed that installation of biogas plants would add to time allocated for water collection after the biogas plant installation. So, the respondents were asked if they had experienced any difference in time allocated for collection of water before and after the installation of biogas plants. However, only two households in Chitwan and three in Lamjung experienced increased time allocation on water collection, and for these households the average time added was 42 minutes/day per household. About 48% of households (SE = 3.99) in Chitwan and 33% (SE = 3.75) in Lamjung did not feel any change in time allocation for water collection after the installation of biogas plants. Collection of additional quantities of water was not a problem for majority of the households, because sufficient water was available from sources located not far from their households. Contrary to expectation, 51% of households (SE = 3.99) in Chitwan and 65% (SE = 3.81) in Lamjung actually saved time on water collection (Table 5.29). The average daily time saved by a household was 27 minutes (SE = 0.04) in Chitwan and 39 minutes (SE = 0.05) in Lamjung.

5.4.6 Time allocation on biogas plant feeding

Feeding a biogas plant, i.e., collection and mixing of dung and water, was an added work allocated each day to the biogas households. On average, one biogas household spent 26 minutes (SE = 0.008) a day to feed a biogas plant and for individual households that ranged from 10 minutes to 1 hour (Table 5.30). More adult females (60%; SE = 3.91) were involved in feeding biogas plants in Chitwan, while more adult males (65%; SE = 3.81) were feeding the plants in Lamjung. Children were responsible for feeding the biogas plant in only one household in Lamjung.

Table 5.30: Time allocation on feeding of biogas plants

District	No. of households			Time allocation	
	Adult male	Adult female	Child	Minute/day	Range (minute)
Chitwan	63 (40)	94 (60)	0	27 (0.014)*	15 - 45
Lamjung	102 (65)	54 (34)	1 (0.6)	25 (0.01)*	10 - 60

Note: Figures in parenthesis are percentage of households.
Figures in parenthesis with an asterisk (…)* are the standard errors.

Source: Field Survey, 2012

5.4.7 Utilisation of saved time

As discussed in Section 5.4, a biogas household saved an average of 4 hours 48 minutes per day (SE = 0.13) on total household activities after the installation of biogas plants. However, utilisation of the saved time for social-economic gain would further add value to the installation of the biogas system. Although female members benefitted the most, they seldom had the opportunity to decide for themselves about how best to utilise the saved time, due to the patriarchal[38] system prevailing in the country. It is the household head, generally male, who usually makes decisions. The saved time was usually reallocated by the male head of the households to other chores for family benefit (Table 5.31). However, this practice might give rise to a debate – whether biogas really reduces drudgery (P. C. Ghimire, 2005). Obviously, biogas substituted the drudgery of fuelwood collection, cooking in a smoke-filled kitchen and cleaning black-sooted utensils, but the biogas households were unable to assess the amount of drudgery reduced after the installation of biogas plants.

Biogas household members utilised their saved time on the IGAs, recreational activities, participating in social/community groups, and giving more time to job/business (Table 5.31). One household was reported to be involved in more than one activity. Almost half of the households (49%; SE = 3.99) under study had utilised the saved time carrying out IGAs, which mainly included vegetable farming (57%; SE = 3.95), milk production (32%; SE = 3.72), poultry (10%; SE = 2.39), handicrafts (3%; SE = 1.35), goat-keeping (8%; SE = 2.16) and fish farming (6%; SE = 1.88). More households in Chitwan (51%; SE = 3.99) carried out IGAs that in Lamjung (43%; SE = 3.95), because of the higher productivity of land and better market opportunities in Chitwan. Such IGAs had significantly contributed to improve the economic condition of most of the participating households. Similarly, installation of biogas plants had given 47% of households (SE = 3.98) in Chitwan and 35% (SE = 3.81) in Lamjung the opportunity to participate in social/community activities such as mothers' groups, community forest users' groups, drinking water management groups and adult literacy groups. Participation in such activities had given the rural people, particularly women, the poor, Dalits and other marginalised ethnic groups, the opportunity to put their voice into community development decision-making and develop their leadership skills. Participation in adult literacy groups had also helped to raise the level of literacy, particularly amongst women and marginalised people through the provision of appropriate learning and life skills programmes.

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[38] The sociological condition where male is the family head and male members of a society tend to predominate in positions of power.

Table 5.31: Utilisation of the saved time after the installation of biogas plants

Activities	Chitwan		Lamjung	
	No. of households	SE*	No. of households	SE*
Income-generating activities	79 (51)	3.99	66 (43)	3.95
More time for the existing job/business	3 (2)	1	5 (3)	1.35
Caring of children/children's education	27 (18)	3.06	34 (22)	3.3
Participation in social/community works	74 (47)	3.99	56 (35)	3.81
Recreational activities/taking rest	66 (43)	3.95	14 (9)	2.27
Other household chores including household and personal cleaning and washing	99 (63)	3.85	117 (74)	3.5
Livestock caring	10 (6)	1.88	2 (1)	0.5
Kitchen gardening for self-consumption	3 (2)	1	8 (5)	1.75

Note: Figures in parenthesis are percentages.
* Standard error on percentage (see Box 1 for detail).

Source: Field Survey, 2012

Around 25% of households (SE = 3.46) used some of the saved time for recreational activities, such as watching TV/movies, taking part in social/cultural events/performances and other leisure activities, and even taking rest (Table 5.31). It is interesting to note that only 9% of households (SE = 2.27) in Lamjung compared to 43% of households (SE = 3.95) in Chitwan utilised the saved time for recreational activities, because Lamjung is a remote district with less opportunities. More households (74%; SE = 3.5) in Lamjung compared with Chitwan (63%; SE = 3.85) reported reallocation of their saved time to other household chores, including household and personal cleaning and washing, particularly by female members. A significant number of households both in Chitwan (18%; SE = 3.06) and Lamjung (22%; SE = 3.3) also utilised the saved time on caring for children and children's education, whereas few households got extra time for their business/job, livestock caring, and kitchen gardening for self-consumption. Overall, it shows that more households in Chitwan utilised some of the saved time for IGA, recreation and livestock caring, while more households in Lamjung utilised the saved time for other household chores.

5.5 Sources of Energy and Changes in Energy Use Pattern

5.5.1 Energy for cooking

Although fuelwood[39] was the most prevalent energy source before the installation of biogas plants, biogas changed the energy use pattern, successfully substituting the

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[39] Air-dried fuelwood with approximately 20% moisture content.

fuelwood and other biomass sources in both the districts. Households reported a peak energy demand for cooking between 7:00am and 8:00am and 7:30pm and 8:30pm (Figure 5.11 and 5.12). None of the households reported the use of energy for cooking between 10:00am to 1:00pm and after 9:00pm till 5:00am next morning. However, it is important to note that the figures show the overall average pattern of hourly energy use in terms of time, which is indicative; individual use patterns may differ from one household to other.

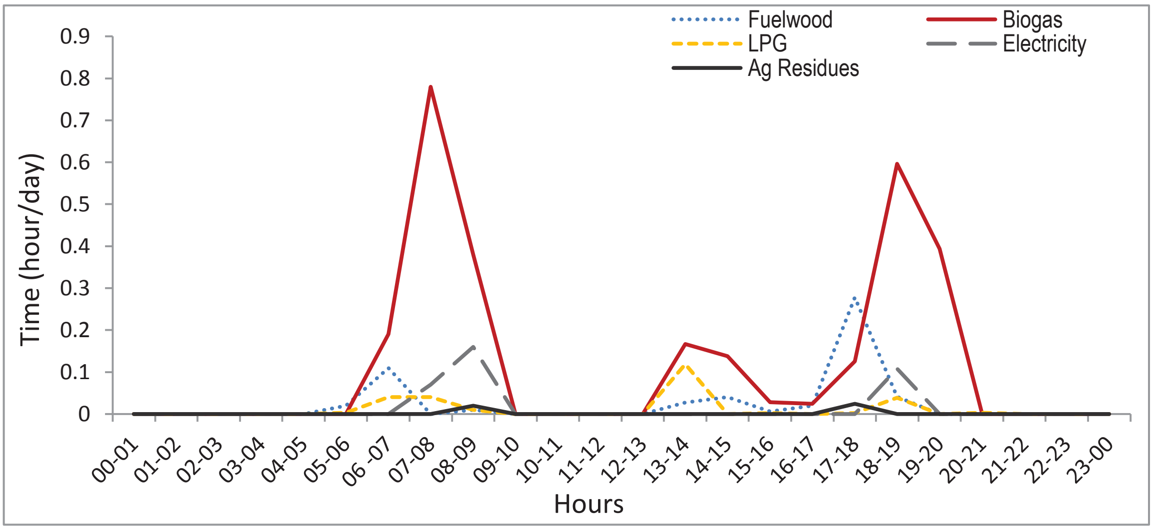


Figure 5.11: Average hourly energy use pattern of a biogas household (Chitwan)

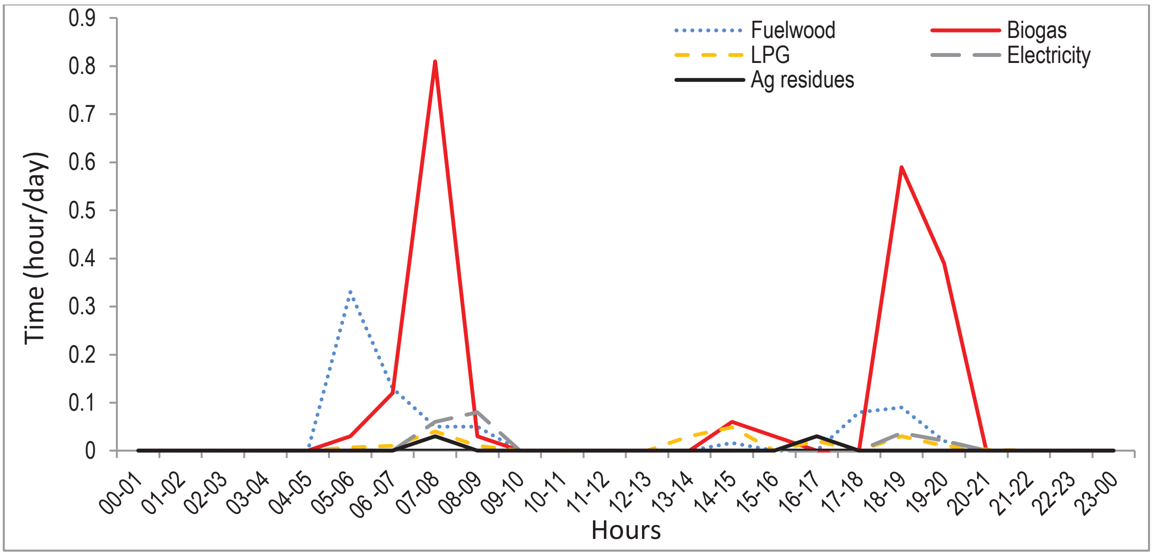


Figure 5.12: Average hourly energy use pattern of a biogas household (Lamjung)

There was a significant reduction in the number of households using traditional biomass energy sources for cooking after the installation of biogas plants in both the districts. Fuelwood was used for cooking by all the surveyed households (except two in Chitwan who used LPG) before the installation of biogas plants, and it was the only source of energy for cooking in 79% of households (SE = 3.27) in Chitwan and 82% of households (SE = 2.99) in Lamjung (Table 5.32). The remaining households combined other energy sources such as kerosene, LPG, electricity and agricultural residues with fuelwood. Although 83% of households (SE = 2.99) in Chitwan and 98% (SE = 1.74) in Lamjung were using fuelwood for cooking even after the use of biogas, none of them were fully dependent on fuelwood. Similarly, all but one household in Lamjung stopped using kerosene for cooking as a result of biogas use. About 50% of households (SE = 3.99) in Chitwan and 38% (SE = 3.87) in Lamjung stopped using agricultural residues after the use of biogas.

However, there was a significant increase in the number of households using LPG and electricity for cooking after the installation of biogas in both the districts (Table 5.32). The number of households using LPG increased by 284% (SE = 2.78) in Chitwan and 200% (SE = 0.0) in Lamjung, whilst electricity use increased by 577% (SE = 3.30) in Chitwan and 540% (SE = 3.91) in Lamjung. Biogas deficit for cooking was reported as the main reason for this increase, coupled with availability of LPG in local markets and access to electricity.

Table 5.32: Number of households using different energy sources for cooking

Energy source	Chitwan	SE*	Lamjung	SE*
Before biogas				
Fuelwood only	124 (79)	3.27	129 (82)	2.99
Fuelwood & kerosene	2 (1)	0.5	7 (4)	1.54
Fuelwood & LPG	19 (12)	2.59	13 (8)	2.16
Fuelwood & electricity	39 (25)	3.46	0	-
Fuelwood & Ag residues	7 (4)	1.54	18 (11)	2.49
Fuelwood, LPG, electricity	13 (8)	2.16	0	-
Fuelwood, kerosene, LPG, electricity, Ag residues	7 (4)	1.54	0	-
After biogas				
Biogas only	26 (17)	2.99	3 (2)	1
Biogas & fuelwood	131 (83)	2.99	154 (98)	1.74
Biogas, fuelwood & LPG	73 (46)	3.98	39 (25)	3.46
Biogas, fuelwood & Ag residues	5 (3)	1.35	9 (6)	1.88
Biogas, fuelwood & electricity	88 (56)	3.96	54 (34)	3.78
Biogas, fuelwood, LPG & electricity	73 (46)	3.98	39 (25)	3.46

Note: Figures in parenthesis are percentage of households.
* Standard error on percentage (see Box 1 for detail).
Source: Field Survey, 2012

The survey data on energy use for cooking after the installation of biogas was also compared with the Census 2011 data. A Chi-square test result shows that there was a significant difference in sources of energy used for cooking between the Census 2011 and the survey data in both the districts (Table 5.33), reflecting the fact that the sample contains only households with biogas.

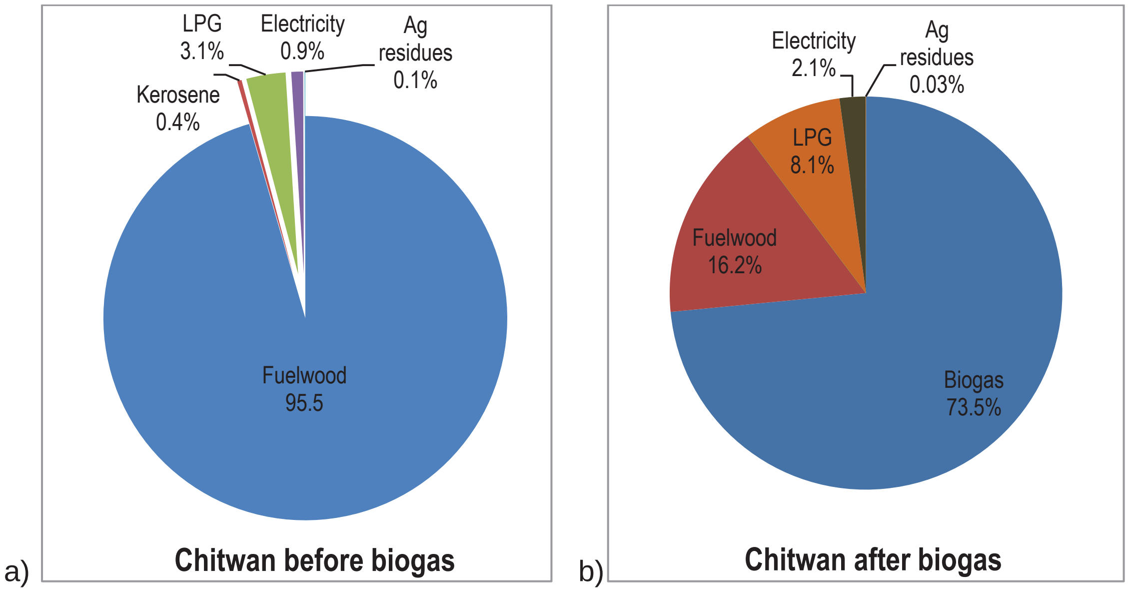
Table 5.33: Comparison of number of households using different energy sources for cooking between Census 2011 and the survey data

Energy Source	Chitwan		Lamjung	
	Census 2011	Survey data	Census 2011	Survey data
Fuelwood	64,933	131	29,255	154
Kerosene	997	0	149	1
LPG	52,545	73	7,997	39
Biogas	12,238	157	4,364	157
Electricity	234	88	53	54
Other	1,398	5	230	9
Chi-squared value	9,892.15		5,885.77	
Degree of freedom	5		5	
p-value	0		0	

Note: Chi-square test for one more table, comparing survey results with known Census proportions.

Source: CBS (2012a) and Field Survey (2012)

Installation of biogas plants had significantly reduced the composition of fuel share in both districts (Figure 5.13). The share of fuelwood to total energy consumption was about 96% and 98% in Chitwan and Lamjung, respectively, before the installation of biogas, which reduced to about 16% in Chitwan and 31% in Lamjung, respectively, after the use of biogas.



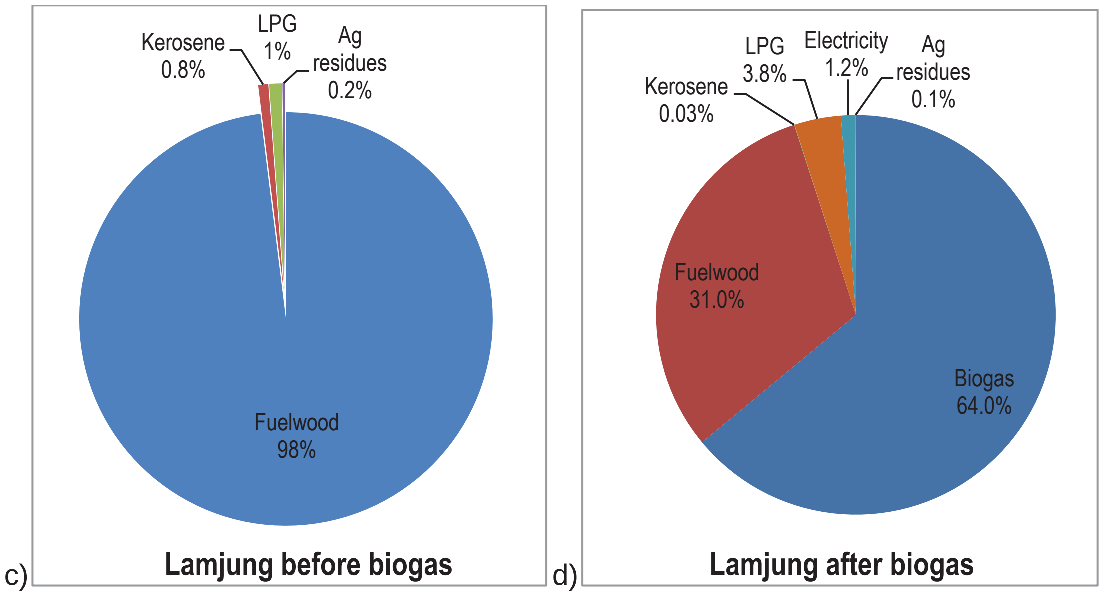


Figure 5.13: Composition of average annual fuel share before and after the use of biogas in Chitwan and Lamjung

Fuelwood was still a major source of energy for cooking for each district even after the installation of biogas plants (Table 5.34). Although 9% of households (SE = 2.27) stopped burning fuelwood after the use of biogas, an average of 114 kg (SE = 7.99) fuelwood/month per household was still reported consumed in the surveyed households. The average monthly consumption of fuelwood per household was reduced by 255 kg (SE = 8.94) in Chitwan and 252 kg (SE = 13.21) in Lamjung, which is a reduction of 69% (SE = 3.70) and 61% (SE = 3.89) in Chitwan and Lamjung, respectively, making the total annual average reduction of 3.04 tonnes (SE = 95.95) per household. But there was a higher standard deviation of fuelwood consumed before the use of biogas in both the districts (Chitwan 136.07, Lamjung 220.28) and after the use of biogas (Chitwan 55.07, Lamjung 97.63) this indicated a larger gap in the quantity of fuelwood used among the households.

Table 5.34: Change in average energy use for cooking (except biogas)

Energy source	Chitwan			Lamjung		
	Before biogas	After biogas	% Change	Before biogas	After biogas	% Change
Fuelwood[40] (Kg/month)	325 (10.86)	70 (4.39)	69 (3.30)	410 (17.58)	158 (7.79)	61 (3.89)
Kerosene (litre/month)	0.1 (0.07)	0	100 (0.0)	0.3 (0.11)	0.01 (0.01)	98 (1)
LPG (cylinder/month)	0.05 (0.01)	0.12 (0.01)	-140 (3.91)	0.02 (0.005)	0.07 (0.02)	-250 (3.99)
Electricity (kWh/month)	2 (0.28)	4.4 (0.33)	-120 (3.19)	0	2.7 (0.32)	-270 (3.66)
Crop residues (kg/month)	0.18 (0.08)	0.07 (0.04)	61 (3.89)	0.78 (0.22)	0.2 (0.09)	74 (3.41)

Note: Figures in parenthesis are standard errors

Source: Field Survey, 2012

The fuelwood use pattern in the surveyed households before and after the biogas is depicted in Figure 5.14, which visualises the range and other characteristics of users' responses. There is a clear distinction between the plots before and after the installation of biogas plants. The plots for fuelwood consumption after the use of biogas in both districts are comparatively short, suggesting less variation in fuelwood use among the households, whereas those before biogas use are comparatively tall, showing variation in the fuelwood use pattern. Similarly, the plots for after biogas are much lower than those for before biogas, indicating a significant difference in fuelwood consumption before and after the use of biogas. A two-tailed, paired t-test at the 5% level of significance also resulted in a statistically highly significant difference between fuelwood consumption before and after the use of biogas in both the districts (Chitwan: p-value = 7.96E-57 < 0.05; Lamjung: p-value = 2.0E-42 < 0.05). However, the t-test resulted in no significant difference (p-value = 0.097 > 0.05) for reduction in the quantity of fuelwood consumption after the installation of biogas plants between the two districts.

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[40] Fuelwood in rural areas of Nepal is measured in term of *bhari* (back load). A *bhari* of fuelwood while measured in five different locations during the field survey was approximately 30 kg in weight, which was used as a standard measure to calculate fuelwood collection/consumption in the surveyed household. Fuelwood consumed was air-dried with approximately 20% moisture content.

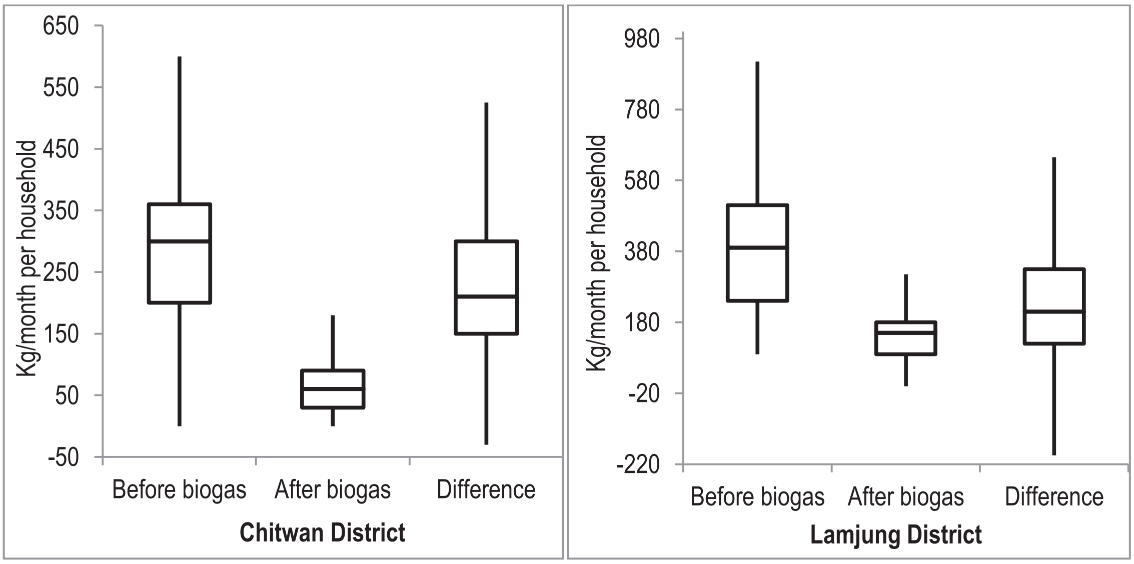

Figure 5.14: Fuelwood consumption pattern before and after the use of biogas

After the installation of biogas plants, fuelwood was mostly used for cooking/heating livestock feed (*kundo*) and cooking meals during the winter season when biogas production was not enough. Another typical use of fuelwood was to heat milk, particularly on a cast iron round bottom pan (*karai*) (Figure 5.15a). Use of biogas to cook livestock feed was not found practical for two reasons. First, there was hardly any surplus biogas after cooking meals, and second, a biogas stove due to its smaller dimensions was not suitable for cooking *kundo,* usually in a large pot (Figure 5.15b).

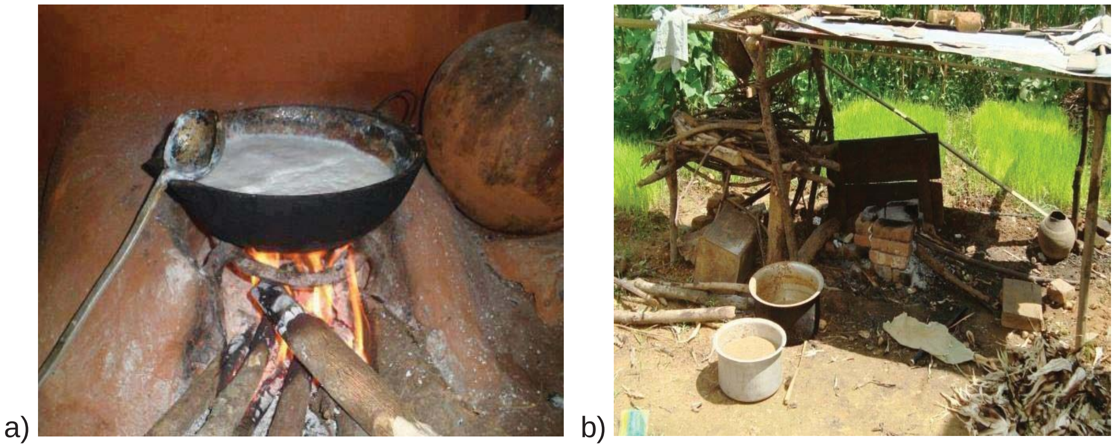

Figure 5.15: Traditional stove for heating (a) milk (b) livestock feed (*kundo*)

Besides fuelwood, the traditional biomass energy source used for domestic cooking purposes was agricultural residues. These were used mainly for cooking or heating livestock feed in a traditional stone or brick stove especially made for cooking livestock feed (Figure 5.15b). On average, the quantity of agricultural residues burnt was reduced by 61% (SE = 3.89) in Chitwan and 74% (SE = 3.41) in Lamjung after the use of biogas (Table 5.34). Biogas did not substitute crop residues directly, but fuelwood substituted by biogas was used to reduce/replace the consumption of agricultural residues. The major implication of reduction in burning of agricultural residues was less GHG emissions into the environment (see Chapter 8). Reduction in burning of these residues only in the surveyed households might not have a significant impact on environment, but the impact will be huge if we consider the total number of biogas plants installed in the country.

Similarly, use of kerosene for cooking was reduced by 98% after the use of biogas, saving a combined total of 62 litres (SE = 0.066) per household per year in the two districts (Table 5.34). However, use of kerosene for cooking in the surveyed households was insignificant in terms of its quantity, associated costs and impacts on GHG emissions. Only one household in Lamjung continued using kerosene for cooking even after the installation of a biogas plant, but the quantity consumed was very small (0.1 litre/month, SE = 0.006). Kerosene was mainly used to initiate the fire for fuelwood burning.

LPG was another important energy source used for cooking in the surveyed households. It was introduced in Nepal as an alternative to kerosene and electricity in urban and semi-urban areas. But, there has been a considerable increase in the use of LPG in recent years even in the rural areas to replace the use of fuelwood, kerosene and electricity. The use of LPG for cooking was an increasing trend even after the installation of biogas plants. The consumption of LPG after the use of biogas increased by 140% (SE = 3.91) in Chitwan and 250% (SE = 3.99) in Lamjung (Table 5.34). The average consumption of LPG per household before the use of biogas was 0.05 cylinders/month (SE = 0.013) in Chitwan and 0.02 cylinders/month (SE = 0.005) in Lamjung, which increased to 0.12 cylinders/month (SE = 0.014) in Chitwan and 0.07 cylinders/month (SE = 0.015) in Lamjung after the use of biogas. LPG was mostly found used to meet the biogas deficit for cooking. However, despite there being sufficient supply of biogas, a few households (7%) reported that they used LPG for their convenience because of its easiness to use. Chitwan district has a higher number of LPG user households (65%, SE = 3.81) than Lamjung district (35%, SE = 3.81), because fuelwood was more scarce in Chitwan district and LPG was easily available in its semi-urban set up.

Like LPG, use of electricity for cooking purposes was also an increasing trend. On average, electricity consumption of a biogas household for cooking increased from 1 kWh/month (SE = 0.15) before the installation of biogas plant to 3.6 kWh/month (SE =

0.23) after the use of biogas, which is an increase of 255% (SE = 3.97). Consumption of electricity for cooking increased from 2 kWh/month (SE = 0.28) to 4.4 kWh/month (SE = 0.33) in Chitwan and from 0 to 2.7 kWh/month (SE = 0.32) in Lamjung (Table 5.34). Rural people's increased access to electricity and the availability of electric rice cookers in local markets were reported as the major reasons for the increased consumption of electricity for cooking. In addition, biogas deficit had obviously contributed to its increased use. So an electric rice cooker could be considered as a potential alternative for reducing the demand of biogas. However, it is still not an option for many poor households, because even a cheaper electric rice cooker costs about NZ$30-35 depending on size, and this is far more than the monthly cash income of many households.

5.5.2 Energy for lighting

Electricity, kerosene and candles were the major sources of energy used for lighting in the study area (Table 5.35). None of the households under study used biogas for lighting, and hence installation of biogas did not have any impact on energy use patterns for lighting. Increased access to electricity was reported as the main reason for not using biogas for lighting. At the time of the field survey, about 97% of households had access to electricity. Besides, insufficient availability of biogas, even for cooking, additional installation costs of the lamp, and impressions about poor performance of the lamp were other reasons reported for not using biogas for lighting.

Table 5.35: Energy use for lighting

Energy source	Chitwan		Lamjung	
	No. of households	SE*	No. of households	SE*
Kerosene	71 (45)	3.97	51 (32)	3.72
Electricity	147 (94)	1.59	157 (100)	0
Candle	64 (41)	3.92	151 (96)	1.54
p-value for two-tailed paired t-test = 0.505				

Note: Figures in parenthesis are percentage of households.
* Standard error on percentage (See Box 1 for detail).

Source: Field Survey, 2012

Kerosene was still used for lighting in 45% of households (SE = 3.97) in Chitwan and 32% of households (SE = 3.72) in Lamjung (Table 5.35). Rural households, who did not have access to electricity, were still forced to use kerosene for lighting purpose. Even in the households with electricity access, kerosene was used in the wick lamps and lanterns for lighting during the load-shedding[41] period of power outages. But

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[41] Nepal is currently facing a high load-shedding period of up to 16 hours a week during dry seasons (NEA, 2014).

frequent shortage of kerosene in the local market made people switch to candles which were easily available in the local markets. A total of 41% of households (SE = 3.96) in Chitwan and 96% (SE = 1.54) in Lamjung used candles, particularly during the load-shedding period. The two-tailed, paired t-test at 5% significance level showed no significant difference (p-value = 0.505) in the use of different energy sources for lighting between the two districts, despite more households in Chitwan using kerosene and more households in Lamjung using electricity and candles (Table 5.35). The survey data were also compared with the Census-2011 data using the two-tailed paired t-test at 5% level of significance, which showed no significant difference in the energy use for lighting between the Census data and the survey data in either districts (Table 5.36).

Table 5.36: Comparison of energy use for lighting between the Census and survey data

Energy Source	No. of households			
	Chitwan		Lamjung	
	Census 2011	Survey	Census 2011	Survey
Kerosene	7211 (6)	71 (45)	6155 (15)	51 (32)
Biogas	333 (0.3)	0	110 (0.3)	0
Electricity	113728 (86)	147 (94)	32302 (77)	157 (100)
Other	11073 (8)	64 (41)	3481 (8)	151 (96)
p-value (paired, two-tailed t-test)	0.308		0.251	

Note: Figures in parenthesis are percentages.
Two-tailed, paired t-test for comparing survey results with known Census proportions.

Source: CBS (2012a) and Field Survey (2012)

5.6 Biogas Production and Utilisation

5.6.1 Biogas demand and consumption

The demand and consumption of biogas in the surveyed households were analysed in order to identify the daily biogas deficit and examine how the users coped with lower gas production. Biogas demand was determined on the basis of present energy consumption for cooking, which involved measuring the present rate of energy consumption in the form of biogas, fuelwood, kerosene, LPG, electricity and agricultural residues. The demand for and consumption of biogas was recorded for major uses of biogas as reported in the field, particularly cooking and heating of two meals, breakfast and afternoon tea/snacks, as no other use of biogas was reported in the surveyed households. Chitwan district was reported to have better production of biogas than Lamjung district. A total of 15% (SE = 2.85) of households in Chitwan compared to only 4% (SE = 4.54) of households in Lamjung reported sufficient gas production throughout the year, whereas 62% (SE = 3.85) of households in Chitwan compared to 31% (SE = 3.69) of households in Lamjung reported sufficient biogas production in summer (Table 5.37). The statistical analysis has also shown that this difference in biogas availability between the two districts is significant (Chi-square = 23.91 at 2 d.f., p-value = 6.4E-06).

Table 5.37: Number of households with availability of biogas

District	Sufficient	SE*	Not sufficient	SE*	Sufficient in summer only	SE*
Chitwan	24 (15)	2.85	133 (85)	2.85	98 (62)	3.85
Lamjung	6 (4)	1.54	151 (96)	1.54	48 (31)	3.69

Note: Figures in parenthesis are percentage of households.
* Standard error on percentage (See Box 1)

Source: Field Survey, 2012

In order to identify the daily biogas deficit, information was collected on daily biogas demand and availability. The information was collected in terms of daily actual and required cooking time from each respondent household, which was later converted into equivalent energy. The respondents were asked about the number of biogas stoves in use, specific gas consumption rate of the stoves, daily required cooking (or stove operating) time, and actual stove operating time. Since production of biogas was hugely affected by temperature, the information was collected separately for summer and winter (see Section 4.6.2). Total daily cooking time (both required and actual) per household was then calculated by adding up the operating time of all the stoves in use (Table 5.38). Overall, both districts combined, the average actual biogas stove burning time in a biogas household was 2.27 hours/day (SE = 0.04) in summer and 1.60 hours/day (SE = 0.04) in winter, whilst the average daily required biogas stove operating time was 2.72 hours/day (SE = 0.03) in summer and 2.91 hours/day (SE = 0.04) in winter. This shows that on average, biogas production per household was not sufficient for 27 minutes/day (SE = 0.030) during summer and 79 minutes/day (SE = 0.038) during winter.

Table 5.38: Required and actual biogas stove burning time

District	Summer (hour/day)		Winter (hour/day)	
	Required burning time	Actual burning time	Required burning time	Actual burning time
Chitwan	2.83 (0.039)	2.48 (0.050)	3.06 (0.047)	1.84 (0.049)
Lamjung	2.61 (0.040)	2.07 (0.054)	2.76 (0.053)	1.35 (0.045)

Note: Figures in parenthesis are standard errors.

Source: Field Survey, 2012

In terms of districts, the average required and actual stove burning time per household in Chitwan during summer was 2.83 hours/day (SE = 0.039) and 2.48 hours/day (SE = 0.050), while that during winter was 3.06 hours/day (SE = 0.047) and 1.84 hours/day (SE = 0.049), respectively. The average daily biogas deficit in the district in terms of required stove burning time was 21 minutes (SE = 0.043) in summer and 73 minutes (SE = 0.059) in winter. In Lamjung district, the average required and actual stove burning time per household during summer was 2.61 hours/day (SE = 0.040) and 2.07 hours/day (0.054), and that during winter was 2.76 hours/day (SE = 0.053) and 1.35 hours/day (SE = 0.045), respectively. The average daily biogas deficit in the district in terms of required stove burning time was 32 minutes (SE = 0.040) in summer and 85 minutes (SE = 0.047) in winter. The reasons for the lower gas availability in Lamjung district could be due to the colder climate of the district and lesser quantity of feedstock available compared to Chitwan. Fuelwood, LPG and/or electricity were used in both districts to cover the biogas deficit (Figure 5.16).

Figure 5.16: Use of fuelwood and LPG in a Lamjung household

The average daily biogas demand per household was calculated by multiplying gas consumption rate of the biogas stoves in use with average daily required stove operating (cooking) time. The gas consumption rate of the GGC 2047 model biogas stove as used in Nepal was 400 litres/hour (BSP-Nepal, 2012b). Similarly, the daily average biogas consumption per household was calculated by multiplying gas the consumption rate of the biogas stoves used with the daily actual stove operating time.

The daily energy consumption was then converted into equivalent energy using the gross calorific values of each type of energy source (Table 5.39).

Table 5.39: Average daily biogas demand and consumption per household

District	Biogas demand (m^3)		Biogas consumption (m^3)		Deficit (m^3)	
	Summer	Winter	Summer	Winter	Summer	Winter
Chitwan	1.13 (27.5) *[0.015]*	1.22 (29.7) *[0.020]*	0.99 (24.1) *[0.019]*	0.74 (17.9) *[0.019]*	0.14 (3.4) *[0.017]*	0.49 (11.9) *[0.023]*
Lamjung	1.04 (25.4) *[0.016]*	1.10 (26.8) *[0.022]*	0.83 (20.1) *[0.021]*	0.54 (13.1) *[0.018]*	0.22 (5.2) *[0.016]*	0.56 (13.7) *[0.019]*

Note: Figures in parenthesis are energy equivalent in MJ, taking 1 m^3 biogas = 24.3 MJ (WECS, 1994).
Figures in brackets [ ] are standard errors.

Source: Field Survey, 2012

The results show that daily average biogas deficit per household in summer and winter was 0.14 m^3 (3.4 MJ) and 0.49 m^3 (11.9 MJ) in Chitwan, and 0.22 m^3 (5.2 MJ) and 0.56 m^3 (13.7 MJ) in Lamjung, respectively (Table 5.39). This indicated that 87% and 79% of the biogas demand for cooking during summer was fulfilled in Chitwan and Lamjung, respectively, whereas only 60% (SE = 3.89) and 49% (SE = 3.99) of the demand during winter was fulfilled in the two districts, respectively.

5.6.2 Reasons for lower biogas production

The respondents were asked about the reasons for low gas production. A household mentioned/chose more than one reason for lower gas production. Lower temperature was felt as a main reason for less gas production during winter in 76% (SE = 3.3) and 87% (SE = 2.59) of households in Chitwan and Lamjung, respectively (Table 5.40). Similarly, insufficient feedstock, lower than the prescribed amount, fed into the digester was considered as another major reason in 49% (SE = 3.99) of households in Chitwan and 46% (SE = 3.98) of households in Lamjung. Besides, 13% (SE = 2.68) of households in Chitwan and 20% (SE = 3.19) in Lamjung did not feed the digester daily, and this irregular feeding practice could be another reason for lower gas production.

Table 5.40: Reasons for lower gas production

Reasons	Chitwan	Lamjung
Insufficient feedstock	77 (49)	72 (46)
Cold in winter	119 (76)	137 (87)
No daily digester feeding	21 (13)	31 (20)
Technical problems	72 (46)	26 (17)
Older plant	37 (24)	68 (43)
Use of chemical to clean toilet	2 (1)	1 (0.6)
Small plant size	1 (0.6)	6 (4)
Don't know the reason	21 (13)	1 (0.6)

Note: Chi-squared value 56.1 at 7 d.f., p-value = 9.02 E-10 for comparison of districts.
Figures in parenthesis are percentages.

Source: Field Survey, 2012

Moreover, 46% (SE = 3.98) of households in Chitwan and 17% (SE = 2.99) in Lamjung experienced technical problems such as pipe leakages, pipe blockage, and main valve leakage (Section 5.3.9). Gas loss due to such leakages was reported as another factor for less gas availability for cooking. About 24% (SE = 3.41) of households in Chitwan and 43% (SE = 3.95) in Lamjung felt that the relatively poor performance of older plants was the reason for less gas production. Use of chemicals to clean toilets attached to the biogas plants was also reported in three households, which inhibited development of bacteria and hence decreased biogas production. One household in Chitwan and six in Lamjung realised that their biogas plants (4 m^3) were too small to hold enough gas to meet their cooking demand. However, 13% (SE = 2.68) of households in Chitwan were not sure about the reasons for lower biogas production. The Chi-square test at 5% level showed that there is statistically significant difference in the reasons for lower gas production between the two districts (Table 5.40), with more households in Chitwan not knowing much about reasons for lower gas production and experiencing technical problems, and more households in Lamjung having older plants and not feeding the digester daily with the prescribed amount of dung.

5.6.3 Efficiency of biogas plants

In order to evaluate the performance of the biogas plants under study, efficiency of the biogas plants was calculated in terms of (i) plant size and biogas output, and (ii) actual daily feeding and stove burning hour (Section 4.7.1). The average theoretical amount of gas production based upon the plant size (considering fully fed plant) was calculated to be 1.54 m^3/day/plant in Chitwan and 1.37 m^3/day/plant in Lamjung (Table 5.41).

Total biogas production per plant based on gas being used was 0.86 m^3/day/plant in Chitwan and 0.69 m^3/day/plant in Lamjung. Thus the efficiency of the biogas plants based upon their size and biogas use was found to be 56% (SE = 3.96) in Chitwan and 50% (SE = 3.99) in Lamjung, indicating that the plants were performing poorly in terms of their potential, based upon their size. Similarly, the efficiency of the plants based upon actual dung feeding and actual stove burning hour was calculated to be 73% (SE = 3.54) in both the districts, indicating that the plants were under-performing even in terms of potential based upon actual feeding.

Table 5.41: Average efficiency of biogas plants in the study districts

Description	Chitwan	Lamjung
Theoretical biogas production based upon plant size (m^3/day)	1.54 (0.061)	1.37 (0.069)
Required quantity of feeding material (dung) (kg/day per plant)	38.5 (0.61)	34.2 (0.69)
Available quantity of feeding material (dung/human waste) (kg/day)	32.2 (1.13)	31.7 (1.22)
Actual quantity of feedstock fed into the digester (kg/day)	29.6 (0.94)	23.6 (0.72)
Actual to required feeding ratio	0.92 (0.01)	0.74 (0.013)
Theoretical gas production based upon actual feeding (m^3/day)	1.18 (0.038)	0.94 (0.029)
Actual gas being produced based upon stove burning hour (m^3/day)	0.86 (0.019)	0.69 (0.029)
Efficiency of biogas plants based upon their size and biogas use	56% (3.96)	50% (3.99)
Efficiency of biogas plants based on actual feeding and stove burning hour	73% (3.54)	73% (3.54)
Required quantity of gas based upon required stove burning hour (m^3/day)	1.2 (0.03)	1.1 (0.04)
Theoretical gas production if all available dung were fed (m^3/day)	1.29 (0.045)	1.27 (0.049)
Efficiency of biogas plants if all available dung were fed	84% (2.92)	87% (2.68)
Required efficiency of the plants to meet biogas demand based upon required stove burning hour	93% (2.03)	92% (2.16)

Note: Figures in parenthesis are standard errors.

Source: Field Survey, 2012

The efficiency of the plants based on the theoretical quantity of gas production would increase to 84% (SE = 2.92) in Chitwan and 87% (SE = 2.68) in Lamjung, if all the available feedstock was fed into the digester (i.e., when actual to required feeding ratio is 1). This highlights that the quantity of feedstock fed into the digester plays an important role in increasing the efficiency of biogas plants to produce sufficient biogas for cooking, although other factors might also have an influence on biogas production. As the required efficiency of the plants to meet the demand for biogas based upon required stove burning hour is estimated to be at 93% (SE = 2.03) in Chitwan and 92% (SE = 2.16) in Lamjung, it seems difficult to achieve the required efficiency of the plants under the existing digester feeding practices. This finding, therefore, supports the rationale of co-digestion of animal dung with other organic materials, such as agricultural residues in order to enhance biogas production through increased efficiency of the plants.

Table 5.42: Performances of different size biogas plants

Efficiency (%)	Number of households				Total	Chi-square
	4 m^3	6 m^3	8 m^3	10 m^3		
Chitwan						
20 – 40	1 (4)	18 (69)	5 (19)	2 (8)	26 (100)	7.98 at 12 d.f., p-value = 0.78
41 – 60	6 (5)	50 (67)	11 (16)	1 (2)	68 (100)	
61 – 80	2 (5)	28 (67)	9 (21)	3 (7)	42 (100)	
81 – 100	2 (14)	10 (72)	1 (7)	1 (7)	14 (100)	
>100	0	4 (57)	2 (29)	1 (14)	7 (100)	
Lamjung						
20 – 40	9 (26)	20 (59)	4 (12)	1 (3)	34 (100)	8.37 at 12 d.f., p-value = 0.76
41 – 60	16 (30)	29 (53)	7 (13)	2 (4)	54 (100)	
61 – 80	10 (30)	17 (53)	5 (17)	0	32 (100)	
81 – 100	9 (41)	11 (50)	2 (9)	0	22 (100)	
> 100	7 (47)	5 (33)	3 (20)	0	15 (100)	

Note: Figures in parenthesis are row percentages.

Source: Field Survey, 2012

The performance of different size biogas plants based upon theoretical gas production from the actual quantity of dung fed and actual stove burning hours is presented in Table 5.42. None of the biogas plants under study were performing too low (less than 20% efficiency), but the efficiency of 16% (SE = 2.91) of plants in Chitwan and 22% (SE = 3.30) of plants in Lamjung was less than 40%. The efficiency of 43% (SE = 3.95) of plants in Chitwan and 34% (SE = 3.78) of plants in Lamjung was between 41% and 60%. The efficiency of 9% (SE = 2.27) plants in Chitwan and 14% (SE = 2.76) plants in Lamjung was between 81% and 100%, whilst that of 27% (SE = 3.54) of plants in Chitwan and 20% (SE = 3.19) plants in Lamjung was between 61% and 80%. Biogas plant of 6 m^3 size was found to be the most efficient. It is interesting to note that the efficiency of 4% of biogas plants in Chitwan and 10% in Lamjung exceeded 100%, which theoretically is not possible. The reason is that the formula to calculate efficiency is based upon amount of feedstock fed into the digester daily; the efficiency of the 22 over-fed plants (fed more than the daily prescribed quantity of feedstock) resulted in efficiency of more than 100%. The Chi-square test, however, showed no statistically significant difference in performance of biogas plants by size in both the districts.

CHAPTER SIX

IMPROVING BIOGAS PRODUCTION EFFICIENCY THROUGH CO-DIGESTION OF MIXED FEEDSTOCKS

6.1 Introduction

The previous chapter analysed the demand and consumption patterns of biogas and identified the main reasons for lower biogas production. Co-digestion of different organic materials, such as municipal solid wastes and energy crops with cattle manure, has been practised in large-scale biogas production around the world to supplement feedstock deficit and increase biogas production efficiency (e.g., Angelidaki et al., 2009), but application of this technology in domestic biogas system is limited. Despite having potential to improve biogas production through co-digestion of crop residues with dung to meet the household energy demands all year round, the biogas development sector in Nepal lacks information about it. Hence, how much biogas can be increased by co-digestion, and what would be its implications on energy costs (Chapter 7), energy consumption and associated environmental emissions (Chapter 8), are analysed in this study

This chapter, therefore, aims to address the problem of low biogas production, mainly due to insufficient feedstock supply as in the context of domestic biogas production in Nepal by exploring the potential for improving production efficiency of biogas plant through co-digestion of crop residues with animal dung and human excreta. The main objectives of this chapter are to explore the theoretical biochemical methane productivity (BMP_{th}) of individual substrates and their co-digestion mixtures at various proportions using methane prediction methods, and to determine appropriate ratios of the co-substrates in co-digestion for optimising the production efficiency of biogas plants. It focuses on technical aspects of improving biogas production through co-digestion (Section 1.3, Research Objectives no.4) and specifically addresses the following questions:

1) What is the biogas production potential of dung, human excreta and selected crop residues?
2) How much biogas production can be increased through co-digestion, and what proportion of the feedstocks is suitable for it?
3) What is the effect of temperature on biogas yield?

4) What factors affect improving biogas production efficiency through co-digestion in household-level biogas systems in Nepal?

This chapter first discusses the characteristics of feedstocks considered for anaerobic co-digestion (i.e., dung and crop residues) and are available in the rural households of Nepal. Theoretical methane productivity of individual feedstocks is then predicted using three widely recognised models, and the results are compared with the experimental values from the literature in order to validate them and evaluate the ability of these theoretical models to accurately estimate methane productivity. Effect of co-digestion on methane productivity over a conventional dung-only digestion process is then evaluated and optimum co-digestion ratios for these substrates are estimated. A range of co-digestion mixtures were selected for this analysis in order to cover all the possibilities that allow co-digestion in real biogas digesters in order to achieve the optimum conditions for obtaining the best biogas productivity. The volumetric methane production (VMP) is then assessed with respect to different temperatures both at mono-digestion and co-digestion conditions. Finally, factors affecting co-digestion and suitability of the existing biogas plant design in Nepal are discussed.

6.2 Characteristics of Available Feedstocks for Biogas Production

Buffalo dung, cattle dung and human excreta[42] were the main feedstocks used for biogas production in the surveyed households, and in almost all biogas plants in Nepal, but were not sufficient to meet daily prescribed feedstock requirement (Section 5.3.6). Crop residues, which have good biogas production potential (Li, Zhang et al., 2013) and are available in the households to use as feedstock, could be suitable to supplement the daily feedstock deficit. Understanding the characteristics of individual feedstocks, such as total solids, volatile solids, chemical oxygen demand (COD) concentration, elemental composition (carbon, hydrogen, oxygen, nitrogen) or organic component composition (carbohydrates, lipid, protein) is important before utilising them efficiently for biogas production (Section 2.2, Figure 2.3). The characteristics determine the biogas production potential, and the efficiency of a biogas plant depends on the production potentials of the substrates (Deublein & Steinhauser, 2011).

Experimental analysis to determine the exact chemical composition of the feedstocks was not within the scope of this study, so the measured chemical compositions described in the literature were used. However, the measured chemical characteristics

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[42] About 90% of plants in the surveyed households (Field Survey, 2012) and 70% plants nationwide are connected with toilets (BSP-Nepal, 2012b).

ranged widely in the literature due to variation in bio-physical-chemical conditions of the feedstocks (e.g., Chandra et al., 2012b; Daisy and Kamaraj, 2011; Fuchigami, et al., 2001; Kalle and Menon, 1984; Meher, et al.,1994; Moller, et al., 2004;Omar, et al., 2008; Sahito et al., 2013, 2014; Steffen, et al.,1998; Watanabe, et al., 1993; Y. Li, Zhang, et al., 2013; Zhong et al., 2012). For example, the differences in chemical characteristics of dung may be due to different breed and growth stages of the animals and their diet that varies from farm to farm or from country to country (Amon et al., 2007; Labatut & Scott, 2008; Moller et al., 2004). Similarly, varied characteristics of crop residues may be accounted for by different varieties of crop, different age and harvesting stages/seasons or grown in different climatic conditions (R. Alvarez et al., 2006; Amon et al., 2007; Labatut & Scott, 2008; Moller et al., 2004). The feedstock characteristics of the available feedstocks for predicting theoretical biogas production was determined by computing a value that best fits the experimental values.

The measured characteristics (values) for each feedstock type from the literature were first summarised (Annex 9), and then plotted in a scatter diagram individually to draw a line of best-fit. The best-fit value, i.e., the data point that fell on the line or closest to the best-fit line was considered as the ultimate characteristics of the feedstock (Table 6.1). However, for the case of buffalo dung and human excreta, due to the limited availability of data, the values were selected directly from the available literature.

Table 6.1: Typical characteristics of livestock dung and crop residues as feedstock

Feedstock	Buffalo dung	Cattle dung	Rice straw	Wheat straw	Corn stover	Human excreta
Total solid TS (%)	19	16.7	84	88.9	84.9	20
Volatile solid (VS) (% TS)	71.8	80	79.5	83.5	76.9	75
Carbon (% TS)	37.8	37.6	41	42.7	46.2	38.8
Hydrogen (% TS)	4.3	5.1	5.4	5.7	5.9	5.4
Oxygen (% TS)	40.1	42.9	38.2	39.6	43.3	40
Nitrogen (% TS)	1.6	1.8	0.7	0.5	0.8	5
C/N ratio	23.6	20.9	53.7	85.4	54	7.8
Carbohydrate (% VS)	45.6	43.5	79.0	72.3	78.0	52.0
Protein (% VS)	16.4	17.0	5.6	3.8	5.0	17.6
Lipid (% VS)	6.2	6.9	5.9	2.3	5.1	5.6
Volatile fatty acid (VFA)(% VS)	2.7	3.6	0	0	0	2.9
Lignin (% VS)	8.9	7.9	10.8	11.8	10.3	6.4

Note: See Annex 9 for the measured characteristics of each feedstock from literature.

6.2.1 Animal dung

Buffalo and cattle dung were the major feedstocks used in biogas digesters in the surveyed households (and also throughout the country), and hence they were considered as major substrates for co-digestion with crop residues. Animal dung contains suitable bacteria for anaerobic digestion and provides buffering capacity[43] and a wide range of micro-nutrients needed for anaerobic digestion during co-digestion with crop residues (Lehtomaki et al., 2007; Sahito, Mahar, & Brohi, 2013). Although dung has a much lower TS content than crop residues, it is still greater than the minimum range of 5-15% necessary for anaerobic digestion (Werner et al., 1989). Dung has a slightly lower carbon content than crop residues (Table 6.1). Higher carbon content usually results in higher methane potential (Lehtomaki et al., 2007). Animal dung has the C/N ratio within the optimum range of 20-30 which is suitable for biogas production (Omar et al., 2008; Sahito et al., 2013). However, dung usually contains high ammonia concentration that could inhibit the anaerobic digestion process (Lehtomaki et al., 2007). Hence, co-digestion of dung with crop residues of higher C/N ratios balances the C/N ratio and decreases the risk of ammonia inhibition.

The methane production potential of dung is also determined by carbohydrate, protein and lipid contents. Carbohydrate content in dung is lower than the selected crop residues (Table 6.1), but is still suitable for methane production (Y. Li, Zhang, et al., 2013). Comparatively higher protein and lipid contents make dung more favourable for biogas production, since higher protein and lipid results in higher methane production potential (Moller et al., 2004).

6.2.2 Crop residues

Crop residues have good potential as a biogas feedstock due to their carbon characteristics (Zhang, et al., 2013). The residues considered here have a higher percentage of carbon content, suggesting higher methane production potential (Lehtomaki et al., 2007). The VS content, which characterises the amount of digestible organic matter that can be converted into biogas, is also higher in the crop residues than in dung or human excreta. But C/N ratios of crop residues are much higher than the optimum of 20-30 for anaerobic digestion (e.g., Demirbas, 2006; Y. Li, Liu, et al., 2013), so a nitrogen supplement is needed to enhance biogas production from crop residues, which can be achieved by co-digestion with animal dung to give a lower average C/N ratio.

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[43] A substrate's ability to maintain a stable pH with the addition of small amounts of base or acid (Lehtomaki, Huttunen, & Rintala, 2007).

Crop residues have higher carbohydrate content, but comparatively lower protein and lipid content than animal dung (Table 6.1). Although lower protein and lipid contents may result in lower biogas production, higher carbohydrates and lignin contents increase the biogas production potential of crop residues (Luostarinen, Normak, & Edström, 2011). However, the literature suggested zero VFA content in the crop residues (Y. Li, Zhang, et al., 2013).

6.2.3 Human excreta

Human excreta is another feedstock conveniently available and used in 90% of the surveyed households. It not only generates energy as a supplement to insufficient feedstock but also solves the waste management problem in the rural households, since *open* defecation used to be a major *problem* in some rural villages (UNICEF, 2013). Despite lower TS content, it has a significant amount of carbon content making it a suitable feedstock. It has a much higher protein content than other feedstocks (Meher, Murthy, & Gollakota, 1994), giving high methane production potential but affected by a low C/N ratio (Table 6.1). It is therefore best used in co-digestion with crop residues in order to balance the C/N ratio. The average proportion of human excreta fed into the biogas digester in the surveyed households was 7-12% of the total feedstock, depending on family size.

6.3 Theoretical Methane Potential of Individual Feedstocks

Three recognised methods of determining BMP_{th} based on elemental composition, organic fraction composition and chemical oxygen demand (COD) characterisation (e.g., Labatut, 2012; Lee, Chantrasakdakul, Kim, Kim, & Park, 2013; Nielfa, Cano, & Fdz-Polanco, 2014) were employed to estimate theoretical methane yield[44] from animal dung, selected crop residues and human excreta, using their biochemical characteristics presented in Table 6.1. The model predictions were then validated comparing them to the experimental biochemical methane production (BMP_{exp}) published in various literatures. Theoretical methods for predicting biochemical methane potential are capable of producing reasonable estimations of specific methane yields with lower error (Labatut, 2012; Lee et al., 2013; Nielfa et al., 2014), and hence are widely used to easily determine the methane productivity of a specific substrate for quick and reliable results and economic advantage (Nielfa et al., 2014). Even the experimental methane yields (from similar substrates) published in different literatures are usually not comparable due to differences in equipment used,

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[44] Methane production and methane yield are often used interchangeably.

environmental conditions and experimental protocols (Angelidaki et al., 2009), and they are validated by comparison with the theoretical values calculated using the prediction models (Triolo et al., 2011).

In addition, in the context of existing biogas plant design in Nepal where biogas is produced through digestion of mostly dung, and existing biogas production is usually not sufficient to meet the energy demand for household cooking all year round, the present need is to develop understanding and awareness among the agencies working in the development and promotion of domestic biogas systems of the potential to increase biogas production through co-digestion of crop residues with dung in order to fulfill the existing biogas deficit and reduce the associated high cost of energy (Chapter 7). Since this study anticipates helping to develop the understanding that co-digestion of crop residues with dung is capable of supplying enough biogas to meet most of the household energy needs for cooking, theoretical models would be sufficient to demonstrate that capability.

6.3.1 Elemental composition analysis method

This method predicts the methane yield through a general reaction of carbon stabilisation by using stoichiometric equation based on the carbon, oxygen, hydrogen and nitrogen composition of a feedstock (Angelidaki & Sanders, 2004; Labatut & Scott, 2008; Lesteur et al., 2010). This method was originally proposed by Symons and Buswell (1993), but it is still the most commonly used method for methane yield prediction (Angelidaki & Sanders, 2004; Labatut, 2012; Labatut & Scott, 2008; Lesteur et al., 2010; Y. Zhang, Banks, & Heaven, 2012). It estimates methane production from the anaerobic breakdown of an organic material with its generalised elemental composition formula, $C_nH_aO_bN_c$ (Banks, 2009), assuming that all the biodegradable organic materials present in the substrate are converted to methane, CO_2 and ammonia (Angelidaki & Sanders, 2004; Y. Li, Liu, et al., 2013).

The elemental composition formula of a substrate was derived based on the elemental composition data, i.e., content (%) of each element (C, H, O, N) in a molecule of the compound (Table 6.1), using the method explained in Silberberg (2010) and Ladon (2001). In order to compare these elements to each other stoichiometrically, they were expressed in terms of moles (Ladon, 2001; Silberberg, 2010). Assuming that the total mass of the elements is 100 gm and the mass of each element is the percent given, the number of moles of each element was calculated by dividing the number of grams of each element by the atomic weight of the element from the periodic table. The empirical formula is then determined by a stoichiometric comparison between the elements, by dividing each of the mole values by the smallest number of moles calculated (Ladon, 2001; Silberberg, 2010) (Table 6.2).

Table 6.2: Elemental composition formula and BMP_{th} of the selected feedstocks

Feedstock	Elemental composition formula	BMP_{th} (m^3/kg VS)		
		Elemental composition	Organic fraction composition	COD stabilisation
Buffalo dung	$C_{27.56}H_{37.63}O_{21.93}N$	0.386	0.408	0.405
Cattle dung	$C_{24.37}H_{39.67}O_{20.85}N$	0.381	0.406	0.401
Rice straw	$C_{68.33}H_{108}O_{47.75}N$	0.464	0.494	0.473
Wheat straw	$C_{99.63}H_{159.60}O_{69.30}N$	0.471	0.475	0.477
Corn stover	$C_{77.0}H_{118.0}O_{54.13}N$	0.459	0.475	0.466
Human excreta	$C_{9.05}H_{15.12}O_{7.0}N$	0.385	0.417	0.443

Note: Elemental composition formula was calculated by using Buswell Formula presented at equation 6.1.

If the elemental composition of an organic matter is known and all the material is converted to biogas, the molecular composition equation can be derived by using the Buswell equation (Equation 6.1) (Angelidaki & Sanders, 2004; Y. Li, Liu, et al., 2013).

$$C_nH_aO_bN_c + (n- a/4 -b/2 +3c/4)H_2O = (n/2 + a/8 -b/4 -3c/8)CH_4 + (n/2 - a/8 + b/4 +3c/8)CO_2 + cNH_3 \qquad \text{(Equation 6.1)}$$

The BMP_{th} can then be calculated using Equation 6.2 (Angelidaki & Sanders, 2004) (Table 6.2):

$$BMP_{th}\ (m^3\ CH_4/kg\ VS) = 22.4 * (n/2 + a/8 - b/4 - 3c/8) / (12n + a + 16\ b + 14c) \qquad \text{(Equation 6.2)}$$

The BMP_{th} of buffalo dung, cattle dung and human excreta calculated from the elemental composition analysis method are almost similar, but lower than the crop residues (Table 6.2). The BMP_{th} of wheat straw was the highest among the crop residues.

6.3.2 Organic composition analysis method

It is often difficult to find out the chemical composition of each and every particular substrate (Labatut & Scott, 2008). In such case, the BMP_{th} can be calculated by organic composition analysis of the substrates using the Buswell formula (Equation

6.1). Organic matter can be separated into easily biodegradable compounds such as protein, carbohydrate, lipids, volatile fatty acid, and poorly biodegradable compounds such as hemi-cellulose and lignin (Koch et al., 2010; Lesteur et al., 2010; Moller et al., 2004), which are the major organic components that affect biogas production (Moller et al., 2004; Triolo et al., 2011). As the contents of C, H, O, and N are different for different substrates, the organic compositions of protein, carbohydrate and lipids are different (Section 2.2), and biogas yields also vary accordingly. Lipid or organic fat is good for biogas production from both yield and methane content perspectives. Carbohydrate gives higher biogas yield than protein but methane contents are high from protein (Koch et al., 2010; Lesteur et al., 2010). Lignin and volatile fatty acid are also taken into account in biogas production (Angelidaki & Sanders, 2004; Moller et al., 2004; Triolo et al., 2011). However, due to high lignocellulose/fibre content, lignin is very resistant to anaerobic degradation, e.g., 44% of fermentable material in wheat straw is shielded by lignin (Robbins, Armold, & Lacher, 1979).

If the organic compositions of a substrate are known, the BMP_{th} can also be calculated using stoichiometric conversion of the compounds, using Equation 6.5 (Angelidaki & Sanders, 2004; Moller et al., 2004; Triolo et al., 2011):

$$BMP_{th} = (0.373*VFA + 1.014*Lipid + 0.496*Protein + 0.415*Carbohydrate + 0.727*Lignin) / 100 \tag{Equation 6.3}$$

where, BMP_{th} is m^3/kg VS, and VFA, lipid, protein, carbohydrate and lignin are % of VS. The BMP_{th} calculated based on the organic composition of feedstocks were slightly higher than the elemental composition method for all feedstocks, but followed the same behaviour as the elemental composition method, where methane yield potential of crop residues was higher than dung (Table 6.2). The BMP_{th} of rice straw was the highest because of higher contents of protein and lipid than other residues.

6.3.3 COD stabilisation method

The COD stabilisation method is another commonly used method for predicting biogas production (Labatut, 2012). The COD is the amount of oxygen required to completely oxidise an organic compound to CO_2 and water (Grady, Daigger, Love, & Filipe, 2011). This method measures the strength of a feedstock for its suitability for anaerobic digestion; an organic material with high COD has a high potential of biogas yield (Grady et al., 2011; Tchobanoglous et al., 2003). The COD stabilisation is the stoichiometric relationship between the COD destroyed during the anaerobic digestion and the methane produced, where one mole of methane requires two moles of oxygen to completely oxidise into one mole of CO_2 and two moles of water (Equation 6.4) (Grady et al., 2011).

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O \qquad \text{(Equation 6.4)}$$

Since one mole of an ideal gas occupies 22.4 l at STP and two moles of oxygen contain 64 g COD, the BMP_{th} from COD stabilisation is 0.35 l/g of COD converted (Henze, van Loosdrecht, Ekama, & Brdjanovic, 2008; Labatut & Scott, 2008, p. 11). Assuming that 100% of the substrate is degraded anaerobically, the COD/VS ratio can be used to estimate methane production (Equation 6.5) (Hansen, 2005; Labatut & Scott, 2008):

$$BMP_{th}\ (l / g\ VS) = 0.35 * COD/VS \qquad \text{(Equation 6.5)}$$

The relationship between COD and VS content can be obtained by the stoichiometry of complete oxidation of the organic material (Angelidaki & Sanders, 2004, p. 125). The oxidation reaction for an organic material $C_aH_bO_c$ can be generalised as (Equation 6.6):

$$C_aH_bO_c + (a + b/4 - c/2)\ O_2 = a\ CO_2 + b/2\ H_2O \qquad \text{(Equation 6.6)}$$

and the COD/VS ratio can be calculated using Equation 6.9 (Angelidaki & Sanders, 2004, p. 125):

$$COD/VS = \frac{(a + b/4 - c/2)*32}{12a + b + 16c} \qquad \text{(Equation 6.7)}$$

The predicted methane yield for various substrates using COD/VS ratio (Equation 6.7 and 6.9) shows that the yield from buffalo dung and cattle dung is almost the same, whereas the yields from rice straw, wheat straw and corn stover are higher at 0.473, 0.477 and 0.466 m^3/kg VS, respectively (Table 6.2). The methane yield from human excreta is 0.461 m^3/kg VS, which is slightly lower than from crop residues, but higher than from cattle/buffalo dung.

6.3.4 Evaluation of methane prediction methods

Although feedstocks are variable in nature in terms of their biodegradability characteristics, the BMP_{th} presented in this study seems to have a considerably good comparison with the reported in literature. The BMP_{th} of buffalo dung in this study compares with Sahito et al. (2014) of 0.391 m^3/kg VS. Similarly, the theoretical yield of cattle dung is like that of Omar et al. (2008) of 0.393 m^3/kg VS, but slightly lower than Moller et al. (2004) of 0.468 m3/kg VS and Triolo et al. (2011) of 0.443 m^3/kg VS due to higher carbon contents reported in the literature. The BMP_{th} of rice straw, 0.460 m^3/kg VS reported by Li, et al. (2013) and 0.432 m^3/kg VS by Sahito et al. (2013) are also close to this study's findings. In the case of wheat straw, the predicted yield compares with 0.473 m^3/kg VS reported by Sahito et al. (2013), 0.466 m^3/kg VS by Triolo et al. (2011) and 0.456 m^3/kg VS by Li, et al. (2013). Likewise, the yield of corn stover reported here is within the range of 0.455-0.469 m^3/kg VS reported by Li, et al. (2013).

In order to evaluate the accuracy of the predicted methane yields and ability of the theoretical models to accurately estimate the yields, this study compared and validated the theoretical yields with the measured yields reported in the literature. Performing a small-scale biochemical methane production experiment would be the best way to predict the expected methane yield under practical conditions, since feedstock characteristics and ultimate biogas production potential greatly depend on physical features, climatic conditions and genetic status of the feedstock source (Angelidaki & Sanders, 2004; Labatut, 2012). But in the absence of an experiment, the accuracy of the predicted yield and validity of the methods can be better evaluated by finding experimentally determined biogas yields in the literature and comparing the theoretical productivity (BMP_{th}) with the experimental productivity, BMP_{exp} (Amon et al., 2007; Angelidaki & Sanders, 2004; Nielfa et al., 2014).

The BMP_{exp} from a particular substrate ranged widely (Table 6.3). The yield from buffalo dung and cattle dung ranged from 0.147-0.540 m^3/kg VS and 0.131-0.360 m^3/kg VS, respectively. Similarly, the BMP_{exp} of crop residues also varied greatly from 0.132-0.350 m^3/kg VS for rice straw, 0.245-0.400 m^3/kg VS for wheat straw and 0.214-0.338 m^3/kg VS for corn stover. The variation in the experimental yield of a substrate could be accounted by differences in equipment used, environmental conditions, experimental protocols (Angelidaki et al., 2009), and varied characteristic biodegradability of the substrate, which can be defined as its capacity to decompose easily by chemical action under anaerobic conditions (Labatut et al., 2010; Li, et al., 2013). In order to compare with the theoretical values, a best-fit value from a range of measured values was computed (Table 6.3).

Table 6.3: Measured methane yields of the selected feedstocks reported in literature

Feedstock	Measured yield (m3/kg VS)	Reference	Best-fit value (m^3/kg VS)
Buffalo dung	0.147	Prateek, et al. (2009)	0.284
	0.284	Abdel-Hadi & Abd El-Azeem (2008)	
	0.391	Sahito, et al. (2014)	
Cattle dung	0.148	Moller, et al. (2004)	0.283
	0.184	Omar, et al. (2008)	
	0.24	IPCC (2007)	
	0.25	Steffen, et al. (1998)	
	0.283	Kumari, et al. (2012)	
	0.3	Ojoli, et al. (2007)	
	0.36	Chynoweth, et al. (1993)	
Rice straw	0.132	Chandra et al., (2012a)	0.302
	0.17	Sahito et al. (2013)	
	0.281	Y. Li, et al. (2013)	
	0.302	Chandra, et al. (2012b)	
	0.35	Lei, et al. (2010)	
Wheat straw	0.245	Y. Li, et al. (2013)	0.322
	0.255	Gunaseelan (1997)	
	0.29	Chandra, et al. (2012b)	
	0.322	Sahito et al. (2013)	
	0.4	Steffen, et al. (1998)	
Corn stover	0.214	Li, et al. (2013)	0.312
	0.241	Y. Li, et al. (2013)	
	0.312	Mumme, et al. (2010)	
	0.338	Chandra, et al. (2012b)	
Human excreta	0.184	Meher, et al. (1994)	0.184

Despite the method used, the predicted methane yields (Table 6.2) are higher than the measured yields for all organic substrates (Table 6.3), which matches with the findings of various literatures (Angelidaki & Sanders, 2004; Labatut, 2012; Y. Li, Zhang, et al., 2013; Moller et al., 2004; Nielfa et al., 2014). The probable cause of the differences could be either experimental error or high variability of the substrate source (Angelidaki & Sanders, 2004; Labatut & Scott, 2008). The differences in methane yield from animal dung may be accounted for by different types of animal diet, since nutrition levels affect the chemical characteristics of the dung, which determines the biodegradability of the substrate (Amon et al., 2007; Moller et al., 2004). Difference in methane yield from a particular crop residue can be explained by different varieties of the crop having different lignocellulose content, or grown in different climatic conditions that affect the amount of lignocellulose content and hence the biodegradability of the substrates

(Ertem, 2011; Moller et al., 2004). Temperature could be another reason for the difference in the measured and theoretical methane yields, since methane production experiments were carried out at different temperatures than the standard temperature pressure conditions (Angelidaki & Sanders, 2004; Labatut & Scott, 2008).

The literature suggests that the theoretical biogas yield is always higher than the measured yield because the theoretical methods consider both biodegradable and non-biodegradable components of the organic matter and assume 100% anaerobic degradability of the substrate (Angelidaki & Sanders, 2004; Labatut, 2012; Y. Li, Zhang, et al., 2013). But a precise prediction of methane yield depends on the accuracy of the anaerobic degradability of the substrates (Labatut, 2012; Labatut & Scott, 2008) and estimation of substrate biodegradable fraction (f_D) is one of the most widely used analytical methods to determine the biodegradability of a substrate under anaerobic conditions (Labatut, 2012). It is the ratio of degradable chemical oxygen demand (COD_D) to total chemical oxygen demand (COD_T) (Equation 6.8). The COD_T, which is the COD/VS ratio, can be determined analytically for each substrate using Equation 6.7, whereas COD_D can be calculated as the product of measured methane yield and the theoretical 350 ml CH_4/g COD stabilised (Labatut, 2012; McCarty, 1964).

$$f_D = \frac{COD_D}{COD_T} \qquad \text{(Equation 6.8)}$$

Table 6.4 presents the biodegradable fraction (f_D) of the substrates using the substrates characteristics presented in Table 6.1 and the corrected theoretical methane yields using the fraction. The corrected theoretical yields are more comparable to the measured average yield for all the theoretical methods.

Table 6.4: Biodegradable fraction of the substrates and corrected methane yields

Substrate	Measured methane yield* (m^3/kg VS)	COD_T	COD_D	f_D	Corrected methane yield (m^3/kg VS)		
					Elemental composition	Organic composition	COD Stabilisation
Buffalo dung	0.284	1.16	0.81	0.70	0.270 (5)	0.285 (0)	0.283 (0)
Cattle dung	0.283	1.15	0.81	0.70	0.267 (6)	0.284 (0)	0.281 (1)
Rice straw	0.302	1.35	0.86	0.64	0.299 (1)	0.318 (-5)	0.305 (-1)
Wheat straw	0.322	1.36	0.92	0.70	0.331 (-3)	0.334 (-4)	0.335 (-4)
Corn stover	0.312	1.33	0.89	0.65	0.299 (-4)	0.309 (1)	0.303 (3)
Human excreta	0.184	1.27	0.53	0.40	0.153 (17)	0.166 (10)	0.176 (4)

Note: * Best-fit value of measured methane yield taken from Table 6.3.
Figures in parenthesis are relative error (%) obtained from comparing the measured and theoretical yields.

After correcting for substrate biodegradability, all three methane prediction methods produced results closer to the measured methane yields (Table 6.4). The highest relative error (%) obtained from Equation 6.9 comparing the experimental and theoretical methane yields is within 6% for all feedstocks, except for humane excreta.

$$\text{Relative error (\%)} = \frac{\text{Measured methane yield - Theoretical methane yield}}{\text{Measured methane yield}} \times 100 \qquad \text{(Equation 6.9)}$$

A line of best-fit was drawn between the average measured yields and corrected theoretical yields using the data in Table 6.4 for each of the methane prediction methods to see the linear association between the two yields (Figure 6.1), which is useful in predicting one variable from the other variable using the graph (Labatut, 2012). All the three methods demonstrate conformity higher than 95% with the measured data, which is determined by their coefficient of determination (R^2). This implies that when the substrate biodegradability data is available, all the three methods are suitable and capable of precise estimation of theoretical methane yields.

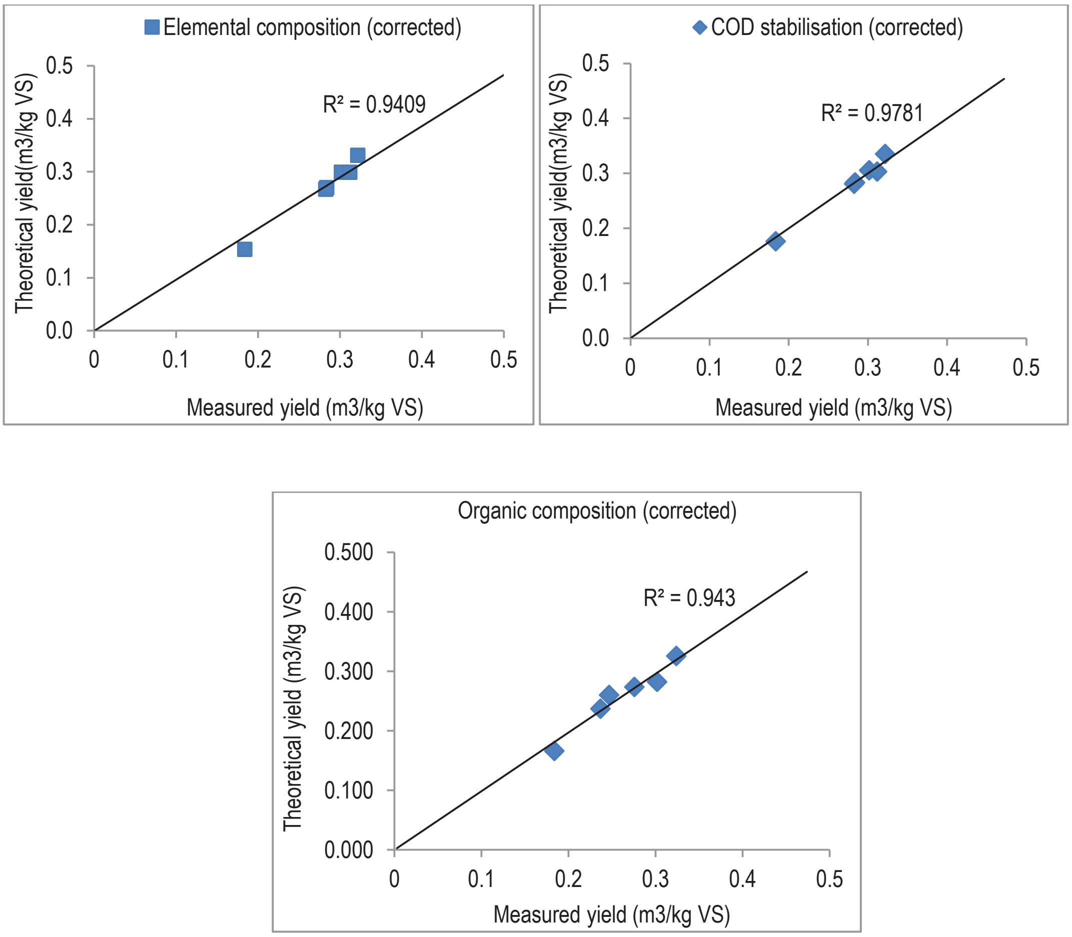

Figure 6.1: Measured vs theoretical methane yields after correcting for substrate biodegradability

6.3.5 Effect of temperature on methane yield

Temperature is one of the most important factors for the anaerobic fermentation process as it affects survival and growth of microorganisms, rate of microbial metabolism and thus methane yield (Angelidaki & Sanders, 2004; Werner et al., 1989). Methane prediction models estimate the amount of methane produced under anaerobic conditions at STP, so may not be accurate to generalise at other temperatures, particularly for a country like Nepal which has its topography ranging from low lying flat lands with tropical climate to high mountains with temperate/alpine climate (WECS, 2010). Installation of biogas plants are recommended for up to 3,000m altitude in Nepal (BSP-Nepal, 2012b). However, increase in elevation lowers the atmospheric and ambient temperature as well and affects biogas production because methane forming bacteria work more slowly at low temperatures (Chae, Jang, Yim, & Kim, 2008; Hashimoto et al., 1981; Werner et al., 1989). The theoretical methane yield at other than STP conditions can be estimated by using the universal gas law, which determines the volume of gas occupied by one mole of methane at the given temperature (Tchobanoglous et al., 2003). Various authors have established the relationship between methane production and temperature (e.g., Angelidaki & Sanders, 2004; Hashimoto et al., 1981; Safley & Westerman, 1992; Tchobanoglous et al., 2003; Toprak, 1995).The most common formula to predict average theoretical methane yield at a given ambient temperature 't' is generalised in Equation 6.10 (Tchobanoglous et al., 2003, pp. 992-993):

$$\text{Theoretical } CH_4 \text{ yield at } t\ °C = (CH_4 \text{ at STP}) * (273.15 + t) / 273.15 \qquad \text{(Equation 6.10)}$$

Equation 6.10 was used to predict the average theoretical methane yield for summer and winter in the study districts, using average summer and winter temperatures (Table 6.5). Average summer and winter temperatures in Chitwan are 29°C and 17°C, and in Lamjung are 23°C and 11°C, respectively (MSTE, 2013a). In general, methane yield from all the feedstocks increased with increase in ambient temperature, the increase being 11% in summer and 8% in winter in Chitwan and 6% in summer and 4% in winter in Lamjung (Table 6.5). Average methane yield during summer is higher than in winter in both districts for all the substrates. Thus it can be said that the higher biogas production in Chitwan compared with Lamjung as reported by the respondent households (see Section 5.6.1) was due to the higher average temperature of the district.

Table 6.5: Theoretical methane yield during summer and winter in Chitwan and Lamjung

Feedstock	At STP (m^3/kg VS)	Chitwan (m^3/kg VS)		Lamjung (m^3/kg VS)	
		At avg. summer temperature (29°C)	At avg. winter temperature (17°C)	At avg. summer temperature (23°C)	At avg. winter temperature (11°C)
Buffalo dung	0.386	0.427	0.418	0.410	0.401
Cattle dung	0.381	0.421	0.413	0.404	0.396
Rice straw	0.464	0.513	0.503	0.493	0.483
Wheat straw	0.471	0.521	0.510	0.500	0.490
Corn stover	0.459	0.506	0.496	0.486	0.476
Human excreta	0.385	0.426	0.417	0.409	0.400

6.3.6 Relationship between methane yield and quantity of feedstock

A multiple linear regression method was computed to understand the relationship between the total theoretical methane yield of a household obtained from the theoretical method based on elemental composition (dependent variable) and the quantity of feedstock (buffalo dung, cattle dung and human excreta) fed into the digester (independent variables) (Equation 6.11). This method estimates the coefficients of the linear equation from more than one independent variable that best predicts the value of the dependent variable (Allison, 1999). It is a method for examining how well a set of independent variables account for the dependent variable (Aiken, West, & Pitts, 2003).

$$BMP_{th}\ (m^3/\text{kg feedstock}) = \beta_1\ \text{Buffalo dung (kg)} + \beta_2\ \text{Cattle dung (kg)} + \beta_3\ \text{Human excreta (kg)} \qquad \text{(Equation 6.11)}$$

where, β_i are the parameters or regression coefficients.

The statistical software package SPSS, version 20 (IBM Corp., 2011) was used. The BMP_{th} in terms of substrate mass (m^3/kg feedstock) for each feedstock type was calculated by dividing the yield (m^3/kg VS) with VS conversion factor, where VS conversion factor is the quantity of feedstock required to produce 1 kg of VS and was calculated based on the TS% and VS% of the feedstock, i.e., [VS factor = 1 / (TS% * VS%)] (Bush, 1985).

The coefficients of regression for the estimation of methane yield from buffalo dung, cow dung and human excreta are presented in Table 6.6. The explanatory power of the model (R-square) was 1, meaning that all the variability of response data around its mean was explained by the model. Similarly, the coefficients of regression were highly significant ($p<0.01$) for all feedstock types (Table 6.6), showing a positive relationship with the predicted methane yield. This implies that, provided other conditions such as retention time, loading rate, pH of the substrate and digester temperature remain the same, the greater the quantity of buffalo/cattle dung and human excreta fed into the digester, the higher the methane yield.

Table 6.6: Coefficients of regression for the estimation of methane yield from buffalo dung, cattle dung and human excreta

Feedstock	Coefficient of regression
Buffalo dung	0.0529
Cattle dung	0.0508
Human excreta	0.0577

The contribution of each of the feedstocks to the net total methane yield can then be written as Equation 6.12.

$$BMP_{th}\ (m^3/kg\ feedstock) = 0.0529 * Buffalo\ dung\ (kg) + 0.0508 * Cattle\ dung\ (kg) + 0.0577 * Human\ excreta\ (kg) \quad \text{(Equation 6.12)}$$

6.4 Effect of Co-digestion on Methane Yield

Co-digestion of organic matter with manure to produce biogas has been studied by a number of researchers since the late 1980s and has highlighted the benefits of co-digestion on promoting the synergistic effect of co-substrates to increase methane yield (e.g., Alatriste-Mondragón, Samar, Cox, Ahring, & Iranpour, 2006; Hashimoto & Robinson, 1982; Labatut & Scott, 2008; X. Li, Li, Zheng, Fu, & Lar, 2009; Y. Li, Liu, et al., 2013) (Table 6.7). Domestic biogas production from dung, as practised in Nepal, has a relatively low gas yield due to the suboptimal performance of the plants (Lungkhimba et al., 2011). Dung has lower cellulose, lignocellulose, lignin and other organic components essential for bacterial growth and biogas production (Corro, Paniagua, Pal, Banuelos, & Rosas, 2013). Use of other organic materials such as agricultural residues with higher organic components as co-substrate can increase efficiency of the biogas plants by improving the overall biodegradability of the mixture and hence can provide a viable solution for the biogas deficit problem (Jingura & Matengaifa, 2009; Lungkhimba et al., 2011). However, co-digestion may not always result in increased methane yield; several factors such as pH inhibition, ammonia toxicity, and highly volatile acid concentration due to unsuitable mixing proportions could have an antagonistic effect reducing the digester performance (Alatriste-Mondragón et al., 2006; Labatut, 2012).

Table 6.7: Review of methane production calculation methods at different conditions

Authors	Feedstock used	HRT (days)	Temperature (°C)	Methods
Triolo, et al. (2011)	Energy crops and animal (pig and cattle slurry)	90	37 °C	• BMP assay tests to calculate BMP_{exp} • BMP_{th} calculated by using organic composition analysis method with lignin content consideration • Comparison of BMP_{th} and BMP_{exp}
Heo, et al., (2004)	Food waste and waste activated sludge	10 - 20	35 °C	• BMP assay tests to calculate BMP_{exp} • BMP_{th} calculated by using elemental composition analysis method (Buswell's formula) • Comparison of BMP_{th} and BMP_{exp}
Klimiuk, et al. (2010)	Energy crops and sewage sludge	60	29 °C	• BMP assay tests to calculate BMP_{exp} • BMP_{th} calculated by using elemental composition analysis method (Buswell's formula) • Comparison of BMP_{th} and BMP_{exp}
Hashimoto and Robinson (1982)	Beef cattle manure and wheat straw	8	45.5 °C	• Batch test to calculate BMP_{exp} • Used experimental data to calculate ultimate methane yield • Calculated volumetric methane production using kinetic equation
Labatut (2012)	Dairy manure, food residue and energy crops	N/A	Mesophilic	• BMP assay tests to calculate BMP_{exp} • BMP_{th} calculated by using elemental composition and organic composition analysis methods (Buswell's formula), and COD stabilisation method. • Compared BMP_{th} and BMP_{exp} to evaluate capability of theoretical methods to precise estimation of methane production
Moller, et al. (2004)	Cattle manure and pig faeces, wheat straw	N/A	35 °C	• BMP assay tests to calculate BMP_{exp} • BMP_{th} calculated by using elemental composition and organic composition analysis methods (Buswell's formula) • Comparison of BMP_{th} and BMP_{exp}
Nielfa, et al. (2014)	Municipal solid waste and biological sludge	N/A	Mesophilic	• BMP assay tests to calculate BMP_{exp} • BMP_{th} calculated by using elemental composition and organic composition analysis methods (Buswell's formula), COD stabilisation method • Comparison of BMP_{th} and BMP_{exp}

Authors	Feedstock used	HRT (days)	Temperature (°C)	Methods
Maya-Altamira, et al. (2008)	Food processing industry waste water and sludge inoculums	50	35 - 37 °C	- BMP assay tests to calculate BMP_{exp} - BMP_{th} calculated by using elemental composition and organic fraction analysis methods - Comparison of BMP_{th} and BMP_{exp}
Sahito, et al. (2013)	Buffalo dung, rice straw and wheat straw	30	37 °C	- BMP assay tests to calculate BMP_{exp} - BMP_{th} calculated by using elemental composition and organic fraction analysis methods (Buswell' formula) - Comparison of BMP_{th} and BMP_{exp}
Raposo, et al. (2012)	Manure and wheat straw	32	35 - 42 °C	- BMP_{th} calculated by using elemental composition and organic fraction analysis methods (Buswell' formula)

This section focuses on assessing the potential for improving biogas production through co-digestion of animal dung with crop residues. Ward et al. (2008) argued that plant materials produce more methane than dung and hence there is a growing use of biomass materials such as energy crops and crop residues to produce biogas. However, biomass materials are difficult to hydrolyse due to higher lignocellulose content, and they need much higher (more than 100 days) hydraulic retention time to hydrolyse completely (Menardo, Airoldi, & Balsari, 2012; Ward et al., 2008). Dung contains high levels of organism that are able to hydrolyse plant materials, and hence co-digestion of plant materials with dung could not only increase methane yield, but also reduce the retention time (Lehtomaki et al., 2007; Ward et al., 2008).

Agricultural residues and animal manure have been co-digested to produce biogas, which compared with the single digestion of animal manure increased the rate of biogas production and improved the efficiency of the biogas plant (Wu, Yao, Zhu, & Miller, 2010; T. Zhang et al., 2013). However, anaerobic co-digestion studies are more focused on co-digestion of animal dung with single co-substrate (e.g., Amon et al., 2007; Demirbas, 2006; Lehtomaki et al., 2007; Y. Li, Liu, et al., 2013; Y. Li, Zhang, et al., 2013; Moller et al., 2004; Wu et al., 2010) than on multiple co-substrates together including human excreta (toilet attached plants). So, the methane production from co-digestion of dung with selected crop residues and human excreta were evaluated and compared with methane production over the conventional dung-only digestion process.

Moisture content of the substrate is also an important factor for methane productivity (Ghosh, 1986; Karki et al., 2005). The varying methane productivity of different substrates is accounted for different TS and VS contents as a result of varying moisture content in it (Karki et al., 2005; Moller et al., 2004). Esposito et al. (2012) mentioned that co-digestion adjusts the moisture content in the anaerobic process, but highlighted the need for further study of the effect of the moisture content of the substrates on the process performance. However, co-digestion produces a synergistic effect, optimising the C/N ratio of the substrate mixture suitable for anaerobic digestion (Birnin-Yauri et al., 2009; Hamilton & Zhang, 2013).

6.4.1 Co-digestion to balance C/N ratio

The amount of carbon and nitrogen present in feedstock could be an important indicator to determine the ratio of co-substrates for co-digestion (T. Zhang et al., 2013). A C/N ratio of 20-30 is considered favourable for anaerobic digestion, with an optimum ratio of 25-30, and a ratio greater than 35 is unsuitable (Demirbas, 2006; Karki et al., 2005; Lin et al., 2011) (Section 2.2.1). As crop residues have a high C/N ratio compared to animal dung, co-digestion of the two increases methane production by balancing the ratio and decreases the threat of ammonia inhibition (Sahito et al., 2013). For example, wheat straw has a low nitrogen content and a C/N ratio above 85 (Table 6.1), so nitrogen needs to be supplemented to enhance the anaerobic digestion of wheat straw (Demirbas, 2006). This can be done by co-digestion of wheat straw with a substrate having lower C/N ratio, such as human excreta.

6.4.2 Characteristics of co-digestion mixtures

Ten different co-digestion mixtures of crop residues with dung and human excreta using weight percentages were compared (Table 6.8). The characteristics of the substrate mixtures were obtained from the theoretical mixture of the individual substrates using Equation 6.14 (Ashekuzzaman & Poulsen, 2011; Nielfa et al., 2014; Werner et al., 1989).

$$\text{Characteristics of mixture} = \frac{(S_1 * W_1) + (S_2 * W_2) + \dots\dots\dots + (S_n * W_n)}{(W_1 + W_2 + \dots\dots\dots + W_n)} \qquad \text{(Equation 6.14)}$$

where,

S_1, S_2, ... S_n are the specific characteristics of individual substrates (e.g., TS, VS, C, H, O, N, C/N ratio); and

W_1, W_2, ... W_n are the weight or proportion of individual substrates.

Table 6.8: Co-digestion mixture with proportion of substrates by weight percent and characteristics of co-substrate mixtures and weighted methane yield

Co-digestion mixture	Substrate mixture proportion (%)	TS%	VS%	C %	H %	O %	N%	C/N
Cod-1	90 Dung/10 HE	18.1	75.8	37.8	4.8	41.4	2.0	20.8
Cod-2	80 Dung/10 RS/10 HE	24.7	76.2	38.1	4.8	41.0	1.9	23.9
Cod-3	65 Dung/25 RS/10 HE	34.6	4.9	38.6	4.9	40.5	1.8	28.7
Cod-4	80 Dung/10 WS/10 HE	25.2	76.6	38.3	4.9	41.2	1.9	27.1
Cod-5	65 Dung/25 WS/10 HE	35.8	77.7	39.1	5.0	40.9	1.7	36.6
Cod-6	80 Dung/10 CS/ 10HE	24.8	75.9	38.7	4.9	41.5	.9	24.0
Cod-7	65 Dung/25 CS/10 HE	34.8	76.1	39.9	5.1	41.8	1.8	28.7
Cod-8	70Dung/10 RS/10 CS/10 HE	32.4	76.3	39.0	5.0	41.2	1.8	27.1
Cod-9	70Dung/10 RS/10 WS/10 HE	31.8	76.9	38.6	4.9	40.8	1.8	30.3
Cod-10	70Dung/10 WS/10 CS/10 HE	1.9	6.7	9.2	.0	1.3	1.8	30.3

Note: RS = Rice straw, WW = Wheat straw, CS = Corn stover, HE = Human excreta

6.4.3 Theoretical methane yield from co-digestion

The theoretical methane yield was calculated as the sum of weighted average of the individual substrates' methane yield based on the proportion of the substrates in the co-digestion admixtures (Labatut, Angenent, & Scott, 2010; Y. Li, Liu, et al., 2013). For example, when BMP_{th} of dung is 0.383 m^3/kg VS and rice straw is 0.464 m^3/kg VS, co-digestion of 65% dung, 25% rice straw and 10% human excreta using the elemental composition analysis method results in a weighted methane yield of 0.404 m^3/kg VS (Table 6.9). Since cattle dung and buffalo dung have almost similar theoretical methane yield values (Table 6.2) and C/N ratio (Table 6.1), they are considered as a single substrate for this co-digestion analysis.

Table 6.9 presents the theoretical weighted methane yield (m^3/kg VS) and percentage increase in methane for different co-digestion mixtures. The methane yield from co-digestion of rice straw with dung increased from 0.392 to 0.404 m^3/kg VS as the proportion of rice straw increased from 10-25%, with an increase in methane yield from 2.3-5.5%. Co-digestion of crop residues with dung showed synergistic effects, which could be due to the synergistic effect of the increased alkalinity and the buffering capacity of the manure as suggested by Li, et al. (2009). The percentage increase in methane yield ranged from 2.3-6.0% in terms of m^3/kg VS, which can be compared with the findings of Li, et al. (2009) that co-digestion increased biogas production by

4.9-7.4% at different cattle manure and corn stover ratios compared to the single digestions. Somayaji and Khanna (1994) reported a 1.9% and 13.1% increase in methane yield from co-digestion of 20% wheat straw and 20% rice straw with cattle dung, respectively. Lee et al. (2013) also reported 4-6% enhancement in methane yield from co-digestion in comparison with single digestion.

Table 6.9: Weighted theoretical methane yield and percentage increase in methane yield at different substrate mixing proportions using three different methods at STP

Co-digestion mixtures	Elemental composition method (m^3/kg VS)		Organic composition method (m^3/kg VS)		COD stabilisation method (m^3/kg VS)	
	Yield	% increase	Yield	% increase	Yield	% increase
Dung only	0.383*	-	0.407*	-	0.403*	-
Cod-1	0.384	0.3	0.408	0.2	0.406	0.7
Cod-2	0.392	2.3	0.417	2.5	0.413	2.5
Cod-3	0.404	5.5	0.430	5.7	0.424	5.2
Cod-4	0.393	2.6	0.415	2.0	0.413	2.5
Cod-5	0.406	6.0	0.425	4.4	0.425	5.5
Cod-6	0.392	2.3	0.415	2.0	0.413	2.5
Cod-7	0.403	5.2	0.425	4.4	0.423	5.0
Cod-8	0.399	4.2	0.424	4.2	0.420	4.2
Cod-9	0.401	4.7	0.424	4.2	0.421	4.5
Cod-10	0.400	4.4	0.422	3.7	0.421	4.5

Note:

1) * Average for buffalo dung and cattle dung
2) The proportion of human excreta is fixed at 10% in this analysis, because the average proportion of it fed into biogas digester in the surveyed households was 7-12% of the feedstock fed, depending on family size.
3) % increase in methane yield = $\frac{\text{(methane yield from co-digestion – methane yield from dung-only)}}{\text{methane yield from dung-only}}$ * 100

Considering the ambient temperature, the increase in methane yield (using elemental composition analysis method and Equation 6.10) could range from 11-17.2% in summer and 6.5-12.5% in winter in Chitwan, and 8.6-14.9% in summer and 4.2-10.2% in winter in Lamjung, depending on the substrate type and co-digestion mixture proportions (Table 6.10).

Table 6.10: Theoretical methane yield after co-digestion during summer and winter in Chitwan and Lamjung and % increase in yield compared to the dung-only yield

Co-digestion mixture	Methane yield (m^3/kgVS) at STP	Chitwan (m^3/kgVS)				Lamjung (m^3/kgVS)			
		At 29°C	% increase	At 17°C	% increase	At 23°C	% increase	At 11°C	% increase
Cod-1	0.384	0.425	11.0	0.408	6.5	0.416	8.6	0.399	4.2
Cod-2	0.392	0.434	13.3	0.416	8.6	0.425	11.0	0.408	6.5
Cod-3	0.404	0.447	16.7	0.429	12.0	0.438	14.4	0.420	9.7
Cod-4	0.393	0.435	13.6	0.417	8.9	0.426	11.2	0.409	6.8
Cod-5	0.406	0.449	17.2	0.431	12.5	0.440	14.9	0.422	10.2
Cod-6	0.392	0.434	13.3	0.416	8.6	0.425	11.0	0.408	6.5
Cod-7	0.403	0.446	16.4	0.428	11.7	0.437	14.1	0.419	9.4
Cod-8	0.399	0.441	15.1	0.424	10.7	0.433	13.1	0.415	8.4
Cod-9	0.401	0.444	15.9	0.426	11.2	0.435	13.6	0.417	8.9
Cod-10	0.400	0.442	15.4	0.425	11.0	0.434	13.3	0.416	8.6

6.4.4 Volumetric methane production

Volumetric methane production (VMP) was calculated to predict how much methane could be produced in a day. VMP is defined as the rate of methane production per day per unit size of biogas digester and can be predicted by using the kinetic equation (Equation 6.15) (Hashimoto & Robinson, 1982, p. 27).

$$\gamma V = \frac{B_o S_o}{HRT} \left[1 - K / (\mu_m * HRT - 1 + K)\right] \qquad \text{Equation 6.15}$$

where,

γV = volumetric methane production rate, m^3/day/m^3 biogas digester

B_o = ultimate methane yield, m^3/kg VS

S_o = VS concentration, kg VS/m^3

HRT = hydraulic retention time, day

K = kinetic parameter (dimensionless)

μ_m = maximum specific growth rate of micro-organism/day

= 0.013 T - 0.129, where T is temperature in °C (Hashimoto et al., 1981)

Table 6.11: Average theoretical and corrected VMP from mono-digestion of selected feedstock during summer and winter in Chitwan and Lamjung

Feedstock	B_o	S_o	Chitwan (m^3/day/ m^3 digester)				Lamjung (m^3/day/ m^3 digester)			
			Summer (29°C)		Winter (17°C)		Summer (23°C)		Winter (11°C)	
			VMP_{th}	VMP_{cor}	VMP_{th}	VMP_{cor}	VMP_{th}	VMP_{cor}	VMP_{th}	VMP_{cor}
Dung	0.383	51.2	0.270	0.189	0.252	0.176	0.265	0.186	0.237	0.166
Rice straw	0.464	250.0	1.599	1.023	1.493	0.955	1.571	1.005	1.400	0.896
Wheat straw	0.471	279.9	1.816	1.271	1.696	1.187	1.785	1.249	1.591	1.114
Corn stover	0.459	245.1	1.550	1.008	1.447	0.941	1.523	0.990	1.358	0.883
Human excreta	0.385	56.2	0.298	0.119	0.279	0.111	0.293	0.117	0.261	0.105

Note:

1) HRT = 70 days (Bajgain, 1994; Karki et al., 2005), K = 0.6 (Hashimoto & Robinson, 1982).

2) VMP_{th} = theoretical VMP without substrate biodegradability correction.

3) VMP_{cor} = VMP after correcting substrate biodegradability using biodegradable fraction from Table 6.4.

4) The basis for S_o calculation is that a 4 m^3 fixed-dome biogas plant typically requires about 1.5 tonnes of feedstock for the plant filling (ENEA, 2013).

Table 6.11 presents the rate of methane production per day per m^3 size of a fully fed biogas digester. The rate of methane production varies with temperature. With dung only digestion, the average theoretical VMP (VMP_{th}) from a fully fed biogas plant in Chitwan is 0.270 m^3/day/m^3 digester during summer (at 29°C) and 0.252 m^3/day/m^3 digester during winter (at 17°C), whereas the corrected VMP (VMP_{cor}), after correcting the substrate biodegradability with the biodegradable fraction given in Table 6.4, is 0.189 m^3/day/m^3 digester during summer and 0.176 m^3/day/m^3 digester during winter. However, the actual biogas production reported by the households was less than the calculated VMP_{cor} (Section 5.6.1) mainly because the biogas digesters in the surveyed households were not fully fed.

Co-digestion of crop residues with dung in different proportions promotes synergistic effects and also supplements the feedstock deficit, thus increasing the volumetric methane production (Table 6.12). For example, 100 gm rice straw added to 800 gm dung and 100 gm human excreta is estimated to produce 0.273 m^3 methane/day/m^3 digester size at 29°C, an increase of 50% production compared with 1 kgdung-only digestion. Similarly, each of 250 gm rice straw added to 650 gm dung and 100 gm human excreta is estimated to produce 0.605 m^3 methane/day/m^3 digester size at 29°C, an increase of 124% (Table 6.12).

Table 6.12: Average weighted VMP_{th} and VMP_{cor} after co-digestion of crop residues with dung in different proportions during summer and winter in Chitwan and Lamjung

Co-digestion mixture	VMP_{th} (m^3/day/m^3 size of digester)				VMP_{cor} (m^3/day/4 m^3 size of digester)				Increase in VMP_{th} (or VMP_{cor}) (%)
	Chitwan		Lamjung		Chitwan		Lamjung		
	29°C	17°C	23°C	11°C	29°C	17°C	23°C	11°C	
Cod-1	0.273	0.255	0.268	0.239	0.191	0.178	0.188	0.167	1
Cod-2	0.406	0.379	0.399	0.355	0.284	0.265	0.279	0.249	50
Cod-3	0.605	0.565	0.594	0.530	0.423	0.395	0.416	0.371	124
Cod-4	0.427	0.399	0.420	0.374	0.299	0.279	0.294	0.262	58
Cod-5	0.659	0.616	0.648	0.578	0.462	0.431	0.454	0.404	144
Cod-6	0.401	0.374	0.394	0.351	0.281	0.262	0.276	0.246	48
Cod-7	0.593	0.554	0.583	0.519	0.415	0.388	0.408	0.364	120
Cod-8	0.560	0.523	0.551	0.491	0.392	0.366	0.385	0.344	108
Cod-9	0.534	0.498	0.524	0.468	0.374	0.349	0.367	0.327	98
Cod-10	0.556	0.519	0.546	0.487	0.389	0.363	0.382	0.341	106

Note:

1) VMP_{cor} was calculated by multiplying VMP_{th} with weighted biodegradable fraction from Table 6.4.

2) $$\text{Increase in VMP (\%)} = \frac{\text{Weighted } VMP_{th} \text{ (or } VMP_{cor}\text{) from co-digestion - } VMP_{th} \text{ (or } VMP_{cor}\text{) of dung}}{VMP_{th} \text{ (or } VMP_{cor}\text{) of dung.}} \times 100\%$$

Co-digestion of crop residues and human excreta with dung could increase methane yield by at least 50%. This finding is consistent with the findings of Asam, et al. (2011) and Moller, et al. (2004). But co-digestion of dung and human excreta only as currently practised in Nepal has a negligible effect on methane yield. Thus, co-digestion of crop residues with dung could be the best solution to increase biogas production in under-fed domestic biogas plants as in the case of Nepal, because it not only supplements the daily feedstock deficit, but also increases the efficiency of the plants. However, various factors could affect biogas production through co-digestion, which are discussed in the next section.

6.5 Factors Affecting Biogas Production Through Co-digestion

6.5.1 Biogas plant design consideration

Design of a biogas plant could affect the use of crop residues as feedstock for biogas production. As discussed earlier, use of lignocellulosic biomass as feedstock may result in separation of solids from the liquid phase developing into a floating scum layer that negatively influences the operation of the biogas plant (Hesse & Cuc, 2007; Oosterkamp, 2011). Austin (2011) argued that most household-level digesters are not designed to handle more than 15% solids. The Chinese-dome type design lacks a slurry mixing feature that prevents mass transfer of substrate to anaerobic digestion (Werner et al., 1989). The GGC-2047 model biogas plant, the design mostly installed in Nepal, is also not considered very suitable for digestion of crop residues due to the absence of a mechanism to remove digested inert materials accumulated at the bottom of the plant, which reduces the biologically active digester volume over time, resulting in a lower biogas production (KC et al., 2013; P. Lamichhane, 2012).

Modifying the design to remove the materials accumulated at the bottom of the digester and provide agitation to minimise scum layer formation will lead to more biological activity in the digester, and could enhance biogas production efficiency of the plants (P. Lamichhane, 2012). The BSP-Nepal, the implementing agency for biogas development and promotion in Nepal, has realised the need to modify the plant design in order to use lignocellulosic materials such as kitchen waste and crop residues, so as to solve the problem of insufficient feedstock and improve plant production efficiency (Zifu et al., 2009). It has undertaken trials of modified plant designs with sloped manhole (Figure 6.3) for removing sediment and agitation for constant mixing of the slurry in order to increase biogas production efficiency by increased metabolic reaction in the digester with encouraging results (P. Lamichhane, 2012). Besides, the BSP-Nepal believes that promotion of such modified plants would be cheaper than the existing design, and hence reach to more poor households (P. Lamichhane, 2012). However, suitability of the modified designs to co-digest crop residues with dung still needs to be examined.

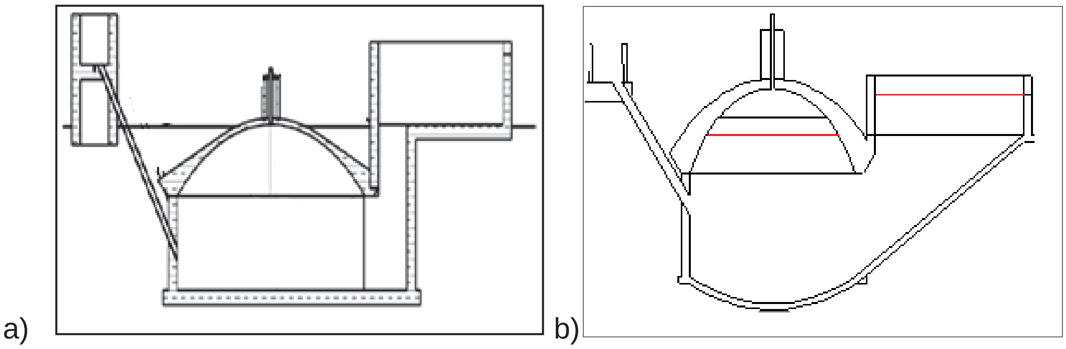

Figure 6.2: General design sketch of (a) existing GGC-2047 biogas plant (BSP-Nepal, 2012b)(b) modified (proposed) GGC-2047 biogas plant design (P. Lamichhane, 2012)

Note: These sketches are only for basic design concept, hence dimensions are not mentioned.

6.5.2 Particle size of the co-substrates

Particle size of the lignocellulosic materials, such as crop residues, significantly affects the biogas production (Palmowski & Müller, 1999; S. K. Sharma, Mishra, Sharma, &

Saini, 1988; R. Zhang & Zhang, 1999). Lignocellulosic materials are difficult to degrade biologically. So, pre-treatment of such materials by reducing the particle size improves the degradability of the materials and minimises the formation of a floating scum layer, thus increasing the biogas yield (R. Zhang & Zhang, 1999). Larger particle size takes a longer time to solubilise and have less surface area available for bacterial degradation due to lower release of intracellular components, resulting in lower biogas production (Palmowski & Müller, 1999; S. K. Sharma et al., 1988; Xiao et al., 2013). However, the relationship between the substrate degradability and particle size is still not clear (Raposo et al., 2012).

Sharma, et al. (1988) argued that particle size is an important parameter for anaerobic co-digestion of rice and wheat straw with optimum particle sizes of about 0.40mm, but reducing the particle size below 0.40mm would be uneconomic as it does not increase biogas production. Similarly, in another experiment, grinding rice straw into 10mm pieces produced more biogas as compared to whole straw (R. Zhang & Zhang, 1999). Corn stover at particle sizes of 0.25-5.0mm significantly increased the substrate utilisation and resulted in the highest methane yield compared to larger sizes (1-20mm) or smaller sizes (0.075-0.25mm) (Xiao et al., 2013). Moller et al. (2004) also found a significant increase in methane productivity of wheat straw by size reduction from 30mm to 1mm. It can be concluded that particle size reduction of cereal straws below 1 mm is needed to accelerate the bacterial degradation process and to minimise the floating scum layer formation for enhanced biogas production from co-digestion of animal dung with crop residues. This can be done by the use of a hay/forage chopper in the rural households.

6.5.3 Socio-economic factors

Besides the availability of crop residues to use as co-feedstock, its associated cost is another consideration factor. Almost all households reported producing one or more types of crop residue and the majority of the households were ready to use them as feedstock for increased biogas production. The average daily feedstock deficit in terms of current digester feeding practice was 9 kg in Chitwan and 11 kg in Lamjung, but this would decrease to 5 kg (13% of total daily feedstock requirement) in Chitwan and 3 kg (8% of total daily feedstock requirement) in Lamjung if all the available dung were fed into the digester (Section 5.3.6). The deficit feedstock can be supplemented with crop residues that were used sub-optimally either by burning for manure or for making compost (Section 5.3.7). Since the sub-optimally used crop residues can be utilised for biogas production, it will not cost anything extra towards the cost of biogas (Section

7.5). However, ensuring availability of crop residues, especially rice straw for animal feed is a priority because crop residue is the major staple animal food during the dry season, and a drop in quantity of animal feed will have direct implications on dung availability and ultimately on biogas production.

Co-digestion could also have an impact on workload of household members, since preparing crop residues for co-digestion, e.g. collecting and chopping, could take a little longer time than feeding of dung alone. The average biogas plant feeding time for dung alone was 26 minutes (Section 5.4.6), which could slightly increase of co-digested. However, if co-digestion increases biogas production, it further reduces the time spent for collecting fuelwood. So, it can be assumed that some of the saved time can be utilised for any additional time required to prepare feedstocks for co-digestion without any additional burden, particularly to women.

The nutritional quality of digested slurry from co-digestion of crop residues with dung is another benefit of co-digestion. Digested slurry from dung-only biogas plant has proved to be a high quality organic fertiliser, which is rich in major plant nutrients (nitrogen, phosphorous and potassium) and the nutrients are readily available for plant growth compared to traditional farm yard manure or compost which has residual effects causing the gradual release of nutrients for plant use (Al Seadi & Lukehurst, 2012; Karki et al., 2005). The percentage of major plant nutrients and micronutrients needed for plant growth in digested slurry is higher than farm yard manure (Karki et al., 2005). However, information is lacking on the fertiliser value of the slurry from co-digestion of dung with crop residues at different proportions, which needs further research. Moreover, use of crop residues as co-substrates could minimise users' hesitation to handle the slurry from a toilet attached plants due to potentially reduced bad odour.

6.5.4 Environmental factors

Environmental benefits of co-digestion of dung with crop residues are obvious. Co-digestion increases biogas production, further reducing the consumption of biomass (e.g., fuelwood) and petroleum fuels that have severe environmental and health impacts. It also reduces the burning practices of agricultural residues for manuring, reducing the adverse environmental emissions. Overall, co-digestion through increased biogas production contributes to minimise deforestation and mitigate GHG emissions, which are elaborated on in Chapter 8.

CHAPTER SEVEN

FINANCIAL ASSESSMENT OF A BIOGAS SYSTEMWITH CO-DIGESTION OF MIXED FEEDSTOCKS

7.1 Introduction

The previous chapter discussed increasing biogas production by supplementing daily feedstock through co-digestion of crop residues with dung. Supplementing feedstock might incur additional cost, which needs to be analysed in order to ensure that biogas production is still viable and cost-effective in terms of total annual cost of energy even after co-digestion. This is the main objective of this chapter. It specifically addresses the following questions:

- What was the annual cost of energy before the installation of biogas?
- What was the annual cost of energy under the existing operation of biogas plants where biogas supply was not enough to fulfil the energy demand for cooking?
- What would be the expected cost of energy after supplementing feedstock with purchased dung or co-digestion of crop residues with dung, and whether investment in such a co-digested plant is still cost-effective and profitable?

This chapter first analyses the energy costs of a household before the installation of biogas plant. It then assesses the existing cost of energy after the use of biogas, which includes the cost of biogas as well as costs of traditional/conventional fuels to supplement for biogas deficit. The expected cost of energy after supplementing feedstock through purchase of dung is analysed next. The projected cost of energy after co-digestion of crop residues with dung is then examined, followed by the comparison of energy costs before and after the co-digestion to evaluate the most cost-effective energy option. A financial analysis of biogas plants to explore the financial viability of biogas production through co-digestion is carried out towards the end of this chapter. Information required for the analysis was obtained from the data collected during the surveys of 314 households in the two districts. Only the cost of energy for cooking is considered. The economic life of a biogas plant is considered 20 years (BSP-Nepal, 2012b) with zero salvage value. The discount rate of 16% equal to the bank's loan interest rate is considered for this study.

7.2 Cost of Energy Before Biogas

The total cost of energy of a household before the use of biogas comprised the cost of fuelwood and the cost of other fuels such as kerosene, LPG, electricity and agricultural residues (Table 7.1). Fuelwood was the major source of energy for cooking; the shares of others were small. The cost of energy was analysed with respect to the plant size installed later.

Table 7.1: Average annual cost of energy before the use of biogas in Chitwan and Lamjung with respect to biogas plant size installed later

Fuel type	Chitwan				Lamjung			
	4 m^3	6 m^3	8 m^3	10 m^3	4 m^3	6 m^3	8 m^3	10 m^3
Fuelwood (purchased)								
Qty (kg/year)	3753	3973	4221	4230	4271	4452	4577	4800
Cost (US$/year)	236	250	266	267	150	155	160	168
Fuelwood (collected)								
Collection time (hour/year)	700	710	760	820	720	770	830	910
Cost (US$/year)	140	142	152	164	144	154	166	182
Kerosene								
Quantity (kg/year)	-	1.6	-	-	-	4.6	3.4	-
Cost (US$/year)	-	1.2	-	-	-	3.4	2.5	-
LPG								
Quantity (kg/year)	7.7	10.8	4.4	5.3	0.6	3.3	4.7	14.2
Cost (US$/year)	8.6	11.9	4.9	5.9	0.7	3.6	5.2	15.7
Electricity								
Quantity (kWh/year)	31	28	11	-	-	-	-	-
Cost (US$/year)	2.2	2.0	0.8	-	-	-	-	-
Total cost of energy (purchased fuelwood)	247	265	271	272	150	163	168	184
Total cost of energy (collected fuelwood)	151	157	158	170	145	161	174	198

Note:

1) 1 US$ = NRs 95.30 [The Central Bank of Nepal (Nepal Rastra Bank), 15 June 2014].
2) The average price of fuels at the time of field survey was kerosene US$0.73/litre, LPG refill US$15.7/cylinder and electricity US$0.07/kWh.
3) No use of kerosene by the households who later installed 4, 6 or 10 m^3 could be because of the limitation of the sampling method that might not have represented the households who used kerosene. The reason might be the same for no electricity use data in the households who later installed 10 m^3 plants in Chitwan.

Source: Field Survey, 2012

The total cost in terms of cost involved in purchasing the fuels in Chitwan (US$247-272) was higher than in Lamjung (US$150-184) because of the higher price of fuelwood[45] in Chitwan. The total cost of energy in terms of labour cost for fuelwood collection[46] was higher in Lamjung due to higher fuelwood consumption (except for 4 m^3 plants because of less fuelwood consumption). The total cost of energy is higher for the households who later installed bigger size plants (Table 7.1), which implies that the cost of energy (or energy consumption) was a factor in households' decisions about plant size.

7.2.1 Cost of fuelwood

The annual cost of fuelwood in terms of cost involved in purchasing it was calculated by multiplying the annual quantity of fuelwood consumed by an individual household with its market price, which ranged from US$236 and US$150 for the households who later installed 4 m^3 plants to US$267 and US$168 for the households who later installed 10 m^3 plants in Chitwan and Lamjung, respectively (Table 7.1). The share of fuelwood cost (if purchased) to the total annual energy cost per household was about 96% in both districts. The higher cost in Chitwan despite lower fuelwood consumption than Lamjung (Section 5.5.1) is because of the higher market price of fuelwood.

Fuelwood in the households however was collected by the family members themselves without involving direct monetary cost, so calculating the cost using the market price may overestimate the actual cost of energy of the households. Hence, the cost was also calculated using a shadow price of fuelwood based on the value of labour saved, which otherwise would have been spent in collecting fuelwood, by multiplying the time spent on its collection with the local wage rate. The average annual cost of fuelwood per household in terms of labour cost for its collection ranged from US$140-164 in Chitwan and US$144-182 in Lamjung, depending on the size of the plants installed later (Table 7.1). The higher cost in Lamjung is due to higher average fuelwood collection time in Lamjung with hilly terrain (3.0 hours/day) than in Chitwan (2.7 hours/day). In addition, the total cost of fuelwood if purchased or collected was almost similar in Lamjung due to the lower price and higher collection time. Despite similar cost but lesser drudgery from purchased fuelwood, the households in Lamjung still

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[45] Although local price of fuelwood varies within a district depending on availability and remoteness, the price set by the respective DDC Offices was taken as the standard market price for the district for this study. The average market price of fuelwood was US$0.063/kg in Chitwan and US$0.035/kg in Lamjung.

[46] The wage for unskilled labour at the time of field survey was US$1.6/day or US$0.2/hour assuming eight working hours per day in both districts (Field Survey, 2012).

preferred to collect fuelwood because of the lower opportunity cost[47] of their time and lack of regular cash required to purchase it.

7.2.2 Cost of other fuels

Kerosene, LPG and electricity shared only about 4% of the total annual cost of energy of a household before the installation of biogas (Table 7.1). Crop residues were available free of cost and hence were not included in the cost. Only 1% of the surveyed households in Chitwan and 4% in Lamjung used kerosene for cooking with an average annual cost of US$1.2 in Chitwan and US$2.9 in Lamjung. LPG was the second fuel consumed after fuelwood in terms of cost but the average annual cost per household in Chitwan (US$7.8) and Lamjung (US$6.3) was much lower at about 3% and 3.4% of the purchased cost of fuelwood, respectively. The households who later installed smaller plants in Chitwan but bigger plants in Lamjung consumed more LPG. None of the households reported use of electricity for cooking in Lamjung mainly because of limited access to electricity and dependency on fuelwood, whereas about 25% of households in Chitwan used it as secondary fuel, but its share of the average annual energy cost was very low (Table 7.1). There was no obvious reason for not using kerosene given by the households who later installed 4, 6 or 10 m^3 plants as shown in Table 7.1; it could be just because of the sampling that might not have represented other plant size households well. This might also be the reason for no electricity use data in the households who later installed 10 m^3 plants in Chitwan.

7.3 Existing Cost of Energy after Biogas

The shift of a household from traditional fuels to biogas involved some costs to the user towards plant construction and operation/maintenance. The total cost of energy after the use of biogas comprised the cost of biogas production and the cost of additional fuels required to supplement for energy deficit from available biogas, since available biogas was not enough to meet the cooking energy demand.

7.3.1 Cost of biogas production

Production and use of biogas comprised three different types of costs: (a) plant installation cost; (b) repair and maintenance cost; and (c) operational cost. The annual cost of biogas use per household with subsidy and free dung was calculated by adding

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[47] Opportunity cost is the benefit that could have been gained from an alternative use of the same resource (Fisher, Houghton, & Jain, 2014, p. 12).

up the annualised installation cost with annual repair and maintenance cost and annual operational cost (Salomon, Lora, Rocha, & del Olmo, 2011), which varied with the size of plants between US$47-65 in Chitwan and US$50-62 in Lamjung (Table 7.2).

Table 7.2: Average annual cost of biogas by plant size in Chitwan and Lamjung

Cost	Chitwan				Lamjung			
	4 m^3	6 m^3	8 m^3	10 m^3	4 m^3	6 m^3	8 m^3	10 m^3
Installation cost with subsidy*	325 (15.1)	369 (5.6)	376 (12.5)	442 (27.4)	362 (7.8)	376 (5.3)	405 (16.8)	458 (25.2)
Annual repair & maintenance cost	2.1 (1.1)	2.4 (0.4)	3.9 (0.9)	4.5 (3.5)	1.6 (0.6)	1.8 (0.4)	2.4 (1.0)	3.5 (3.1)
Annual operating cost	28.7 (2.5)	32.6 (1.2)	33.2 (2.3)	38.2 (5.3)	30.6 (1.2)	31.2 (1.0)	31.6 (2.1)	35.9 (0)
Annual cost of biogas use with subsidy	47	53	56	65	50	52	54	62

Note:

1) * Excludes the cost of construction materials and unskilled labour arranged by the users, which vary from one district to another depending on availability of the materials, cost and accessibility.
2) The wage for unskilled labour cost (e.g., biogas plant operation) was US$0.2/hour.
3) Figures in parenthesis are standard errors.

Source: Field survey (2012)

Biogas plant installation cost

Installation of a biogas plant includes cost of construction materials, pipes and fittings, appliances, transportation, skilled/unskilled labour and administrative cost. The cost is based on the quotation approved by the government, which increases almost every year to reflect the increase in market price of construction materials, equipment and labour cost (BSP-Nepal, 2012a). The unskilled labour and construction materials are to be arranged by the households themselves, which share over 30% of total installation cost (BSP-Nepal, 2012a). Hence, the installation cost varies with location, size of the plant and the government subsidy. The total installation cost of a biogas plant including subsidy but excluding the cost of construction materials and unskilled labour that were arranged by the users themselves ranged from US$325-442 in Chitwan and US$362-458 in Lamjung (Table 7.2). The installation cost increased with the size of the plant and the cost of a 10 m^3 plant is about 36% and 26% higher than a 4 m^3 plant in Chitwan and Lamjung, respectively. The higher installation cost in Lamjung was mainly because of the higher transportation cost of equipment/fittings in the hill district. The higher standard errors show larger variations in the cost among the households.

Operational cost

Operational cost of biogas use includes the cost of feedstock (dung) and cost of labour for the plant operation. Dung was available free of cost in all the surveyed households, and hence no cost of feedstock was considered. However, operation of a plant resulted in opportunity cost such as time spent on digester feeding (collection of water/dung and mixing of dung and water), which would otherwise have been used for IGAs. The annual operational cost in terms of value of time spent on digester feeding increased with the increase in plant size from US$29-38 in Chitwan and US$31-36 in Lamjung (Table 7.2). The cost is slightly higher in Chitwan due to more time spent on digester feeding. The annual operational cost is less than 10% of the plant installation cost.

Annual repair and maintenance cost

Repair and maintenance costs were spent to fix problems when they arose and included costs of changing parts (e.g., gas valve, fittings, stove replacement) and procuring technical/support services. These costs differed from one plant to another irrespective of location and size of the plants. About 38% of households in Chitwan and 16% in Lamjung reported repair and maintenance costs which is reflected in higher average annual repair cost in Chitwan (Table 7.2). Bigger sized plants needed larger repair costs in both districts because they were comparatively older (Section 5.3.3).

7.3.2 Cost of additional fuels to supplement for biogas deficit

Although 17% of households in Chitwan and 2% of households in Lamjung reported having enough biogas throughout the year, the remaining households with all sized plants experienced energy deficit from available biogas in both districts and they used other energy sources, particularly fuelwood, LPG and electricity to fulfill the demand. The average annual cost of additional fuels ranged from US$73-90 in Chitwan and US$72-92 in Lamjung, depending on plant size (Table 7.3). The variation in cost among plant size and between the districts is due to the difference in fuelwood price and consumption of high-priced LPG. The higher cost of LPG accounts for the higher cost of additional fuels in 4m^3 households in Chitwan and 8 m^3 households in Lamjung.
The annual total cost of additional fuels to supplement for biogas deficit (Table 7.3) is still much higher than the annual total cost of biogas production (Table 7.2). This implies that increase in biogas production is necessary to minimise the existing high cost of other fuels and reduce the overall cost of energy. Since an insufficient amount of feedstock fed into the digester was identified as one of the major reasons for lower

biogas production, the households have two options to supply the prescribed amount of feedstock in order to increase biogas supply: (a) purchase of dung to fully feed the digesters, or (b) co-digestion of crop residues with dung for feedstock supplement and improved efficiency of the plants.

Table 7.3: Average annual quantity and cost of other fuels by plant size and district

Fuel type	Chitwan				Lamjung			
	4 m^3	6 m^3	8 m^3	10 m^3	4 m^3	6 m^3	8 m^3	10 m^3
Fuelwood								
Quantity (kg/year)	764	732	913	1035	1814	1900	1920	1920
Cost (US$/year)	48	46	58	65	63	66	67	67
LPG								
Quantity (kg/year)	33	20.7	18.2	17.6	6.3	9.5	20.2	14.2
Cost (US$/year)	36.2	22.9	20.1	19.5	7.0	10.5	22.3	15.7
Electricity								
Quantity (kg/year)	83.0	59.0	30.0	10.5	30.4	31.0	45.7	28.0
Cost (US$/year)	5.8	4.1	2.1	0.7	2.1	2.2	3.2	2.0
Total cost (US$/year)	90	73	80	85	72	79	92	85

Source: Field survey (2012)

7.4 Estimated Cost of Energy with Purchased Dung

One way of feeding the digesters with the prescribed quantity of feedstock is through purchased dung. Although a fully-fed digester could result in increased biogas production, it also incurs additional cost to the user. This section analyses the estimated cost of energy with purchased dung, and compares that with the existing cost of energy with feeding of free but insufficient dung (Section 7.3).

7.4.1 Cost of biogas production

If all dung available in the households were fed, there would be no need to purchase additional dung for 4 m^3 plants. The average quantity of dung to be purchased to fulfill the feedstock deficit by a household (if all available dung were fed) is up to 4.98 tonnes/year in Chitwan and 4.90 tonnes/year in Lamjung and the cost of biogas is expected to increase from US$47-165 in Chitwan and US$50-160 in Lamjung with the increase in plant size (Table 7.4). The higher standard errors of the quantity of dung to be purchased indicate higher variation among the households even within the same sized plants.

Table 7.4: Average annual quantity of dung required to purchase to cover the feedstock deficit and associated costs

	Chitwan				Lamjung			
	4 m^3	6 m^3	8 m^3	10 m^3	4 m^3	6 m^3	8 m^3	10 m^3
Quantity to be purchased (kg/year)	-	1,710 (4.2)	3,600 (9.8)	4,980 (29.8)	-	1,330 (6.5)	4,490 (11.6)	4,890 (31.4)
Cost of dung (US$/year)	-	34	72	100	-	26	90	98
Cost of biogas (US$/year)	47	87	128	165	50	77	144	160
Estimated biogas deficit after purchased dung (m^3/year)	122	64	28	-	142	104	78	12
Fuelwood required to fill the energy deficit (kg/year)**	1100	580	250	-	1274	936	700	108
Cost of fuelwood (US$/year)	69	37	16	-	45	33	24	4
Total cost of energy (US$/year)	116	158	216	265	95	136	258	262

* The local price of dung was 0.02 US$/kg at the time of field survey in both districts.

** Assuming that only fuelwood was used to fill the energy deficit.

Figures in parenthesis are standard errors.

7.4.2 Cost of conventional fuels

Assuming that one kg dung added to the digester increases biogas production by 0.04 m^3 (Karki et al., 2005), there would still be biogas deficit for all size plants except 10 m^3 plant in Chitwan and the deficit would be higher for smaller size plants due to their smaller gas-holding capacity (Table 7.4). So, the households would still experience energy deficit and need to use other fuels to cover the energy deficit from available biogas. Assuming that only fuelwood is used to supplement for biogas deficit, the cost of purchasing fuelwood would be US$16-69 in Chitwan and US$4-45 in Lamjung depending on plant size; the cost being higher for smaller sized plants (Table 7.4). But the total annual cost of energy with purchased dung would be much higher, even higher than the annual cost of energy before the use of biogas with collected fuelwood (Table 7.1). The higher cost of energy is due to the higher cost of purchased dung. This implies that purchasing dung to supplement for feedstock deficit is not a cost-effective option. Besides, much less dung, even none in some villages, were available for daily purchase in both districts because dung was widely used as fertiliser to maintain the subsistence agriculture in the rural areas that sustain their livelihoods. In this context, co-digestion of crop residues with dung could be a viable and cost-effective solution, which is evaluated in the next section.

7.5 Estimated Cost of Energy after Co-digestion

Although co-digestion of crop residues with dung increases biogas production by at least 50% (Section 6.4), a household will only adopt this if it proves to be a cheaper alternative to other cooking fuels. The total cost of energy after co-digestion, including the cost of biogas and other energy sources to supplement biogas deficit, is calculated in this section.

7.5.1 Cost of biogas

The expected cost of biogas after co-digestion was calculated taking into account the initial capital cost of biogas plant construction, annual repair and maintenance cost, cost of labour for plant operation[48] as presented in Table 7.2 and cost of feedstock. Since dung was available free of cost, it is not priced. Users preferably use dung freely available in the households as feedstock for biogas production, since biogas is a cheap source of energy while producing high quality organic fertiliser. Although crop residues were also available free of cost in all the surveyed households, not all of them can be used as feedstock because of their use as livestock feed during the dry season. According to WECS (2010), about 50% of the total crop residues can be considered for fuel purposes without affecting their other uses. So, this study assumes that 50% of the crop residues to be used as feedstock are purchased, the average annual cost of which (at the rate of US$0.03/kg) ranges from US$26-75 in Chitwan and US$20-74 in Lamjung, depending on the size of the plants (Table 7.5). There is no need to purchase crop residues for smaller sized plant (4 m^3) in both districts because of a smaller amount of daily feedstock deficit in those plants that can be supplied with free crop residues available at the households. The higher standard errors of quantity of crop residues show higher variation among the households across all plant sizes.

The annual cost of biogas of a household after co-digestion with purchased crop residues increased with increase in plant size and ranged between US$47-140 in Chitwan and US$50-136 in Lamjung with increase in plant size (Table 7.5). There would be no change in the cost of biogas from a 4 m^3 plant for no purchase of crop residues. Considering the existing energy demand, even a 50% increase in biogas production might not be sufficient to meet all energy needs of a household for cooking.

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[48] The time spent on biogas plant operation before and after co-digestion is assumed to be the same.

Households with smaller sized plants would have a higher energy deficit, which could be because of smaller gas holding capacity of the plants. A 4 m^3 plant household would have an annual energy deficit of about 937 MJ in Chitwan and 770 MJ in Lamjung, particularly during winter (Table 7.5). No biogas deficit is expected from 10 m^3 size plants in Chitwan, the warmer district.

Table 7.5: Annual cost of biogas after co-digestion of crop residues with dung in Chitwan and Lamjung

	Chitwan				Lamjung			
	4 m^3	6 m^3	8 m^3	10 m^3	4 m^3	6 m^3	8 m^3	10 m^3
Quantity of crop residues to be purchased (kg/year)	-	850 (4)	1800 (10)	2490 (19.5)	-	660 (3.9)	2240 (8.9)	2450 (9.9)
Cost of crop residues (US$/year)	-	26	54	75	-	20	67	74
Cost of biogas with purchase of crop residues (US$/year)	47	79	110	140	50	71	121	136
Estimated energy deficit after co-digestion (MJ/year)	937	245	155	0	770	720	680	35
Electricity required to fill the energy deficit (kWh/year)	367	96	61	0	301	282	266	14
Cost of electricity (US$/year)	34	15	13	0	30	28	27	10
Total cost of energy (purchase of crop residues) (US$/year)	81	94	123	140	80	99	148	146
Total cost of energy (free crop residues) (US$/year)	81	68	69	65	80	79	81	72

Note: 1) Figures in parenthesis are standard errors.

2) Half of the crop residues used for co-digestion was assumed to be purchased; the local average price being US$0.03/kg (Field Survey, 2014).

3) Dung was available free of cost, and is not priced.

4) All households are assumed to use electricity to supplement biogas deficit after co-digestion.

5) Heat value of electricity is 3.6 MJ/kWh.

7.5.2 Cost of other energy sources to supplement biogas deficit

A biogas household in general had three alternative fuel choices to meet the energy deficit – LPG, electricity (electric rice cooker) and fuelwood. Considering the higher cost of imported LPG and irregular supply issues, and the several adverse health and environmental impacts of fuelwood burning, electricity is considered as the suitable energy source. Increasing use of electricity for cooking, particularly an electric cooker for cooking rice[49], has already been reported in biogas households due to its convenience in use. The estimated cost of electricity is estimated to be US$13-34 in Chitwan and US$10-30 in Lamjung, depending on plant size (Table 7.5).

Electricity is one of the cheapest sources of energy in Nepal as compared to diesel, kerosene and LPG (NEF, 2014). However not all rural households have access to electricity and the supply is very irregular even where it is available (Section 3.3.2). These factors were considered by the respondent households as a major problem for its wider use for cooking. Besides, electricity tariff structure in Nepal is such that the per unit price increases with increase in consumption, i.e., US$ 0.07/kWh for up to 50 kWh/month increases to US$0.9/kWh for 51-150 kWh/month, US$0.10/kWh for 151-250 kWh/month and US$0.15/kWh for above 250 kWh/month(NEA, 2014). A household could end up with a higher electricity bill (roughly US$250-300/year) if electricity were used for all their cooking energy needs. But the cost of electricity as an alternative to supplement for biogas deficit would be much less than the cost of LPG.

7.6 Comparison of energy cost before and after the co-digestion

The total cost of energy before and after the installation of biogas plants and the estimated cost after biogas production through co-digestion were compared in order to identify a cost-effective energy option (Table 7.6). The total annual cost of energy after co-digestion (free crop residues) is the cheapest option. Considering no purchase of crop residues for co-digestion, a household could save US$70-105/year in Chitwan and US$65-126/year in Lamjung compared with a non-biogas household with collected fuelwood depending on plant size. The saving would be much higher at US$166-207/year in Chitwan and US$70-112/year in Lamjung if fuelwood were purchased. The saving would still be about US$56-85 in Chitwan and US$42-76 in Lamjung over the existing dung-only digestion practice. Biogas production even with purchased crop residues is still a cheaper option compared with the existing cost of energy (Table 7.6).

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[49] Rice is the staple daily diet of most of the households in the country.

Table 7.6: Total annual cost of energy before biogas and after biogas, biogas with purchased dung and biogas with co-digestion

Energy situation	Chitwan (US$/year/household)				Lamjung (US$/year/household)			
	4 m^3	6 m^3	8 m^3	10 m^3	4 m^3	6 m^3	8 m^3	10 m^3
Before biogas (collected fuelwood)	151	157	158	170	145	161	174	198
Before biogas (purchased fuelwood)	247	265	271	272	150	163	168	184
After biogas (existing)	137	126	136	150	122	131	147	148
After biogas (with purchased dung)	116	158	216	265	95	136	258	262
After co-digestion with purchased crop residues	81	94	123	140	80	99	138	148
After co-digestion with free crop residues	81	68	69	65	80	79	81	72

The per unit cost of energy before biogas and for different biogas production options in terms of average total annual energy demand of a household were plotted against plant size for both districts (Figure 7.1). The per unit cost after biogas with co-digestion (free crop residues) is much cheaper than other energy or biogas operation options, bigger sized plants being more cost-effective than smaller sized plants. This implies that if a household has sufficient crop residues, bigger sized plants are more suitable. For a household which needs to purchase crop residues for co-digestion, however, plant size up to size 6 m^3 is more suitable.

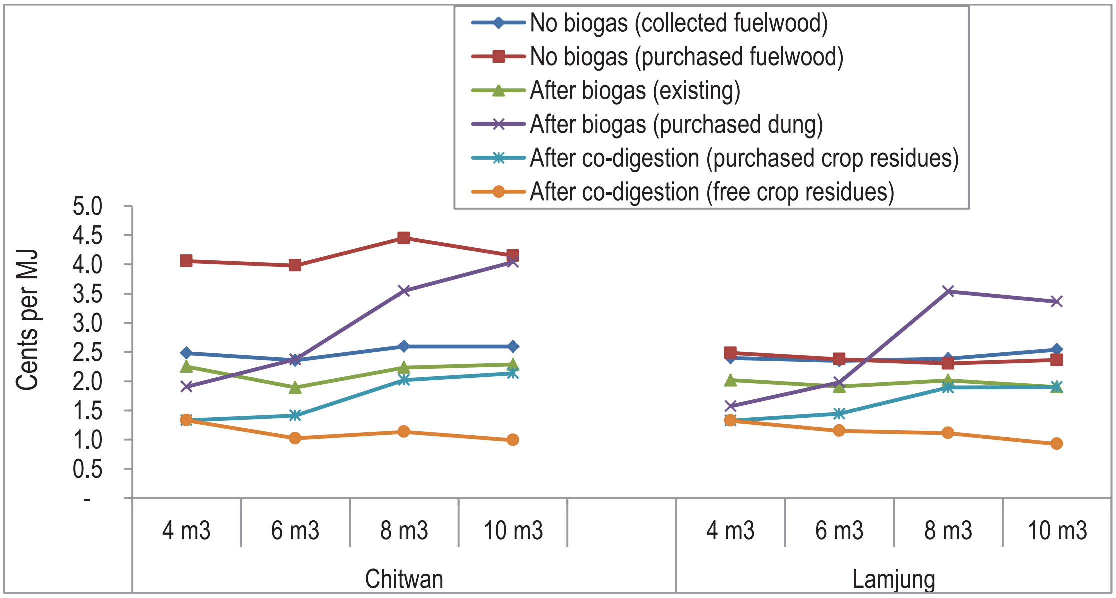

Figure 7.1: Comparison of average annual per unit cost of energy per household before the use of biogas and after biogas with purchased dung and co-digestion

7.7 Financial Analysis of Biogas Plants

7.7.1 Benefits of a biogas plant

Based on the information collected from the surveyed households in the two districts, the monetary benefits or income associated with the use of a biogas plant, which determines a household's decision on whether to install a plant, were derived mainly from savings on the cost of traditional fuels, income from utilisation of saved time and savings by replacing chemical fertilisers with bio-slurry. Indirect income from intangible benefits, such as improvement in health and sanitation conditions or reduction in GHG emissions that will not have direct influence on a household's decision about biogas plant, were not quantified.

Table 7.7: Quantifiable monetary benefits associated with the use of a biogas plant size in Chitwan and Lamjung (US$/year)

Income from	Chitwan				Lamjung			
	4 m^3	6 m^3	8 m^3	10 m^3	4 m^3	6 m^3	8 m^3	10 m^3
Saving on fuelwood (purchased)	154 (31.0)	182 (8.5)	186 (14.5)	165 (35.2)	100 (9.2)	114 (8.5)	144 (31.0)	183 (9.9)
Saving on fuelwood (collected)	104 (21.6)	136 (6.2)	123 (13.9)	147 (37.3)	132 (10.7)	144 (8.4)	144 (14.7)	177 (20.7)
Utilisation of saved time	59 (16.2)	50 (6.8)	57 (14.7)	88 (48.5)	81 (18.8)	76 (12.4)	96 (24.6)	42 (42.0)
Replacing chemical fertiliser	1.0 (1.0)	1.5 (0.6)	1.5 (0.9)	2.9 (1.9)	1.1 (0.4)	1.2 (0.4)	9 (9.0)	5.6 (3.0)
Total benefits (in terms of purchased fuelwood)	214 (40.1)	234 (10.4)	245 (24.6)	256 (53.3)	182 (21.2)	191 (17.2)	249 (42.5)	231 (49.3)
Total benefits (in terms of collected fuelwood)	164 (20.8)	188 (9.4)	182 (23.6)	238 (70.0)	214 (22.0)	221 (16.0)	249 (40.2)	225 (63.2)

Note: Figures in parenthesis are standard errors.

The total income earned by an individual household after the installation of a biogas plant varied greatly among the households, which is reflected by the higher standard errors. The average annual saving on traditional fuels per household in terms of cost avoided in purchasing the fuels varied with plant size from US$154-185 in Chitwan and US$100-183 in Lamjung (Table 7.7). The saving was higher in Chitwan because of the higher price of fuelwood. However, fuelwood in almost all surveyed households was collected by the family and they perceived the price of fuelwood as near zero since they did not value the time highly. Considering the time value of labour saved on collecting fuelwood, the annual saving on traditional fuels per household increased from US$104 for a 4 m^3 plant to US$147 for a 10 m^3 plant in Chitwan and US$132-177 in Lamjung (Table 7.7). The higher saving on fuelwood based on time value for its collection in Lamjung was probably due to the slightly higher time saving on fuelwood collection (Section 5.4.4).

Another important benefit associated with the use of biogas was income from utilisation of the saved time. About 55% of households in Chitwan and 43% in Lamjung reported earning additional income (see Section 5.4.7). Average annual income of a household ranged between US$50-88 in Chitwan and US$42-96 in Lamjung (Table 7.7). There is no obvious relationship between size of the plant and income from utilisation of the saved time.

Slurry from a biogas plant has soil nutrient and productivity value higher than fresh or composted dung due to the addition of some enzymes and vitamins during the anaerobic digestion process (K. J. Singh & Sooch, 2004). However, the monetary value of such benefits was realised by only 11% of the surveyed households in Chitwan and 9% in Lamjung, who reported savings on expenditure of chemical fertilisers due to the application of slurry. Although the amount saved was not significant compared to savings on alternative fuels (Table 7.7), biogas has a potential to save expenditure on chemical fertilisers through proper utilisation of digested slurry as soil nutrient.

7.7.2 Financial analysis

In order to evaluate whether investment in a biogas system, particularly after co-digestion is profitable, a financial analysis of a biogas plant was carried out computing three most common financial ratios: net present value (NPV), FIRR and benefit cost ratio (B/C ratio) (Annexes 10 and 11) based on the total annual cost of energy from biogas plant operation (existing and co-digestion) (Table 7.2) and monetary benefits associated with the use of biogas (Table 7.7). Although a number of studies have reported the viability of biogas systems in Nepal (Bajgain & Shakya, 2005; N. Dhakal, 2008; Karki et al., 2005), financial analysis of a co-digested plant is lacking. The discount rate was considered at 16%, because the rate of interest that a bank/micro-finance institution charges on loans is up to 16% (CFM, 2013). The rate is much higher compared with the interest rate offered by the banks on saving deposits (2.0-3.5%) (NBL, 2014). Similarly, the life of a biogas plant is considered as 20 years (Karki et al., 2005).

The benefits from investment in a biogas plant outweighed costs for all sizes in both districts, giving a net benefit in monetary terms throughout its life period (Table 7.8). This clearly indicates that biogas plants are beneficial to all households. The financial ratios however are higher for biogas with co-digestion (except for 8-10 m^3 plants in Lamjung due to higher cost of crop residues) due to the lower total cost of energy. This implies that biogas with co-digestion is more profitable than the existing operation, which further justifies the need for modification in domestic biogas plant operation practice in rural Nepal from mono-digestion of dung to co-digestion with crop residues.

Table 7.8: Financial analysis of existing biogas plant operation and biogas with co-digestion of crop residues and dung

Financial ratios	Chitwan				Lamjung			
	4 m^3	6 m^3	8 m^3	10 m^3	4 m^3	6 m^3	8 m^3	10 m^3
Existing biogas plant operation (with subsidy)								
NPV (US$)	171	298	296	238	132	134	320	194
IRR	27%	33%	32%	27%	24%	24%	32%	25%
B/C ratio	4.7	5.7	5.6	4.8	4.2	4.2	5.7	4.4
Biogas plant operation with co-digestion (purchased crop residues and with subsidy)								
NPV (US$)	482	487	393	325	301	247	269	153
IRR	46%	43%	37%	31%	33%	30%	30%	23%
B/C ratio	8.0	7.4	6.5	5.4	5.8	5.2	5.2	4.1

The financial analysis further indicates that investment in a biogas plant of all sizes is highly attractive even without a subsidy (Figure 7.2). Moreover, investment in a biogas plant is a profitable proposition even for the households who do not buy fuelwood but save time for its collection. This result matches with the findings of Dhakal (2008), Bajgain and Shakya (2005) and Karki, et al. (2005); the differences in the values are due to the differences in the local cost of fuelwood that largely determine the actual net cash flow realised by the users (Bajgain & Shakya, 2005). Fuelwood cost at local market at the time of this study was almost two to three times higher than reported in those studies.

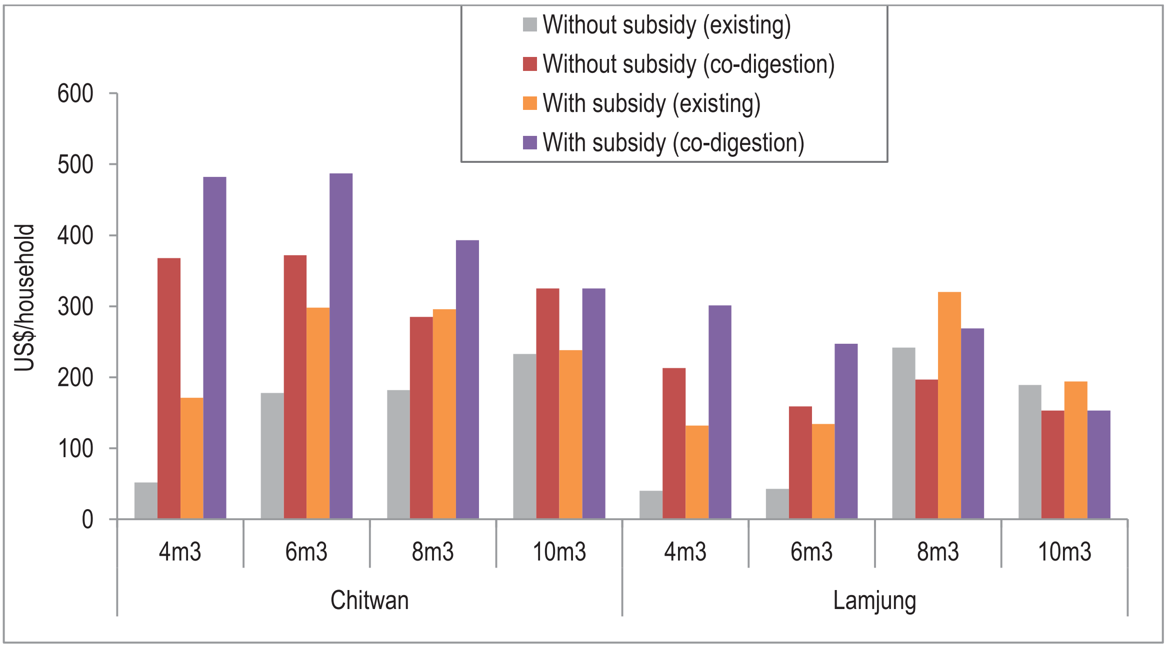

Figure 7.2: Net present values of biogas plants of different size with and without subsidy, and before and after co-digestion of feedstocks

The benefit of biogas plant use in terms of saving on traditional fuels is higher than other benefit streams, which implies that even if the time saved is not utilised for generating income for the family, a biogas plant would still be profitable. The profitability of investment in biogas will increase with the increase in the price of fuelwood, and hence in financial terms, a subsidy is not warranted for replication of biogas technology.

However, a poor household may not be able to afford the capital cost without subsidy (about US$300[50] excluding unskilled labour and construction materials to be arranged by the household), since the average annual per capita income of a poor household is merely about US$245 (CBS, 2011a). Shrestha (2010) revealed that despite their interest to own a biogas plant, about 42% of households cannot afford it due to the high capital cost. Although micro-finance institutions are providing soft loans at 14-16% interest rate for biogas construction to help users in capital cost (BSP, 2012) (see Section 3.7.4), lack of collateral to secure a loan or lack of regular cash flows to repay it had deprived the poor households from owning a biogas plant (CFM, 2013; N. Dhakal, 2008). In this context, subsidy that covers a considerable proportion of the installation cost (e.g., about 30% of the capital cost for a 4 or 6 m^3 plant in the Hill), is crucial to promote the poor's access to biogas technology and achieve the full technical potential

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[50] BSP-Nepal approved cost of 6 m^3 biogas plant for a hilly district (BSP-Nepal, 2012a).

of biogas plant installation in the country. Continuation of the subsidy on biogas plant installation can also be justified as the government incentive payment to a biogas user for the contribution to attain government's long-term social objectives such as reduction in deforestation, reduction in spending of foreign currency earnings for importing fuels and improved health conditions of women and children (particularly respiratory diseases in women and children caused by fuelwood smoke).

CHAPTER EIGHT

IMPACT OF BIOGAS ON HOUSEHOLD ENERGY CONSUMPTION AND GHG EMISSION REDUCTION

8.1 Introduction

The previous two chapters, Chapters Six and Seven, analysed the co-digestion of animal dung with crop residues to improve the biogas production efficiency of the biogas plants, and assessed the cost of energy before and after the installation of biogas plants, respectively. This chapter aims for the comprehensive analysis of the potential of biogas to reduce energy consumption and corresponding emissions under different technical and policy scenarios, selecting a suitable model for analysing energy demand and GHG emission. This chapter specifically examines how much traditional fuels, particularly fuelwood consumption, and environmental emissions could be reduced after improving the production efficiency of biogas plants, and what will be the implications on the balance of social costs, including the carbon credit earned and externality costs. It also estimates the resource requirements for transformation into final energy demands and assesses potential of biogas in reducing non-energy emissions of these resources.

This chapter first reviews the existing models for analysing energy demand and GHG emissions to select the most suitable model to be applied to this study. The LEAP model was considered as the most practical due to its capabilities to be used in a wider context in terms of analysing integrated energy and environmental scenarios, sectoral and geographical coverage, complexity and data requirements. Scenario generation for the LEAP model is then described. Three alternative scenarios derived from the business-as-usual scenario are used for the impact analysis. Finally, this chapter presents the data analysis results and discusses the impact of biogas on household-level energy consumption and GHG emissions reduction.

8.2 Review of Energy Demand Forecasting and GHG Emission Reduction Models

In general, a model is required to solve complex problems in a systematic manner and in less time (Mai, Logan, Blair, Sullivan, & Bazilian, 2013; van Beeck, 1999). It is not always necessary to make a new model when there are already existing models for similar objectives (Bhattacharyya & Timilsina, 2010b). Different models may have similar objectives, scope or analytical approach, but may not match exactly the specific research objectives (Murray, 2005). Hence, a thorough review of the existing models is necessary to choose the best model that matches the required objective. In order to assess the most suitable model for energy forecasting and GHG emissions reduction for this study, existing energy forecasting and climate change mitigation models were reviewed by comparing the most commonly used models, using different sets of criteria and modelling approaches. Of the many energy system models, the most commonly used energy models found in the majority of the energy model-reviewed literature (Bhattacharyya & Timilsina, 2010a, 2010b; COMMEND, 2013; ETSAP, 2011; IAEA, 2006; NRCan, 2013; UNFCCC, 2005; van Beeck, 1999) are listed below:

- Market allocation model/the integrated MARKAL-EFOM system (MARKAL/TIMES)
- Energy and power evaluation program (ENPEP)
- Hybrid Optimization Model for Electric Renewables (HOMER)
- Modèle d'Evolution de la Demande d'Energie/model for analysis of energy demand (MEDEE/MAED)
- RETscreen
- National energy modelling system (NEMS)
- Long-range energy alternatives planning system model (LEAP)
- Perspective outlook on long-term energy system (POLES)
- Modular energy system analysis and planning (MESAP)
- Regional energy scenario generator (RESGEN), and
- World energy model (WEM).

Different literatures used different sets of criteria and modelling approaches for the review and comparison of the energy system models (e.g., Bhattacharyya & Timilsina, 2010a, 2010b; COMMEND, 2013; van Beeck, 1999). The most common criteria and approaches were selected for this study (Table 8.1). Some of these models are also included in the World Bank's climate-smart planning platform (CSPP) (WorldBank, 2013). The CSPP gives access to a set of well-established and linked planning tools, methods, approaches and climate-related global and national datasets to cover most of the modelling needs of developing countries and individual users for climate-resilient and low-carbon development analysis (WorldBank, 2013). The models were compared against the selected criteria and approaches to assess their suitability based on their characteristics and capabilities that fitted with the aims of this study (Table 8.1).

Table 8.1: Result of the comparative review of the energy system model capability relative to this study

Models	Capability to analyse integrated energy and environment policies	Bottom-up analytical approach	Applicable to local & national level	User controlled time horizon (medium and long term)	Limited data version model suitable for developing countries	Default data included	Very high or special skill set is not required for running a complex model	Software is free	Capability to analyse rural energy	Scenario-based analysis	Included as a tool in the Climate-Smart Planning Platform	**Total Score**
MARKAL/TIMES	√	√	√	√	√	X	X	X	√	√	X	**7**
ENPEP	√	√	√	√	√	X	X	√	√	X	X	**7**
HOMER	X	√	√	√	√	√	X	X	X	X	√	**6**
MADEE/MAED	X	√	√	√	√	X	√	√	√	√	X	**8**
RETscreen	X	√	√	√	√	√	√	√	X	√	√	**9**
NEMS	X	√	√	√	√	√	X	X	X	X	X	**5**
LEAP	√	√	√	√	√	√	√	√	√	√	√	**11**
POLES	X	√	X	√	X	X	X	X	x	X	X	**2**
MESAP	X	X	√	√	X	√	X	X	√	X	X	**4**
RESGEN	X	√	√	√	√	X	√	X	√	X	X	**6**
WEM	√	√	√	√	X	X	X	X	√	√	X	**6**

Source: Adapted from Bhattacharyya & Timilsina (2009, 2010a, 2010b); van Beeck (1999); ETSAP (2011); NRCan (2013); COMMEND (2013); IAEA (2006); UNFCCC (2005); Heaps (2012); World Bank (2013).

The model for assessing the impact of biogas systems on fuelwood consumption and GHG emissions reduction should be capable of modelling integrated energy and environmental policies in order to examine the interactions among energy, economy and environmental systems and scenarios while the models that focus on one aspect only fail to address the interactions (van Beeck, 1999). Similarly, the model for this study should be capable for analysing the energy demand and consumption of individual households. Bottom-up models generally analyse energy demand and consumption of individual households and extrapolate the results to the regional or national context (Swan & Ugursal, 2009; Yuning, 2012). Bottom-up models are considered more suitable for evaluating the options for specific sectoral and technological implications (UNFCCC, 2005) and address local concerns (R. Pandey, 2002). This approach is helpful in analysing impact of various individual components on energy and GHG emissions reduction. Hence, the model for this study should have a bottom-up analytical approach in order to consider the details of the energy systems to meet the end-user's requirement, and allow a wide range of policy options for evaluation (Bhattacharyya & Timilsina, 2010b; Swan & Ugursal, 2009; van Beeck, 1999; van Vuuren et al., 2009).

Similarly, the model for this study should be capable of a local to national geographical coverage and user controlled medium to long-term time horizon. Geographical coverage is an important criteria to differentiate the models, because it indicates the geographical spread over which the analysis takes place (van Beeck, 1999). Besides this, local to national models do not require highly aggregated data, but usually operate on a bottom-up approach using disaggregated data, and hence such models are considered suitable for small-scale studies (Bhattacharyya & Timilsina, 2010b; van Beeck, 1999). This study considers a time horizon of 20-30 years, the average expected life period of a biogas plant, and hence the time horizon is another important factor to define the structure and objectives of the models, because social, economic and environmental outcomes differ with different time-scales (Bhattacharyya & Timilsina, 2009, 2010a). Short time forecasting horizons may not reflect these outcomes properly (van Beeck, 1999). Similarly, a very long time-horizon may not be suitable since the forecasts are over deterministic, failing to recognise the possible technological transformation which changes users' behaviours and consumption patterns (McDowell & Eames, 2004; Smil, 2000).

Moreover, data and skills requirements, and costs of software were other considerations for choosing the model since they are linked to the ease of access and availability of use (Bhattacharyya & Timilsina, 2010b). Data requirement is another major issue for any demand model since models that require large data inputs can create problems for developing countries(Bhattacharyya & Timilsina, 2009). It is important to look at how much data is required and what is the nature of the data required to run the model. In this study, a simple end-use model is preferred to the complex estimation models (Adeyemi & Hunt, 2007), since this study focused on end uses or final energy needs. Similarly, skill requirement is another important consideration if the model requires any special complex skill set to run a complex model. Craig, et al. (2002) and Armstrong (2001) also suggested that models with complex skill and data requirements could result in inaccurate forecasts, and a simple model should have a low skill and data requirement. Models that are suitable for developing countries and had capability to analyse rural conventional energy and scenario-based projections were other factors considered for choosing the most suitable model in this study (R. Pandey, 2002).

Each model was given a score based on whether the requirements were met or not (Table 8.1). The LEAP model was chosen to be used for the analysis of the impacts of biogas in this study. The screening results indicated LEAP as the most suitable model that addressed all of the requirements considered for choosing a model. Of the many energy system models reviewed, LEAP was the model that appeared in the majority of the research papers reviewed (Table 8.2).

Table 8.2: Selected references to energy system model applications in the literature

Author	Title of the research paper	Model used
Dhakal (2003)	Implications of transportation policies on energy and environment in Kathmandu Valley, Nepal	LEAP
Rajesh, et. al. (2003)	Analysis of long-term energy and carbon emission scenarios for India	MARKAL
Kumar, et. al. (2003)	Greenhouse gas mitigation potential of biomass energy technologies in Vietnam using the long range energy alternative planning system model	LEAP
Shakya (2005)	Application of renewable energy technology for greenhouse gas emission reduction in Nepalese context: A case study	LEAP
Ghanadan & Koomey (2005)	Using energy scenarios to explore alternative energy pathways in California	LEAP
Pradhan et al., (2006)	Mitigation potential of greenhouse gas emission and implications on fuel consumption due to clean energy vehicles as public passenger transport in Kathmandu Valley of Nepal: A case study of trolley buses in Ring Road	LEAP
Hainoun, et. al. (2006)	Analysis of the Syrian long-term energy and electricity demand projection using the end-use methodology	MAED
APERC (2006)	APEC energy demand and supply outlook, 2006	LEAP
Lin, et al. (2006)	Achieving China’s target for energy intensity reduction in 2010: An exploration of recent trends and possible future scenarios	LEAP

Author	Title of the research paper	Model used
Kadian, et. al. (2007)	Energy-related emissions and mitigation opportunities from the household sector in Delhi	LEAP
Limmeechokchai & Chawana (2007)	Sustainable energy development strategies in the rural Thailand: The case of improved cooking stove and the small biogas digester	LEAP
Shabbir & Ahmad (2010)	Monitoring urban transport air pollution and energy demand in Rawalpindi and Islamabad using LEAP model	LEAP
Davis (2010)	Jamaica's greenhouse gas mitigation assessment	LEAP
Jun, et al. (2010)	The assessment of renewable energy planning on CO_2 abatement in South Korea	LEAP
Shrestha & Rajbhandari (2010)	Energy and environmental implications of carbon emission reduction targets: Case of Kathmandu Valley, Nepal	MARKAL
Sulukan, et.al. (2010)	Determining optimum energy strategies for Turkey by MARKAL model	MARKAL
Atabi, et. al. (2011)	Scenario analysis of the potential for CO_2 emission reduction in the Iranian cement industry	LEAP
Zhangemail, et. al. (2011)	Alternative scenarios for the development of a low-carbon city: A case study of Beijing, China	LEAP
Shrestha & Shakya, (2012)	Benefits of low carbon development in a developing country: Case of Nepal	MARKAL
Malla (2013)	Household energy consumption patterns and its environmental implications: Assessment of energy access and poverty in Nepal	LEAP

8.3 LEAP for Energy Demand and GHG Emission Analysis

The LEAP model was used to analyse the impact of biogas systems on fuelwood demand and GHG emissions reduction. It is a widely used modelling tool for the study of integrated energy policy analysis and climate change mitigation assessment (SEI, 2013). It can be used for forecasting energy production and consumption, and analysis of GHG emission mitigation policies. It is a tool for scenario-based analysis with a decision support system capable of providing extensive data management and reporting (Heaps, 2012; SEI, 2013). Many researchers have used LEAP for studying the impact of different energy systems and environmental policies at local, national and global levels (Table 8.2). It can be used to analyse the effects of population, number and size of households, and income on energy and environmental policies (Kadian et al., 2007).

When LEAP is used for end-use analysis of the household energy sector, the demographic pattern, such as population, number of households and household size, and per capita income that influence energy consumption and the corresponding emissions were taken as the key variables. In this study, all the existing and potential biogas households were assumed to be rural households. The data collected during the field surveys and from secondary sources were used as the baseline for the analysis. The energy demand analysis was carried out for household cooking only, since biogas was only used for cooking. Alternative scenarios were developed to analyse the implications of biogas systems on energy use and emissions depending on various policy initiatives, which are described in Section 8.4.

The energy demand and environmental emission analysis were carried out both at the surveyed district level (Chitwan and Lamjung) and modelled regional levels (Terai and Hill)[51] with respect to biogas plant size for each scenario based on the findings of the existing energy use practices in the two studied districts. The activity data required for the energy and emission prediction were obtained from the analysis of data collected during the household survey in Chitwan and Lamjung, while the emission factor[52] data (IPCC tier 1 factors[53]) contained in LEAP were used.

LEAP was used for projecting four energy and emission related categories: (a) energy demand, (b) energy transformation, (c) energy resources and (d) non-energy sector effects. The LEAP structure and calculation flows used in this study are presented in Figure 8.1 and an example of data structure in LEAP is presented in Figure 8.2. A brief description of key terms used in LEAP is presented in Table 8.3. The modules and various sub-categories were determined based on the objective and availability of data (Table 8.4).

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[51] Chitwan represents the Terai and Lamjung represents the Hill region.

[52] The average emission rate of a GHG for a given source, relative to units of activity (IPCC, 2007).

[53] Tier 1 emission factor is the simplest method for estimating GHG emission that utilises emission factors recommended by the IPCC that are often applicable for all countries (IPCC, 2007).

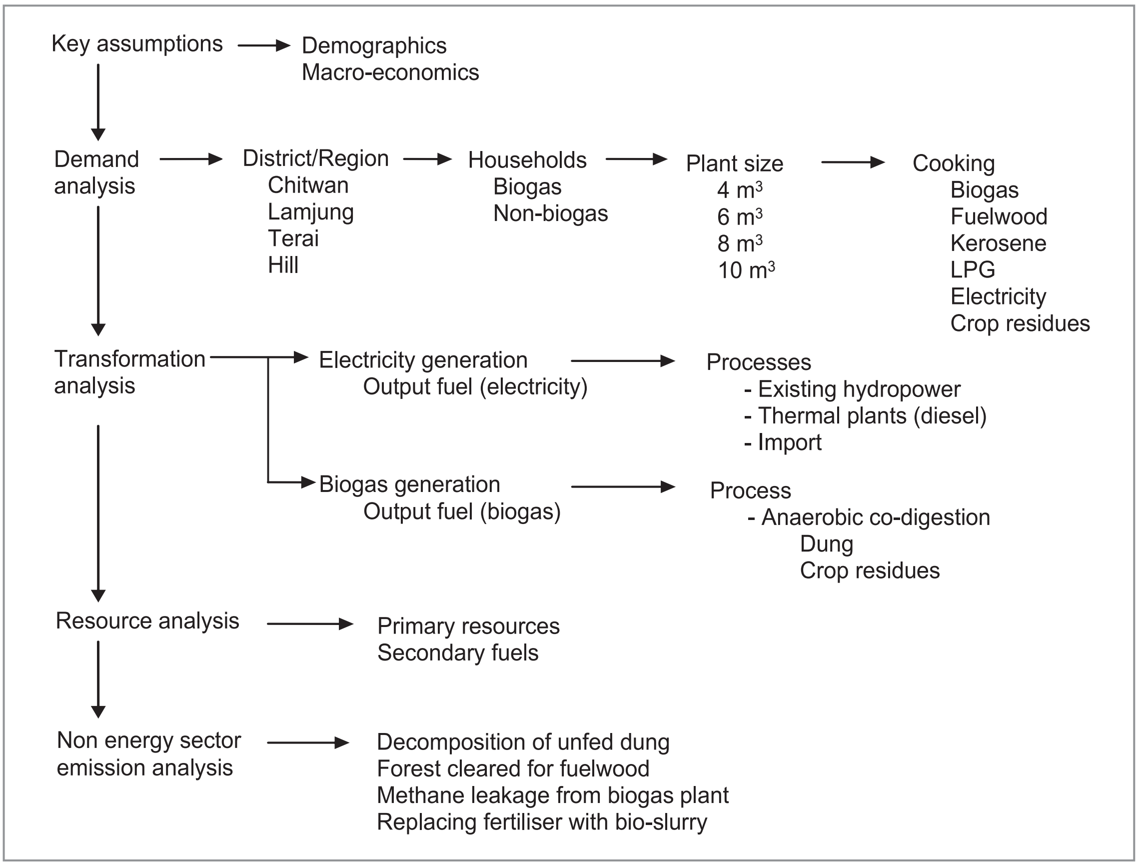
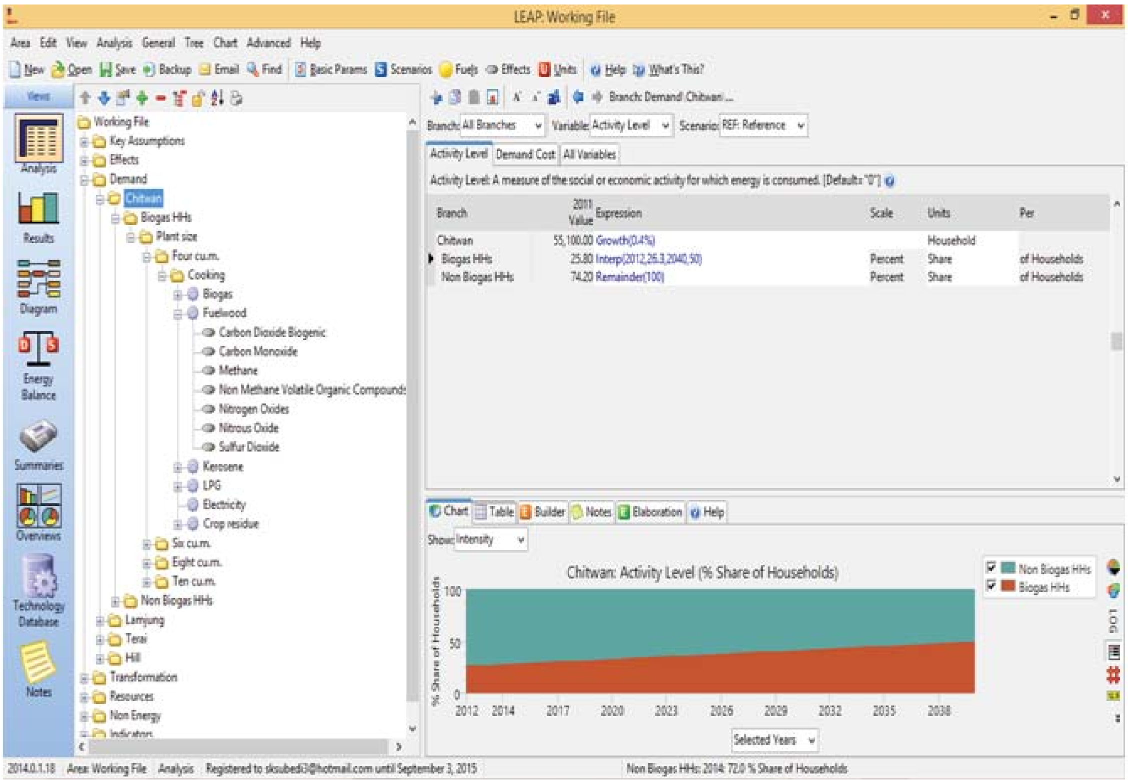


Figure 8.1: LEAP structure and calculation flow



Branch: Demand\Chitwan\...

Branch: All Branches Variable: Activity Level Scenario: REF: Reference

Activity Level | Demand Cost | All Variables

Activity Level: A measure of the social or economic activity for which energy is consumed. [Default="0"]

Branch	2011 Value	Expression	Scale	Units	Per
Chitwan	55,100.00	Growth(0.4%)		Household	
Biogas HHs	25.80	Interp(2012,26.3,2040,50)	Percent	Share	of Households
Non Biogas HHs	74.20	Remainder(100)	Percent	Share	of Households

2014.0.1.18 Area: Working File Analysis Registered to sksubedi3@hotmail.com until September 3, 2015 Non Biogas HHs: 2014: 72.0 % Share of Households

Figure 8.2: Example of data structure in LEAP to the left in the figure

Table 8.3: Brief description of key terms used in LEAP analysis

Key terms	Definition
Tree	The main data structure used for organising data and modules, and for reviewing results as used in LEAP
Module	The branch representing the energy sector, e.g., demand, transformation, resources or non-energy
Branch	An item on the tree, which includes categories, technologies, modules, fuels, effects and other user-defined variables. • Category branches are used for organising other branches into hierarchical data structures • Technology branches represent final energy consuming devices and type of fuel consumed • Effect branches are used for viewing or editing data on different environmental loadings or pollution emissions from the consumption or production of energy. • Fuel branches indicate the feedstock and output fuels in the transformation module, whereas resource branches represent primary resources and secondary fuels produced, imported or exported in the resource tree. Feedstock fuel is an input fuel consumed by a energy transformation process, whereas output fuel is a fuel thus produced.
Key assumptions	The branch used to store the assumptions made for the scenario analysis. Key assumptions are not used directly in LEAP's calculations but can be linked to them.
Demand	Module that comprises activity level data and final energy intensity for energy demand analysis.
Activity level	A measure of social and economic activity for which energy is consumed.
Energy intensity	Energy consumed at a specific branch per unit of activity level per year.
Transformation	A module that analyses energy conversion, extraction, transmission and distribution.
Resource	The branch used to indicate primary resources (which has not been converted) and secondary fuels (converted from primary resources) produced, imported or exported.
Scenario	A consistent set of assumptions about the future to analyse expected changes in future energy systems over time defined by a set of conditions that is expected to change over time
Current accounts	The data describing the base year or first year of the study period

Source: SEI (2010, pp. 299-301); IPCC (1999); UNFCCC (2014a)

Table 8.4: Modules and subcategories to projecting for energy consumption and emissions in the LEAP model

Key assumptions	Demand	Transformation	Resources	Non-energy sector effects
Population	Chitwan, Lamjung; Terai, Hill	Transmission & distribution	Primary	Decomposition of unfed dung
Population growth rate	Potential biogas household	Bottled LPG	Fuelwood	Forest cleared for fuelwood
Households	Biogas households	Kerosene import	Crop residues	Methane leakage from plants
Household size	Biogas plant size	Fuelwood fire	Hydro	Digested slurry replacing fertilisers
Per capita income growth	Cooking	Electricity generation	Animal waste (dung)	
GDP growth rate	Biogas	Electricity import	Human excreta	
Biogas households	Fuelwood	Crop residue fire	Diesel	
Potential biogas household	Kerosene	Anaerobic digestion		
Crop residues potential	LPG		Secondary	
Dung produced	Electricity		Biogas	
Forest cover	Crop residues		Electricity	
			Kerosene	
	Non biogas households		LPG	
	Cooking			
	Biogas			
	Fuelwood			
	Kerosene			
	LPG			
	Electricity			
	Crop residues			

8.3.1 Description of the LEAP modules

Key assumptions

The *Key assumptions* module is the branch to store the assumptions made for the scenario analyses and comprises demographic variables (population, population growth rate, households, household size), microeconomic data (GDP, GDP growth rate, per capita income/growth), existing and potential biogas households and feedstock potential (dung and crop residues) for the studied districts and the representative regions. The demographic details were taken from the National Population and Housing Census 2011 (CBS, 2012a) (Table 8.5). It is assumed that the population growth rate, household growth rate and household size remain the same over the study period for all the scenarios.

Table 8.5: Demographic profile of Nepal for the base year 2011 as used in the *Key assumptions* module of LEAP

Description	Total	Rural	Chitwan	Lamjung	Terai	Hill
Population (million people)	26.5	21.97	0.58	0.17	13.32	11.39
Household size (people)	4.88	5.02	4.38	3.99	5.27	4.50
No. of households (million)	5.43	4.38	0.13	0.042	2.54	2.53
Population growth (%)	1.35	1.71	2.30	1.46	1.9	1.2
Per capita GDP (US$)	735	735*	NA	NA	NA	NA
GDP growth rate (%/year)	4.63	4.63*	NA	NA	NA	NA
Per capital income (US$)**	489	489*	NA	NA	120	126
Per capita income growth (%)**	3.56	3.56*	NA	NA	NA	NA
Biogas households by 2011 [a]	268,400	268,400	14,372	7,822	129,600	130,248
Potential biogas households[b]	1.93 million	1.93 million	57,100	14,300	1.08 million	723,600
Crop residues potential (m. tonnes)#	19.38	18.2	0.36	0.11	11.60	6.80

NA = Not available

**MoF (2014); [a] BSP-Nepal (2012b); [b] BSP-Nepal (2009b); # WECS (2010)

*The GDP and per capita income for rural areas were not available, and were thus assumed to be the same as the national value (1 US$ = NRs. 95.3; 2014 value)

Source: CBS (CBS, 2012a), CBS (2012b)

A steady national per capita income growth of 3.56% per annum (2012 value) (MoF, 2013) was also assumed to remain constant over the study period for all the scenarios. The growth of biogas system installation was considered as a function of two factors – subsidy and gas production; the more the subsidy and/or biogas production, the higher the possibility of biogas plant installation. The data on existing and potential biogas households were taken from the BSP-Nepal reports (BSP-Nepal, 2009b, 2015). The total potential of biogas households is estimated at 1.93 million (BSP-Nepal, 2012b) with assumed growth of 0.4% per annum across all regions. The growth rate assumption is based on the annual increase in the number of households and additional potential of domestic biogas plants operating on crop residues as co-substrate. UNDP (2013) estimates a potential of more than 200,000 family-sized plants when crop residues are used as co-substrate.

Demand

The *Demand* module comprises activity level data and final energy intensity to calculate the total annual energy consumption. The demand module was further divided into various hierarchical branches such as physical area (Chitwan and Lamjung as well as the Terai and the Hill regions), biogas and non-biogas households, biogas plant size, cooking as end-use and fuel branch according to fuel use (Figure 8.3). Six different fuels, namely biogas, fuelwood, kerosene, LPG, electricity and crop residues were used for cooking in the surveyed households, which were included as the fuel branch. These branches were selected to analyse the energy demand and environmental emissions in terms of studied district/region as well as biogas plant size. LEAP calculates the energy demand of each region/plant size and thereby the total energy demands of the districts/regions. The environmental loadings associated with the fuel branch helps to estimate environmental emissions and environmental impacts associated with each scenario. These emissions are estimated using the emission coefficients contained in the LEAP Database. The data for this module were obtained primarily from the 314 surveyed households and secondary sources such as the BSP-Nepal website/publications.

The demand analysis consists of final energy demand in which energy consumption is calculated as the product of total activity level and final energy intensity at each given technology branch (Equation 8.1) (SEI, 2013).

$$(\text{Energy demand})_{b,s,t} = (\text{Total activity})_{b,s,t} \times (\text{Energy intensity})_{b,s,t} \qquad \text{(Equation 8.1)}$$

Where *b* is the branch, *s* is scenario and *t* is year (from base year [0] to the end year). LEAP calculates the total final energy demand for each branch, scenario and fuel (SEI, 2013). The total activity level for a technology is computed as the product of the activity levels in all branches from the technology branch back up to the original *Demand* branch (Equation 8.2) (SEI, 2010, p. 76; 2013).

$$(\text{Total activity})_{b,s,t} = (\text{Activity})_{b',s,t} \times (\text{Activity})_{b'',s,t} \times (\text{Activity})_{b''',s,t} \times \ldots\ldots. \qquad \text{(Equation 8.2)}$$

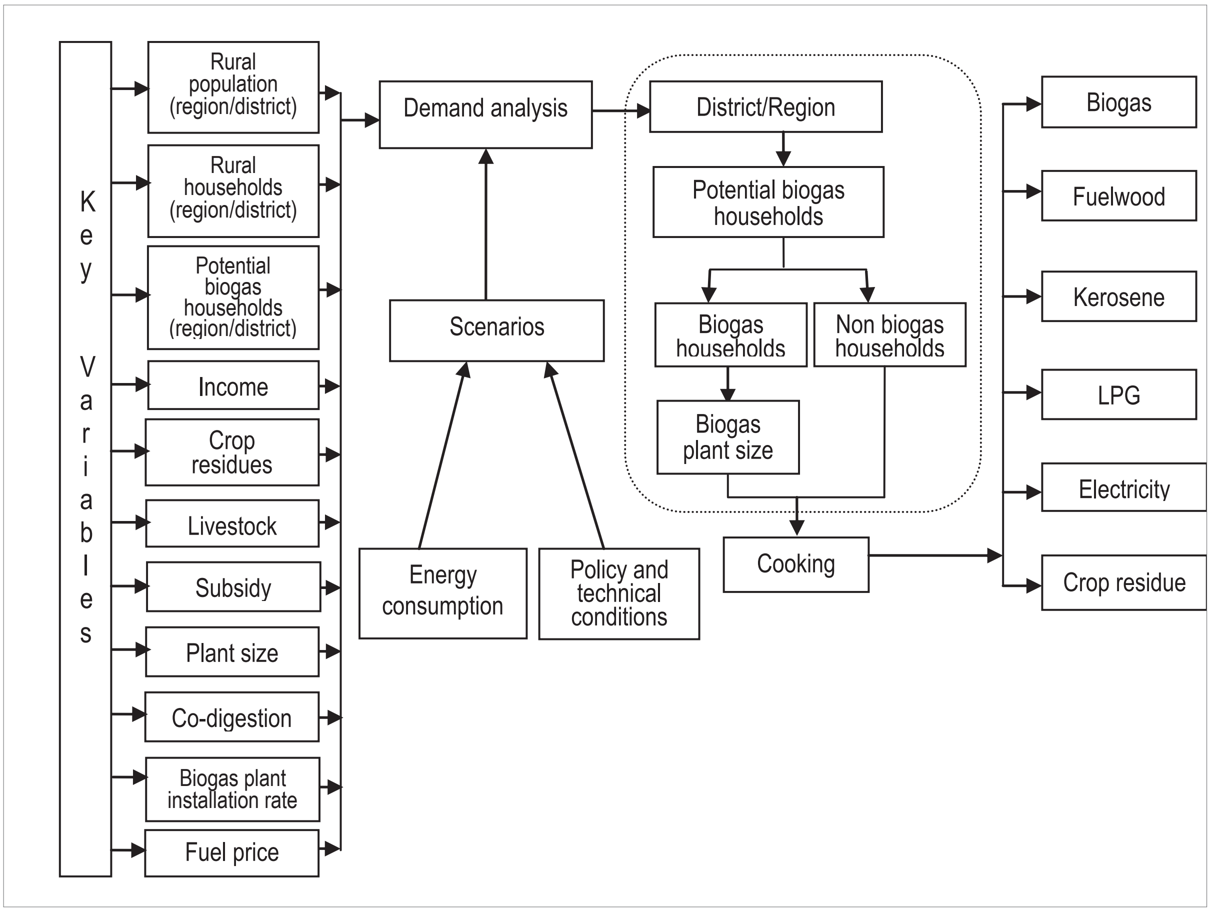


Figure 8.3: LEAP framework for analysing energy consumption and GHG emission

Where *b'* is the parent of branch *b*, *b"* is the grandparent of branch *b* and so on. The top level *Demand* branch is treated as having an activity level of 1 (SEI, 2010).

The environmental emissions (pollutants and other direct environmental impacts) are calculated in LEAP as the product of energy consumption and emission factor for each technology, year and pollutant (Equation 8.3) (Kadian et al., 2007; SEI, 2010).

$$(\text{Emission})_{t,y,p} = (\text{Energy consumption})_{t,y} \times (\text{emission factor})_{t,y,p} \qquad \text{(Equation 8.3)}$$

Where *t* is technology, *y* is year and *p* is pollutant. The IPCC Tier 1 default emission factors contained in LEAP were used for the emission analysis. The environmental emissions or effects were expressed in terms of GHG emission using the default global warming potential

(GWP)[54] factors available in LEAP for a 100-year time horizon. This study estimated GHG emissions using the global warming potential (GWP) factors based on a 100-year time horizon under different scenarios. UNFCCC/Kyoto Protocol requires the countries to use 100-year values for the national inventories report (WRI & WBCSD, 2013), and hence a 100-year time horizon is chosen for this study to make easy comparison between findings of this study and the values in the national inventory report. The IPCC Tier 1 factor contained in LEAP was utilised for categorising the emission factors.

Transformation

The *Transformation* analysis, which is demand driven, examines how the primary energy is transformed through to secondary energy or final energy and calculates the total amount of primary energy required to produce the final energy demanded (IGCS, 2014; SEI, 2013). Different levels of transformation processes used in this study are presented in Figure 8.4. The transformation module comprises different processes for the conversion of primary energy to final energy such as electricity and biogas, and includes electricity generation and distribution, anaerobic digestion, fuel transmission and distribution, and fuel import to meet the energy demand for cooking in the residential sector. Hydro, crude oil/diesel, wood, animal wastes and crop residues are the main feedstock fuels used to produce final energy. The capacity requirements in each of the scenarios were computed in terms of the merit order dispatch rules. The merit order rule ranks available sources of energy based on increasing order of price and amount of energy generated, so that lower cost energy is generated first to meet demand and thus minimises the cost of energy production (SEI, 2010).

Resources

The *Resource* branch in LEAP is always divided into primary resources and secondary fuels, which helps to analyse individual fuels consumed and produced in the energy system under study (SEI, 2010). Any changes in fuels in *Demand* and *Transformation* analyses are automatically updated in the *Resources*. *Resource* analysis was used to assess the availability of primary resources and cost of production of the primary resources and secondary fuels, which are determined by the levels of final energy demand in demand analysis (SEI, 2013).

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[54] An index measuring the ratio of the radiative forcing of the non-CO_2 GHG to that of CO_2, and relates the impact of emissions of a gas to that of emission of an equivalent mass of CO_2. GWP is always expressed relative to CO_2; GWP of CO2 is 1.0 for all time horizons (IPCC, 1999). GWP is specified over a specific time interval, usually 20, 100 or 500 years. The contribution of methane and nitrous oxide, the potent GHGs, to the GWP is 25 and 298 times of CO_2 over a 100-year period.

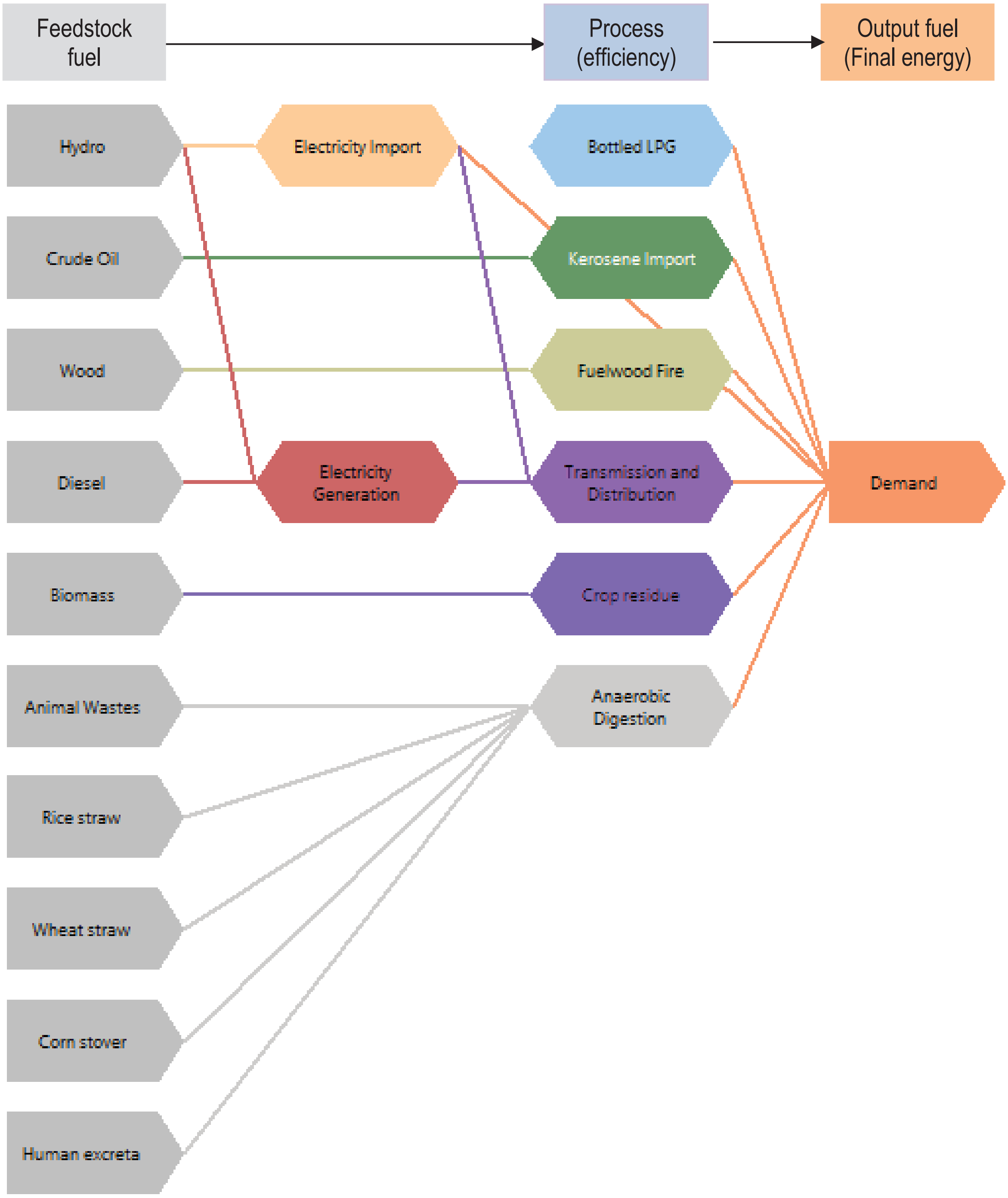

Figure 8.4: Transformation of energy forms from primary resources to final energy

Non-energy sector effects

The non-energy sector effects module is an optional module to create inventories and scenarios for non-energy related GHG emissions as a complement to energy sector emissions and mitigation measures (SEI, 2010). It was used in this study to examine the potential of biogas technology to reduce non-energy sector GHG emissions related to biogas production and consumption, which include emissions from decomposition of unfed dung (compost), methane leakage from biogas plants, forest cleared for fuelwood, and use of digested slurry replacing fertiliser. Where data from the survey were not available, such as methane leakage, non-energy emission factors and quantity of chemical fertilisers used, the analysis was based on projections from the national emission inventory and other relevant literature.

8.3.2 Time horizon

Year 2011 was taken as the common base year for all the scenarios and the first and last projection years were 2012 and 2040. Because the policy options/conditions for the alternative scenarios are still not in place and would take few years to come into effect, the time frame for the alternative scenarios was considered as 2018-2040. Projections were made for four sets of scenarios, which are discussed in the subsequent section.

8.4 Scenario Generation

Scenarios are the most commonly used conditions in the study of energy systems and climate change to analyse expected changes in future energy systems over time defined by a set of socio-economic and policy conditions, and are usually used to answer the 'what if' questions related to the conditions (Ghanadan & Koomey, 2005; Kadian et al., 2007; SEI, 2010). The scenarios in LEAP include the factors or the set of conditions that is expected to change over time (Kadian et al., 2007). The socio-economic, demographic and energy use information and related policy conditions are applied to construct alternative scenarios that analyse how the total final energy consumption changes over time in a particular sector of the economy (SEI, 2013).

The impacts of biogas on household energy consumption and GHG emissions reduction were analysed using LEAP, generating four different scenarios under different set of options: (a) reference scenario, (b) improved biogas production efficiency scenario, (c) increased subsidy scenario, and (d) integrated scenario with cumulative effect of improved biogas production efficiency and increased subsidy scenarios. All three alternative scenarios were taken over from the reference scenario and hence they reflect sensitivities on the reference scenario (Figure 8.5). The policy options and assumptions for scenario development are discussed in the following sections. Details of policy options/conditions and various assumptions for the scenarios are given in Table 8.6.

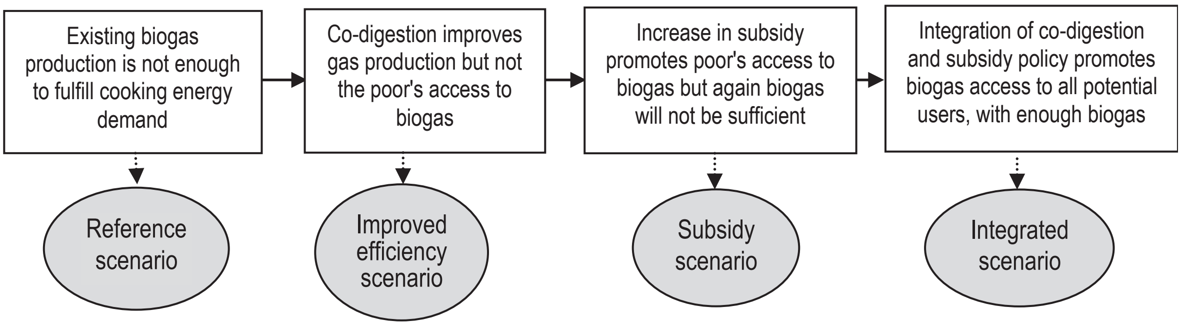

Figure 8.5: The logic connecting the alternative scenarios to the reference scenario

Table 8.6: Overview of policy options and assumptions for scenario development

Scenario	Policy options/conditions	Assumptions
Current account	Base year values	• About 25.8% of potential biogas households in Chitwan, 54.7% in Lamjung, 12% in the Terai, 18% in Hill had installed biogas plants (Table 8.5). • Biogas fulfilled about 73.5% and 64% of total energy demand for cooking in biogas households in Chitwan/Terai and Lamjung/Hill, respectively (Section 5.5.1). • Biogas households using fuelwood, LPG, electricity and crop residues were about 83%, 46%, 56% and 3% in Chitwan/Terai and 98%, 25%, 34% and 6% in Lamjung/Hill, respectively (Field survey, 2012). • Fuelwood, kerosene, LPG, electricity and crop residues were used by 99%, 1%, 12%, 25% and 4% of non-biogas households in Chitwan/Terai and 100%, 8%, 4%, 0% and 11% of the households in Lamjung/Hill, respectively (Field survey, 2012). • The average final energy intensity per non-biogas household was 3.75 tonnes fuelwood, 7.7 kg LPG, 31 kWh electricity, and 2.1 kg crop residues in Chitwan/Terai and 4.3 tonnes fuelwood, 2.8 kg LPG, 0.6 litre kerosene, 30 kWh electricity, and 9.5 kg crop residues in Lamjung/Hill (Field survey, 2012).
Reference scenario	Extension of the present practices and trend of energy consumption and biogas policy	• All biogas households are rural households • Households continue using more than one energy source for cooking to supplement biogas deficit, and the energy efficiency improvement of cooking devices and energy use pattern remain the same throughout the scenario. • Biogas households increase to 50% in Chitwan, 70% in Lamjung, 50% in the Terai and 50% in Hill in 2040.

Scenario	Policy options/conditions	Assumptions
		• The proportions of 4, 6, 8 and 10 m^3 plants are 10%, 71%, 17% and 3% in Chitwan and Terai, and 33%, 55%, 11% and 1% in Lamjung and Hill region, respectively (based on the existing size-wise proportion of biogas plants). No installation of additional 10 m^3 plants was due to no subsidy provision. • In Chitwan/Terai, fuelwood from 83% to 60% of households, LPG from 46% to 70% of households and electricity from 56% to 80% of households in 2040. • In Lamjung/Hill region, fuelwood from 98% to 80% of households, LPG from 25% to 50% of households and electricity from 34% to 60% of households in 2040. • Use of kerosene and crop residues decrease gradually and none of the households uses them by 2040. • The existing subsidy provision and other biogas related policy remain unchanged. • In non-biogas households, fuelwood to 90% of households, LPG to 25%, electricity to 50% and kerosene/crop residues to zero household in 2040.
Improved production efficiency scenario	At least 50% increase in biogas production through co-digestion of dung with crop residues (Section 6.4). Modification of plant design to suit co-digestion and biogas co-	• Biogas extends to additional 10% of households than in the reference scenario by 2040. • The proportions of biogas plant size remain the same as in the reference scenario. • None of the biogas households uses kerosene, LPG and crop residues. Electricity fully replaces fuelwood after 2030 when all rural households have access to it. • Existing biogas policy/priorities remain unchanged. • Education is provided to the households as a support tool to improve adoption of co-digestion.

Scenario	Policy options/conditions	Assumptions
	digestion policy are in place by 2018.	
Increased subsidy scenario	Increased subsidy policy to cover at least 75% of the cash cost of biogas plants installation in place.	• Biogas extends to 80% of the potential households in Chitwan, Terai and Hill, and 90% in Lamjung. • The proportions of biogas plant size remain the same as in the reference scenario. • Biogas availability and intensity of other fuels remain same as in the reference scenario. • Existing biogas policy/priorities, except subsidy provisions remain unchanged.
Integrated scenario	Combined effect of improved production efficiency and increased subsidy scenario	• Biogas extends to 100% of households in both districts and regions by 2040. • The proportions of biogas plant size remain the same as in the reference scenario. • Household energy use pattern remains the same as in the improved production efficiency scenario, where only biogas and electricity are used for cooking after 2030. • Existing biogas policy/priorities, except subsidy provisions remain unchanged. • Education is provided to the households as a support tool to improve adoption for co-digestion technology.

8.4.1 Current account

The *current account* is the base year value, which forms the basis for the reference and alternative scenarios, and facilitates comparison of energy demand and emissions. The data for the base year is mainly based on the household surveys of the 314 households in two districts and literature reviews. All current and potential biogas households are considered as rural households. About 25.8% of potential biogas households in Chitwan, 54.7% in Lamjung, 12.0% in the Terai and 18.0% in the Hill had installed biogas plants in the base year (Table 8.7).

Table 8.7: Biogas plants installation in the base year and assumption for four scenarios by 2040 (% of potential biogas households in the district/region)

Region	Current account	Reference Scenario	Improved efficiency Scenario	Subsidy Scenario	Integrated Scenario
Chitwan	25.8	50	60	80	100
Lamjung	54.7	70	80	90	100
Terai	12.0	50	60	80	100
Hill	18.0	50	60	80	100

Biogas was the major energy source for cooking, which fulfilled about 73.5% and 64% of the energy demand for cooking in biogas households in Chitwan and Lamjung, respectively (Section 5.5.1). The households used other energy sources for cooking such as fuelwood, kerosene, LPG, electricity and crop residues to fulfill the energy deficit from available biogas, but the share of those energy sources was small (Section 7.3). About 83% of the households in Chitwan and 98% in Lamjung used fuelwood (Table 8.6), although the energy intensity[55] was much lower than before the use of biogas. Similarly, about 46% and 56% of households in Chitwan, and 25% and 34% of households in Lamjung used LPG and electricity, respectively, to supplement for the biogas deficit. The proportion of households using crop residues was much lower at 3% of households in Chitwan and 6% in Lamjung. Only one surveyed household in Lamjung used kerosene for cooking. The energy efficiency improvement of cooking devices and the current trend of energy consumption pattern were assumed to remain the same in this case.

The average final energy intensity per non-biogas household in Chitwan/Terai (Table 8.6) was:

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[55] Energy intensity in LEAP is the energy consumption at a specific branch per unit of activity level (i.e., household) per year (SEI, 2013).

- 3.75 tonnes fuelwood,
- 7.7 kg LPG,
- 31 kWh electricity, and
- 2.1 kg crop residues

The average final energy intensity per non-biogas household in Lamjung/Hill was:

- 4.3 tonnes fuelwood,
- 2.8 kg LPG,
- 0.6 litre kerosene,
- 30 kWh electricity, and
- 9.5 kg crop residues.

8.4.2 Reference scenario

The *reference scenario* is also called the *business-as-usual (BaU)* scenario. It is based on the current energy use pattern and the current government plans and policies. It is an extension of the present practices (*current accounts*) and trends of the energy consumption and the starting point for analysis of the impact of alternative scenarios with different policy options. It attempts to depict the likely effects of present trends and practices of fuel consumption and emissions under a number of specific assumptions, incorporating growth projections and historical trends (H. Jacobsen & Blarke, 2005). The *reference scenario* in this study is guided by the findings in the surveyed households. The key assumptions for the reference scenario are as below:

- The households with access to biogas increases from 26.3% and 57.4% in 2012 to 50% and 70% of the total potential households in Chitwan and Lamjung by 2040, respectively (Table 8.7). This predicted increase is based on the average biogas penetration rate of the districts.
- At regional level, the households with biogas plants are predicted to increase to 50% of the total potential biogas households in the Terai and Hill by 2040, based on the existing penetration rate in the regions and annual biogas installation target of 26,000 plants set by the Alternative Energy Promotion Centre/Government of Nepal (AEPC, 2013a).
- Biogas is not enough to fulfill the cooking energy needs all year round. Households continue using fuelwood, kerosene, electricity, LPG and crop residue to fill the biogas deficit. Because of the growing consumption of LPG and electricity to supplement biogas, use of fuelwood was assumed to reduce to 60% of the households in Chitwan/Terai, and 80% of the households in Lamjung/Hill. Consumption of LPG and electricity is assumed to increase to 70% and 80% of the

households in Chitwan/Terai, and 50% and 60% of the households in Lamjung /Hill, respectively by 2040 (Table 8.6). The higher predicted consumption of LPG in Chitwan/Terai is because of the existing higher consumption rate and easier availability of the fuel than in the hill district. Consumption of kerosene, which was already negligible, and crop residues reduces to zero by 2040.

- The energy consumption per household is assumed to be constant. The annual energy intensity used in the reference scenario is calculated based on the data collected from the 314 surveyed households in two districts (Table 8.8). The Terai region is assumed to have a similar energy intensity to Chitwan, whereas the Hill region has a similar energy intensity to Lamjung.

Table 8.8: Energy intensity per year per household in the reference scenario

Energy source	Chitwan/Terai by digester size				Lamjung/Hill by digester size			
	4 m^3	6 m^3	8 m^3	10 m^3	4 m^3	6 m^3	8 m^3	10 m^3
Biogas (m^3)	265	304	304	339	208	249	250	318
Fuelwood (kg)	760	730	910	1035	1810	1900	1920	1920
Kerosene (litre)	0	0	0	0	0	0.1	0.1	0
LPG (kg)	33	21	18	18	6	10	20	14
Electricity (kWh)	83	59	30	11	30	31	46	28
Crop residues (kg)	0	0.4	3.4	0	0.9	3.9	1.1	0

Source: Field Survey, 2012

- In non-biogas households, consumption of fuelwood is projected to reduce to 90% of households, while use of LPG and electricity is expected to increase to 25% and 50% of households, respectively, in 2040. This assumption is based on the increased consumption of LPG and electricity at the national level. Consumption of kerosene and crop residues reduces gradually over time and none of the households use them by 2040.

8.4.3 Improved production efficiency scenario

In this scenario, the implications of co-digestion option to improve the production efficiency of biogas system are considered. Chapter 6 revealed that co-digestion of animal dung with crop residue improves the efficiency of biogas plants, resulting in at least 50% increase in biogas production. This scenario assumes that increased biogas production would meet most of the energy demand for cooking, except about 350 MJ/yr in Chitwan and 700 MJ/yr in Lamjung, particularly in winter (Section 7.5), and the deficit is fulfilled by electricity in the households that have electricity access and by fuelwood in the households without electricity. But use of electricity extends to 100% of households by 2030, since all rural areas will have electricity access by 2030 (IEA, 2011; Malla, 2013).

It is assumed that none of the biogas households use LPG and kerosene due to its higher and ever-increasing price. Crop residues could be used as feedstock for biogas production instead, and according to the respondents, use of crop residues as feedstock is manageable and should not have any negative effect on livestock number and land use practices (Section 5.3.7). Besides this, the households could start utilising the wasted/burnt residues. The household energy consumption pattern for this scenario is presented in Table 8.9. Biogas fulfills all the energy needs of the households with 10 m^3 plants in Chitwan/Terai. It is further assumed that there will be no change in the biogas policy and the current priority of biogas plant installation. As a result of increased biogas production through co-digestion, the biogas penetration rate increases, extending biogas plant to 50% and 70% of the total potential biogas households in Chitwan and Lamjung, respectively, by 2040 (Table 8.7). At the regional level, the percentage of households using biogas increases to 50% in the Terai and Hill by 2040.

Table 8.9: Energy intensity per household in the improved production efficiency scenario (after 2018) by digester size

Energy source	Chitwan/Terai				Lamjung/Hill			
	4 m^3	6 m^3	8 m^3	10 m^3	4 m^3	6 m^3	8 m^3	10 m^3
Biogas (m^3/year)	398	455	455	508	311	374	375	476
Electricity (kWh/year)	367	96	61	-	301	282	266	14

8.4.4 Increased subsidy scenario

The rate of biogas technology replication in Nepal has been very responsive to the government subsidy (Bajgain & Shakya, 2005; FAO/CMS, 1996; MSTE, 2013b). Hence, this *increased subsidy* scenario assumes that initial plant installation cost is the major factor for lower access of potential households, particularly for the poor. This is because the average annual per capita income of a poor household is merely about

US$245 (CBS, 2011a), and the current subsidy is not sufficient to encourage poor households to install biogas plants, as also suggested by Pant (2012). The average cost of a biogas plant installation is above US$ 500 for a 6 m^3 plant (BSP-Nepal, 2012a) (Section 7.3.1). The current subsidy covers only about 60% and 50% of the cash required for the installation in the Hill and the Terai districts, respectively (MSTE, 2013b) (Section 3.7.4). The current subsidy policy does not provide subsidy for a 10 m^3 plant and hence households would not be interested in constructing bigger plants any more. This scenario assumes that if the subsidy is increased to cover at least 75% of the cash cost of biogas plant installation, 80% of potential households in Chitwan and 90% in Lamjung install biogas plants by 2040 (Table 8.7). The biogas installation rate would almost be double that of the reference scenario and 80% of the potential households in the Terai and Hill would be expected to install biogas plants by 2040. However, the household energy consumption pattern and final energy intensity is assumed to remain the same as in the reference scenario (Table 8.8).

8.4.5 Integrated scenario

The *integrated scenario* considers the combined implications of the technology option (co-digestion) to increase biogas production and the increased subsidy policy to increase potential households' access to biogas technology. In this scenario, the assumptions of the production efficiency scenario and subsidy scenario are combined to analyse the impact of biogas on reducing consumption of traditional fuels and GHG emissions. As stated in the production efficiency scenario, increased production of biogas to meet the energy demand for cooking will motivate households to install biogas plants and increased subsidy will support poor households to own biogas plants, resulting in biogas plant installation in 100% of the potential households in both districts and regions by 2040 (Table 8.7). The household energy consumption pattern and final energy intensity is assumed to be the same as in the improved production efficiency scenario (Table 8.9). The subsequent sections present the results of the energy consumption and GHG emissions analysis in LEAP.

8.5 Results

8.5.1 Impact of biogas on energy consumption

Energy consumption after the installation of biogas plants

The energy consumption after the installation of biogas is mainly driven by the activity level and impacts of various scenarios. In the reference scenario, the total final energy consumption in the potential biogas households for cooking from all fuels is projected to decrease by 506 TJ from 2012-2040 in Chitwan with an average annual reduction of 0.8%, and 72 TJ in Lamjung with an average annual reduction of 0.4% in the same period (Table 8.10). The reduction in total energy consumption is due to the reduction in inefficient fuelwood consumption replaced by biogas.

Table 8.10: Final energy consumption projection of potential biogas households in Chitwan and Lamjung under different scenarios for selected years (TJ)

Fuels	2012	Reference		Improved efficiency		Subsidy		Integrated	
		2020	2040	2020	2040	2020	2040	2020	2040
Chitwan									
Electricity	2.7	3.8	6.5	6.5	17.0	4.0	8.4	7.3	26
LPG	8.4	12.1	24.5	2.2	2.3	13.2	35.9	2.0	-
Fuelwood	2485	2310	1840	2096	1295	2207	1004	1930	-
Biogas	106	137	225	213	401	154	359	246	668
Crop residue	0.05	0.03	-	0.03	-	0.04	-	0.03	-
Total	2602	2463	2096	2318	1715	2378	1407	2184	694
Lamjung									
Electricity	0.3	0.5	1.0	4.1	9.9	0.5	1.1	4.6	15
LPG	1.0	1.4	2.6	0.01	0.02	1.4	3.3	0.03	-
Fuelwood	642	618	550	427	271	603	431	337	-
Biogas	47	52	64	79	109	54	82	82	137
Crop residue	0.12	0.08	-	0.06	-	0.08	-	0.06	-
Total	690	672	618	510	390	659	518	424	152

Total fuelwood energy consumption is estimated to decrease by 645 TJ with an average annual reduction rate of 1.1% in Chitwan and by 92 TJ with an average annual reduction rate of 0.6% in Lamjung in the reference scenario from 2012-2040. The total consumption of biogas is predicted to increase by 2.7% per annum from 106 TJ in 2012 to 225 TJ in 2040 in Chitwan and 1.1% per annum from 47 TJ to 64 TJ in Lamjung in the same period (Table 8.10). Consumption of electricity and LPG are predicted to increase annually by about 3.2% and 3.9% in Chitwan and 4.3% and 3.7% in Lamjung respectively in the same period. The lower total energy consumption in

Lamjung is due to the lower number of potential biogas households in the district compared with Chitwan.

In the improved production efficiency scenario, the total final energy consumption is predicted to decrease by 1.5%/year in Chitwan and 2%/year in Lamjung from 2012-2040, which is about 44% and 37% less than the total energy in Chitwan and Lamjung in the reference scenario in 2040, respectively. Total energy consumption from biogas and electricity is projected to increase by 4.9% and 6.8% per year in Chitwan and 3.1% and 12.9% per year in Lamjung, while energy consumption from fuelwood and LPG is expected to decrease by 2.3% and 4.6% per year in Chitwan and 3.1% and 12.4% per year in Lamjung (Table 8.10). The total energy consumption in this scenario is lower than the reference scenario due to the higher consumption of efficient fuels such as biogas and electricity.

In the increased subsidy scenario, the total energy consumption is expected to reduce by 1,195 TJ in Chitwan and 172 TJ in Lamjung from 2012-2040 (Table 8.10). With increase in biogas households to 80% of the potential households in Chitwan and 90% in Lamjung by 2040 (Table 8.7), consumption of biogas is predicted to increase by 4.4%/year in Chitwan and 2.0%/year in Lamjung from 2012-2040, while fuelwood is expected to decrease by 3.2%/year in Chitwan and 1.4%/year in Lamjung in the same period (Table 8.10). Electricity and LPG consumption is predicted to increase by above 4.4%/year in Chitwan and 4.6%/year in Lamjung.

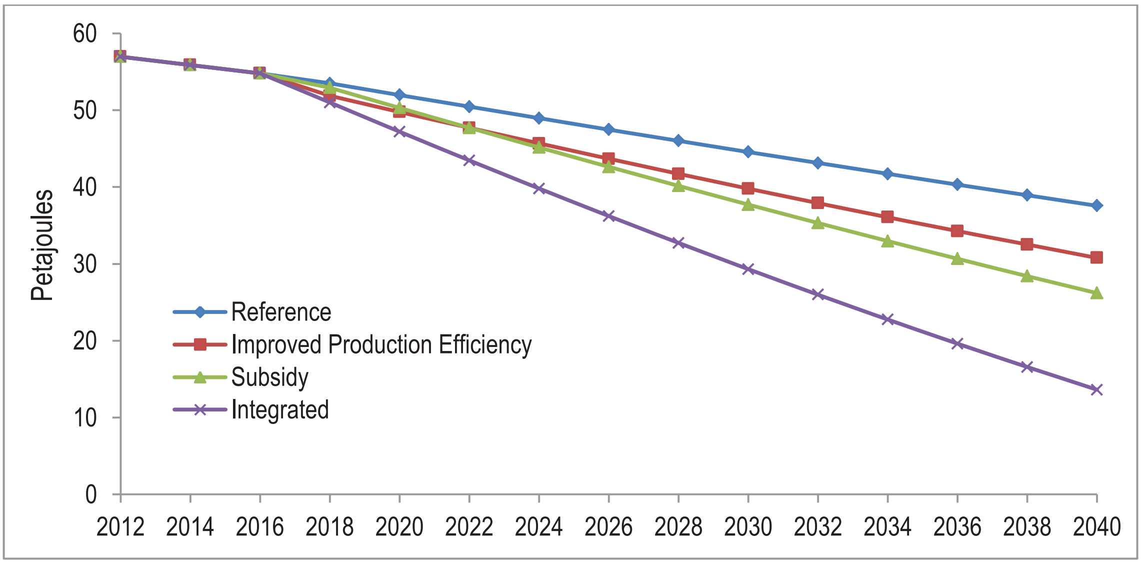
In the integrated scenario, the total energy consumption from all fuels is predicted to decrease by 4.6%/year from 2,602 TJ in 2012 to 694 TJ in 2040 in Chitwan and 5.2%/year from 690 TJ to 152 TJ in Lamjung in the same period (Table 8.10). Consumption of biogas increases by 562 TJ in Chitwan and 90 TJ in Lamjung from 2012-2040, whereas consumption of fuelwood decreases by 2,485 TJ in Chitwan and 642 TJ in Lamjung in the same period. The total predicted energy consumption in this scenario in 2040 is over 60% less than in the reference scenario, and over 50% less than in the subsidy scenario. This implies that biogas technology has the potential to significantly reduce consumption of inefficient, unhealthy, expensive and environmental unfriendly fuels.

In terms of size of the biogas plants, there is significant reduction in total energy consumption in all the scenarios across all size plants in both districts. The final energy consumption from 6 m^3 plants is the highest for all scenarios in both the districts (Table 8.11), mainly due to the higher potential of that sized plant. It is assumed that households do not install 10 m^3 size plants after 2018 due to the lack of subsidy (BSP-Nepal, 2012b), higher cost of energy (Section 7.4) and larger feedstock deficit to feed bigger digesters (Section 5.3.6). The total energy consumption from 10 m^3 plants as shown in Table 8.11 is from the existing biogas plants.

Table 8.11: Final energy demand projection of biogas households in Chitwan and Lamjung under different scenarios for selected years by plant size (TJ)

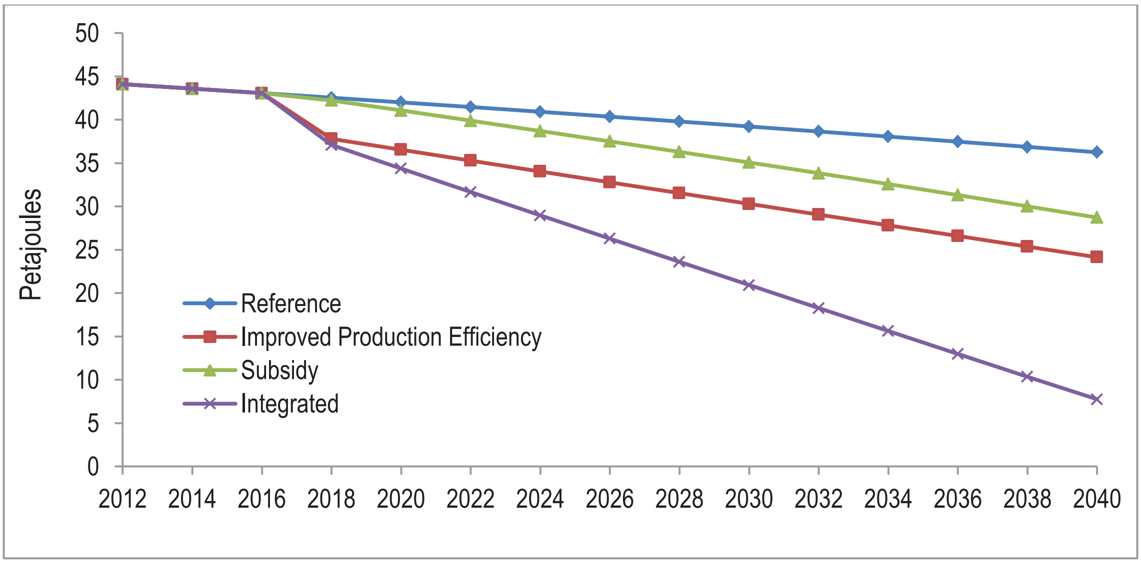
Plant size	2012	Reference		Improved efficiency		Increased Subsidy		Integrated	
		2020	2040	2020	2040	2020	2040	2020	2040
Chitwan									
4 m^3	181	179	166	170	146	173	115	160	74
6 m^3	1841	1742	1480	1646	1219	1680	986	1551	495
8 m^3	420	399	341	371	274	385	234	349	110
10 m^3	160	144	109	132	76	139	72	124	15
Lamjung									
4 m^3	216	210	193	161	124	206	159	133	45
6 m^3	383	373	343	184	218	366	290	236	88
8 m^3	77	75	69	56	42	74	56	47	17
10 m^3	14	13	12	9	5	13	10	8	2

As in the case of the surveyed districts, the most striking feature in the final energy demand prediction for the Terai (Figure 8.6) and the Hill regions (Figure 8.7) is the significant decrease in demand in the improved biogas production efficiency and integrated scenarios as a result of increased availability of biogas after co-digestion of crop residues with dung. The total energy consumption is predicted to decrease by about 19.3 PJ (1.5%/year) in the Terai and 7.8 PJ (0.7%/year) in the Hill in the reference scenario, and by about 43.4 PJ (5%/year) in the Terai and 36.3 PJ (6.02%/year) in the Hill in the integrated scenario from 2012-2040. The lower reduction rate in the Hill is because of the higher fuelwood consumption and lower biogas production. The predicted average energy consumption in the improved efficiency and increased subsidy scenarios are higher than the reference scenario but lower than the integrated scenario in both regions (Figure 8.6 and 8.7). Total energy consumption in the improved production efficiency scenario in the Terai is higher than the subsidy scenario (Figure 8.6) because of higher number of potential households installing biogas plants in the later scenario. Although a higher number of potential households is projected to install biogas plants in the subsidy scenario in the Hill, the total energy consumption would still be higher because of the higher energy intensity of fuelwood (Figure 8.7).



Note: Drop in the energy demand trend represents the year of technical/policy option implementation.

Figure 8.6: Final energy demand projection of potential biogas households from all fuels in the Terai region for the four scenarios



Note: Drop in the energy demand trend represents the year of technical/policy option implementation.

Figure 8.7: Final energy demand projection of potential biogas households from all fuels in the Hill region for the four scenarios

Total energy consumption without biogas plants

The energy use pattern (fuel type and quantity) before the installation of biogas plants reported by the respondent households during the household surveys was used to predict the final energy consumption without biogas plants. Assuming that the energy use pattern before the installation of biogas continues, the final energy consumption of the potential biogas households without biogas plants is predicted to increase by 420 TJ in Chitwan and 348 TJ in Lamjung from 2012-2040, with an average annual growth of 0.4% in both districts (Table 8.12). Fuelwood is the major source of energy supplying above 99% of the energy demand, followed by LPG and electricity, but their share is almost negligible. The Terai and Hill follow the similar trend of energy consumption and increase in total energy consumption is projected at 7,385 TJ in the Terai and 5,732 TJ in Hill from 2012-2040 (Table 8.12).

Table 8.12: Total energy consumption projection in all potential biogas households without biogas by fuel-type (TJ)

Fuels	Chitwan		Lamjung		Terai		Hill	
	2012	2040	2012	2040	2012	2040	2012	2040
Electricity	1.5	1.6	0.39	0.44	30.2	33.8	19.9	22.2
Kerosene	0.03	0.04	0.12	0.13	0.6	0.7	5.9	6.6
LPG	2.6	3.2	0.10	0.11	48	82	5.2	5.8
Fuelwood	3,132	3,550	957	1,070	62,235	69,581	48,421	54,147
Crop residue	0.05	0.06	0.23	0.25	1.11	1.24	11.5	12.9
Total	3,136	3,556	958	1,306	62,314	69,699	48,463	54,195

Saving of energy after the use of biogas

Comparison of total predicted energy consumption of potential biogas households in the studied districts and both regions with and without biogas plants shows a large reduction in total energy consumption after the installation of biogas plants across all scenarios (Figure 8.8). The reduction in total energy consumption is about 40% in the reference scenario and slightly above 80% in the integrated scenario compared with the without biogas case. Total energy consumption per household per year without biogas in 2040 is predicted at 57.4 GJ in Chitwan/Terai and 66.5 GJ in Lamjung/Hill, which is projected to reduce to 11.2 GJ in Chitwan/Terai and 9.5 GJ in Lamjung/Hill in the integrated scenario, saving 46.2 GJ/year in Chitwan/Terai and 57.1 GJ/year in

Lamjung/Hill. This saving is mainly due to the reduction in burning of inefficient fuelwood and use of efficient cooking fuel such as biogas and electricity, which illustrates the impact of biogas technology in reducing energy demand of user households.

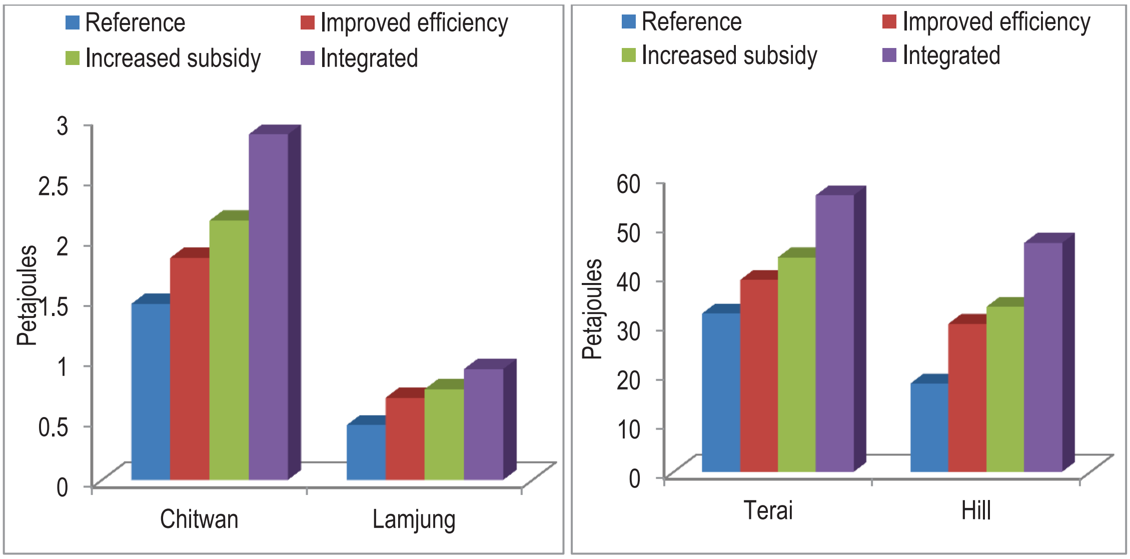


Figure 8.8: Saving on total energy consumption (GJ) projection after the installation of biogas plants compared with no biogas household for the four scenarios in studied districts and two regions in 2040

8.5.2 Impact of biogas plants on GHG emissions reduction

Biogas replacing burning of emission-intensive fuels

Biogas is a lower carbon fuel and it can reduce GHG emissions from the domestic sector by replacing burning of emissions-intensive fuels with efficient fuels/stoves. Replacement of traditional biomass and petroleum fuels has a significant impact on environmental emissions reduction. If the current trend of fuelwood consumption continues, the total GHG emissions in the reference scenario is predicted to decrease by 0.72%/year from about 22,500 tCO$_2$e in 2012 to 18,300 tCO$_2$e in 2040 in Chitwan, and by 0.42%/year from 5,800 tCO$_2$e in 2012 to 5,100 tCO$_2$e in Lamjung (Table 8.13). The emissions are predicted to reduce further in the integrated scenario to about 2,000 tCO$_2$e (8.3%/year) in Chitwan and 400 tCO$_2$e (9%/year) in Lamjung in the same period. The total emissions from burning of fuelwood is projected to decrease by about 21,600 tCO$_2$e in Chitwan and about 5,600 tCO$_2$e in Lamjung in the integrated scenario from 2012-2040. The total emission from biogas is predicted to increase by about 1,700

tCO_2e (2.7%/year) in Chitwan and 270 tCO_2e (1.1%/year) in Lamjung in the same period when all potential households have access to biogas. The predicted emissions from fuelwood in the integrated scenario is virtually zero in 2040 in both districts and regions, as none of the biogas households are expected to use fuelwood for cooking (Table 8.13).

Table 8.13: GHG emissions projection of potential biogas households in Chitwan and Lamjung by fuel-type under different scenarios for selected years (tCO_2e)

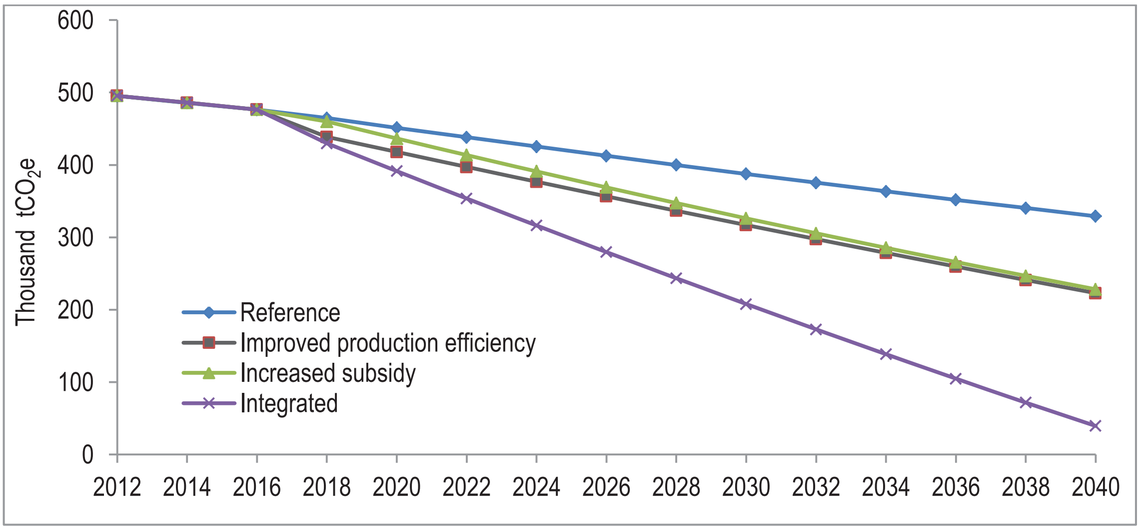
Fuels	2012	Reference		Improved efficiency		Increased subsidy		Integrated	
		2020	2040	2020	2040	2020	2040	2020	2040
Chitwan									
LPG	575	831	1670	146	154	899	2454	135	0
Fuelwood	21,598	20,084	16,005	18,220	11,250	18,186	8,723	16,772	0
Biogas	319	399	677	643	1210	463	1082	740	2,013
Crop residue	0.4	0.3	0	0.2	0	0.4	0	0.2	0
Total	22,492	21,314	18,352	19,010	12,614	20,548	12,259	17,648	2,013
Lamjung									
LPG	65	92	179	1.8	1.5	96	228	1.0	0
Fuelwood	5,578	5,369	4,777	3,708	2,349	5,244	3,750	2,930	0
Biogas	141	155	193	237	329	162	248	247	412
Crop residue	1	0.7	0	0.5	0	0.7	0	0.5	0
Total	5,785	5,617	5,149	3,948	2,680	5,502	4,226	3,179	412

In terms of plant size, the GHG emissions from 6 m^3 plants is projected to be the highest (Table 8.14) because the majority of the households (71% in Chitwan and 55% in Lamjung based on the existing proportions of plant size) are expected to install 6 m^3 plants. Although both districts follow similar trends of GHG emissions reduction in 2040, Chitwan has higher emissions due to a higher number of potential biogas households than in Lamjung.

Table 8.14: GHG emissions projection of potential biogas households in Chitwan and Lamjung under different scenarios for selected years by plant size (tCO_2e)

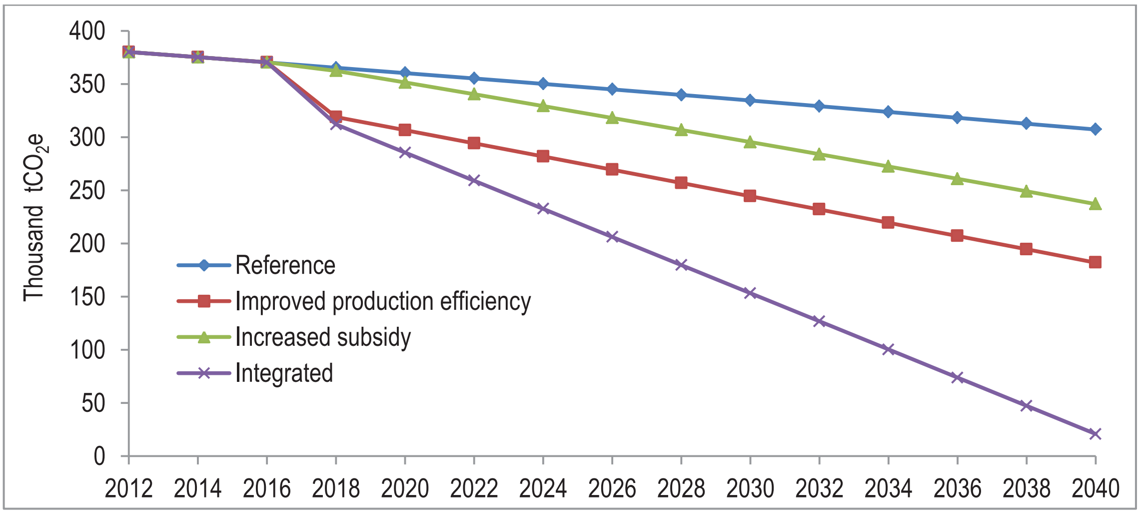
Plant size	2012	Reference		Improved efficiency		Subsidy		Integrated	
		2020	2040	2020	2040	2020	2040	2020	2040
Chitwan									
4 m^3	1594	1585	1525	1386	1025	1530	1125	1287	196
6 m^3	15910	15070	12929	13499	8966	14508	8540	12532	1446
8 m^3	3624	3439	2958	3042	2020	3318	1995	2824	326
10 m^3	1348	1219	941	1083	604	1192	599	1004	45
Lamjung									
4 m^3	1815	1761	1603	1265	861	1722	1290	1205	118
6 m^3	3205	3113	2855	2188	1494	3050	2353	2088	239
8 m^3	651	636	595	430	290	624	502	410	48
10 m^3	118	111	96	66	36	109	81	62	7

The impact of biogas on reducing GHG emission is also obvious in two regions, which follow a similar trend to the two studied districts (Figure 8.9 and 8.10). The total GHG emissions are predicted to decrease by about 165,000 tCO_2e (1.4%/year) in the Terai and 73,000 tCO_2e (0.8%/year) in the Hill from 2012-2040 in the reference scenario, by about 455,000 tCO_2e (8.6%/year) in the Terai and 359,000 tCO_2e (9.8%/year) in the Hill in the integrated scenario in the same period. The predicted emissions in the improved efficiency and increased subsidy scenarios are lower than the reference scenario but higher than the integrated scenario in both regions. The average annual rate of decrease in GHG emissions in the Terai (1.4%) is higher than in the Hill (0.8%) in the reference and increased subsidy scenario because of the higher fuelwood consumption in the Hill even after the use of biogas. The higher fuelwood consumption in the Hill is projected to be replaced completely by biogas in the improved efficiency/integrated scenarios, and hence the higher average annual rate of emissions in the Hill (9.8%) than in the Terai (8.6%).



Note: Drop in the energy demand trend represents the year of technical/policy option implementation.

Figure 8.9: GHG emissions projection from all fuels in Terai region for four scenarios



Note: Drop in the energy demand trend represents the year of technical/policy option implementation.

Figure 8.10: GHG emissions projection from all fuels in Hill region for the four scenarios

Reduction in GHG emissions relative to no biogas

Assuming that if no biogas plants were installed, and the energy consumption pattern of before the installation of biogas plants continues, the GHG emissions are predicted to be about 30,900 tCO_2e in Chitwan and 9,300 tCO_2e in Lamjung in 2040, and 610,000 tCO_2e in the Terai and 472,000 tCO_2e in the Hill (Table 8.15). The average annual growth of GHG emissions from 2012-2040 is predicted at 0.4% for both districts and regions.

Table 8.15: GHG emission projection from burning of emission-intensive fuels in all the potential biogas households without biogas by fuel-type (tCO_2e)

Fuels	Chitwan		Lamjung		Terai		Hill	
	2012	2040	2012	2040	2012	2040	2012	2040
Kerosene	2.3	2.6	8.5	9.5	50	50	430	440
LPG	180	220	6.9	7.8	3,200	5,600	350	400
Fuelwood	27,560	30,640	8,320	9,300	541,000	605,000	421,000	471,000
Crop residue	0.5	0.6	2	2.2	10	10	100	110
Total	27,750	30,860	8,330	9,320	544,000	610,000	422,000	472,000

Comparing the GHG emissions without biogas with the scenarios demonstrates the contribution of biogas systems in reducing the emissions (Figure 8.11). Total reduction in emissions from reducing the burning of emission-intensive fuels compared to no biogas case is projected at 12,700 and 4,200 tCO_2e in the reference scenario, and 29,000 and 8,900 tCO_2e in the integrated scenario in Chitwan and Lamjung respectively in 2040 (Figure 8.11). Similarly, reduction in the emissions in the Terai and Hill compared with non-biogas households is predicted at about 281,000 and 164,000 tCO_2e in the reference scenario, and 571,000 and 451,000 tCO_2e in the integrated scenario in 2040, respectively (Figure 8.11). The reduction in the emissions in the improved efficiency scenario is higher than the increased subsidy scenario in both districts and regions because of a higher availability of biogas that replaced more fuelwood. The impact of biogas on reducing non-energy related emissions are discussed in the following section.

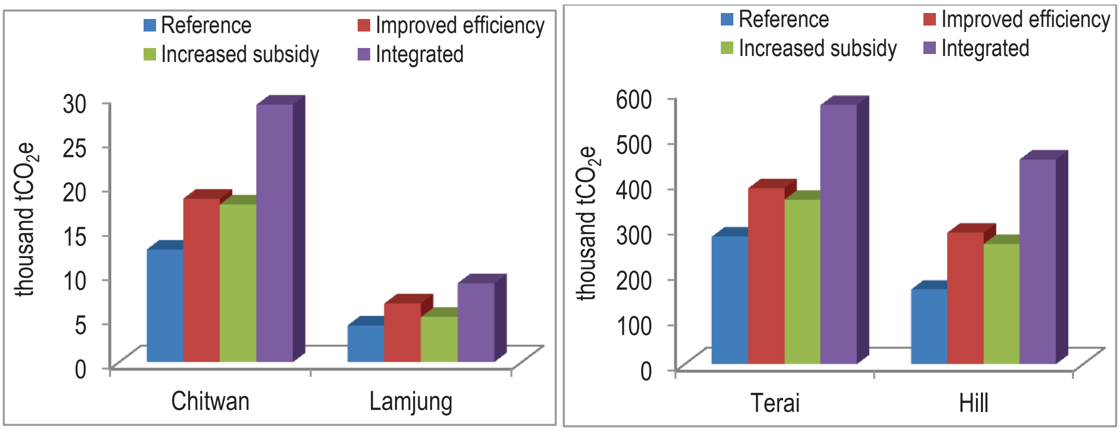


Figure 8.11: Reduction in predicted GHG emissions in the four scenarios compared with *non-biogas* case in studied districts and two regions in 2040

Reducing non-energy emissions

A domestic biogas plant not only mitigates GHG emissions by reducing burning of emission-intensive fuels but also contributes significantly to reducing non-energy related emissions. Biogas has a potential of reducing environmental emissions from: (a) reducing deforestation for fuelwood (b) avoiding decomposition of farm yard manure, and (c) use of digested slurry replacing fertilisers. Biogas however contributes to GHG emissions due to methane leakage from biogas plants.

Reducing deforestation for fuelwood

The initial national communication to the conference of the parties of the UNFCCC of Nepal (2004) estimated the average net carbon released into the atmosphere due to deforestation at 40.2 tonnes C/ha or 147.4 tonnes CO_2/ha[56], which was used to predict the GHG emissions from forest cleared for fuelwood in this study. The forest area saved by per tonne of fuelwood saving was taken as 0.030 ha (Winrock & Eco Securities, 2004). If the current trend of energy use and fuelwood consumption continues, the total GHG emissions from forest cleared for fuelwood in the reference scenario is projected to decrease by 108,000 tCO_2e (0.6%/year) in Chitwan and 19,000 tCO_2e (0.4%/year) in Lamjung from 2012-2040 (Table 8.16). Similarly, the total emissions are predicted to decrease by 4.11 million tCO_2e (1%/year) in the Terai and 1.37 million tCO_2e (0.4%/year) in the Hill in the same period.

Table 8.16: GHG emissions projection from forest cleared for fuelwood for selected years in the four scenarios (1,000 tCO_2e)

District/ Region	2012	Reference		Improved efficiency		Increased subsidy		Integrated		No biogas		
		2020	2040	2020	2040	2020	2040	2020	2040	2012	2020	2040
Chitwan	725	701	617	625	410	671	371	576	0	917	947	1026
Lamjung	182	180	163	106	61	178	146	99	0	273	282	305
Terai	16,203	15,372	12,091	14,319	8,043	14,793	7,281	13,350	0	17,981	18,564	20,107
Hill	12,328	12,114	10,957	10,380	6,179	11,789	8,263	9,636	0	13,814	14,262	15,448

The annual rate of emission reduction from 2012-2040 in Chitwan, Lamjung, the Terai and the Hill is projected at 2%, 3.8%, 2.5% and 2.4% in the improved efficiency scenario and 2.4%, 0.8%, 2.8% and 1.4% in the increased subsidy scenario,

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[56] 1 tonne C = 44/12 tonne CO_2 (MoPE, 2004).

respectively. Since all potential biogas households are assumed to have installed biogas plants, and biogas households are assumed to use only biogas and electricity by 2040, virtually no CO_2 emissions from forest cleared for fuelwood is projected in the integrated scenario in 2040 in both districts and regions (Table 8.16).

Comparing the CO_2 emissions from forest cleared for fuelwood with the case of no biogas shows a huge impact of biogas on reducing deforestation related emissions across all four scenarios (Table 8.16). The reduction in CO_2 emissions per biogas plant is equivalent to 13.2 tCO_2e in Chitwan/Terai and 12.7 tCO_2e in Lamjung/Hill in the reference scenario, which is projected to increase to 16.6 tCO_2e in Chitwan/Terai and 18.9 tCO_2e in Lamjung/Hill in the integrated scenario in 2040.

Reducing decomposition of farm yard manure

Farm yard manure composted aerobically is considered as one important factor for environmental emissions from the agriculture sector (B. Amon, Amon, Boxberger, & Pöllinger, 1998). By using dung as feedstock to produce biogas through anaerobic digestion, which otherwise would be stored in uncovered pits to make compost, the biogas plant prevents the release of methane and nitrous oxide (N_2O) into the environment. Methane and N_2O are potent GHGs, the contribution of which to the GHG effect is 25 and 298 times of CO_2 over a 100-year period (Forster et al., 2007) respectively. So, it was attempted to analyse the emissions from the animal dung that were aerobically composted as compost heaps and the impact of biogas plants in reducing the emissions from the decomposition of dung.

Amon et al. (1998) revealed that methane and N_2O emissions from composted dung are 151.1 gram/tonne and 49.8 gram/tonne, respectively, which was used to calculate the emissions in the present study. The average dung produced per household was 32.2kg/day or 11.75 tonnes/year in Chitwan and 31.7 kg/day or 11.57 tonnes/year in Lamjung (Section 5.3.6). If dung were not utilised to produce biogas, the annual methane and N_2O emissions per household from composting of this dung would be about 1.8 kg and 0.6 kg in Chitwan and Lamjung, respectively. After the installation of biogas plants, an average of 29.6 kg dung per household in Chitwan and 23.6 kg dung per household in Lamjung was fed into the biogas digesters. So the existing quantity of dung per household not fed into the digesters was 0.95 tonnes/year in Chitwan and 2.9 tonnes/year in Lamjung, decomposition of which produces 0.14 kg methane and 0.047 kg N_2O per household in Chitwan and 0.45 kg methane and 0.14 kg N_2O per household in Lamjung. The quantity of unfed dung per household in the Terai is assumed to be the same as in Chitwan, and in the Hill is assumed to be the same as in Lamjung.

Assuming that the current biogas feeding practice continues and there is no change in the quantity of dung produced or fed into the digesters, the emissions from decomposition of unfed dung in the reference scenario is predicted to decrease with an annual average rate of 0.8% in Chitwan and 0.3% in Lamjung from 2012-2040 (Table 8.17). The lower rate of reduction in Lamjung is due to the higher quantity of unfed dung decomposed aerobically to make compost compared with Chitwan (see Section 5.3.6).

Table 8.17: GHG emissions projection from decomposition of dung for selected years in the four scenarios (1,000 tCO_2e)

District/ Region	2012	Reference		Improved efficiency		Increased subsidy		Integrated		No biogas		
		2020	2040	2020	2040	2020	2040	2020	2040	2012	2020	2040
Chitwan	9.38	8.89	7.46	8.39	5.54	8.43	3.64	7.73	0	12.38	12.78	13.84
Lamjung	1.81	1.77	1.67	1.25	0.72	1.71	1.12	1.17	0	3.21	3.32	3.59
Terai	215	197	146	190	111	188	71	176	0	243	250	271
Hill	140	133	112	119	73	128	70	111	0	163	168	182

The annual average rate of the GHG emissions reduction from decomposition of unfed dung in the improved production efficiency from 2012-2040 are much higher than in the reference scenario at 1.9% in Chitwan/Terai and 3.2% in Lamjung/Hill (Table 8.17), because this scenario assumes that all available dung is co-digested with crop residues to produce biogas. Virtually no emission is projected in the integrated scenario in 2040 in both districts and regions, because all potential households are assumed to install biogas plants and use all available dung to produce biogas. This implies that co-digestion of crop residues with dung not only reduces the emissions from reducing burning of biomass fuels and associated deforestation, but also mitigates the GHG emissions from decomposition of dung in compost heaps.

Digested slurry replacing chemical fertilisers

Biogas slurry when applied as manure to substitute chemical fertiliser reduces CO_2 and nitrous oxide emissions emitted from the production of fertiliser. The CO_2 emission for N, P and K fertiliser production is 1.3, 0.2 and 0.2 kg/kg fertiliser, respectively (Lal, 2004; Pathak, Jain, Bhatia, Mohanty, & Gupta, 2013). Emission reduction of nitrous oxide due to saving on N fertiliser replaced by biogas slurry is 0.07 kg/kg fertiliser (Malla et al., 2005). Annual consumption of chemical fertiliser per household in Nepal was 24.4 kg N, 6.6 kg P and 3.7 kg K, respectively, in 2010 (B. Ghimire, 2013).

Table 8.18: Projection of reduction in GHG emissions from digested slurry replacing chemical fertilisers in four different scenarios

District/ Region	2012	Reference		Improved efficiency		Increased subsidy		Integrated	
		2020	2040	2020	2040	2020	2040	2020	2040
Chitwan	7.9	9.8	13.4	10.2	16.8	11.5	26.9	12.3	33.6
Lamjung	4.5	4.9	6.1	5.0	7.0	5.1	7.8	5.2	8.7
Terai	73	123	263	131	329	155	527	171	658
Hill	73	100	176	105	220	121	353	132	441

Assuming that biogas slurry fully replaces the use of chemical fertilisers, reduction in the GHG emissions is projected at 5,500 tCO_2e (1.9%/year) in Chitwan and 1,600 tCO_2e (1.1%/year) in Lamjung from 2012-2040 in the reference scenario (Table 8.18). The reduction in the emissions in other scenarios is higher than in the reference scenario, the rate of reduction in the integrated scenario being 5.3%/year (25,700 tCO_2e) in Chitwan and 2.4%/year (4,200 tCO_2e) in Lamjung. Similarly, a total of approximately 1 million tCO_2e is predicted to reduce in the integrated scenario in 2040 in the Terai and the Hill combined, which is equivalent to about 540 kg CO_2e/year/plant (Table 8.17). This implies that biogas slurry is not only suitable for increased agricultural productivity, but also has a great potential in reducing the emissions.

Methane leakage from biogas plants

Installation of a biogas plant however could increase environmental emissions from methane leakage from the plant. Average methane leakage from a biogas plant in Nepal is estimated at 40.63 kg/year (G. Devkota, 2003). Assuming the leakage remains the same for both districts and regions, the GHG emissions due to the leakage is estimated to increase by about 10,300 tCO_2e in Chitwan and by 3,000 tCO_2e in Lamjung in the reference scenario from 2012-2040 (Table 8.19). Similarly, the emissions are projected to increase by 356,000 tCO_2e in the Terai and 194,000 tCO_2e in the Hill in the reference scenario from 2012-2040.

Table 8.19: GHG emissions projection from methane leakage in Chitwan and Lamjung in four different scenarios (1,000 tCO_2e)

District/ Region	2012	Reference		Improved efficiency		Increased subsidy		Integrated	
		2020	2040	2020	2040	2020	2040	2020	2040
Chitwan	14.8	18.4	25.1	19.2	31.4	21.4	50.3	23.0	62.8
Lamjung	8.4	9.2	11.4	9.4	13.0	9.6	14.7	9.8	16.3
Terai	137	230	493	245	616	290	985	319	1232
Hill	136	187	330	197	413	227	660	247	825

The GHG emissions from methane leakage in other scenarios is higher than the reference scenario due to the projection of increased numbers of biogas system installations. The total emissions are projected to increase by about 48,000 tCO_2e in Chitwan and 7,900 tCO_2e in Lamjung in the integrated scenario from 2012-2040, which are more than double than in the reference scenario (Table 8.19). Increase in the total emissions in the Terai and Hill combined in the integrated scenario is estimated at about 1.78 million tCO_2e in the same period. Thus a biogas plant could increase the environmental emissions equivalent to about 1.02tCO_2e/year in the integrated scenario in both districts/regions. Moreover, such leakage not only reduces gas availability but also contributes to global warming. Biogas construction companies need to address such technical issues in order to promote biogas plants as an efficient alternative for providing energy security and reducing environmental emissions.

8.5.3 Potential of GHG mitigation and carbon credit earning

The GHG mitigation potential (GMP) of domestic biogas plants in different scenarios was calculated considering five emission reduction sources (Equation 8.5).

$$\begin{aligned}\text{GMP (CO}_2\text{ equivalent)} = &\ \text{reduction in GHG emissions from burning of conventional fuels}\\ &+ \text{reduction in GHG emissions from forest cleared for fuelwood}\\ &+ \text{reduction in GHG emissions from decomposition of unfed dung}\\ &+ \text{reduction in GHG emissions from replacing chemical fertilisers}\\ &- \text{GHG emissions from methane leakage from biogas plants} \qquad \text{(Equation 8.5)}\end{aligned}$$

The GMP of biogas plants from all sources increases significantly with the increase in number of biogas plants. Total GMP in a 100-year time horizon (including both energy and non-energy related emissions) of all the biogas plants installed in the reference scenario is estimated at 410,000 tCO_2e in Chitwan and 143,000 tCO_2e in Lamjung in 2040 (Table 8.20). This is projected to further increase to 1.04 million tCO_2e and 309,000 tCO_2e, respectively, in the integrated scenario when all the potential biogas plants are installed and biogas (and electricity to supplement biogas deficit) replaces all conventional fuels. Similarly, the total GMP is projected at 8.2 million tCO_2e in the Terai and 4.4 million tCO_2e in the Hill in the reference scenario in 2040, which is estimated to increase to about 20.4 million tCO_2e in the Terai and 15.3 million tCO_2e in the Hill.

Table 8.20: Total global warming mitigation potential of biogas plants in different scenarios including energy as well as non-energy emissions (1,000 tCO_2e)

District/ Region	2012	Reference		Improved production		Increased subsidy		Integrated	
		2020	2040	2020	2040	2020	2040	2020	2040
Chitwan	194	248	410	326	621	278	660	377	1039
Lamjung	91	102	143	178	248	104	160	185	309
Terai	1,791	3,249	8,191	4,336	12,324	3,824	12,948	5,310	20,374
Hill	1,414	2,072	4,394	3,862	9,255	2,370	6,870	4,586	15,255

In terms of GMP per biogas plant, the mitigation potential (in 100-year time horizon) is expected to be 13.3 tCO_2e/plant in Chitwan/Terai and 11.1 tCO_2e/plant in Lamjung/Hill in the reference and increased subsidy scenarios, and 16.7 tCO_2e/plant in Chitwan/Terai and 19.3 tCO_2e/plant in the improved production efficiency and integrated scenarios. Considering an assumed price of US$10/$tCO_2e$ and taking both energy and non-energy sector emissions into account, a biogas plant has the potential to earn carbon credit of US$133/year in Chitwan/Terai and US$111/year in Lamjung/Hill in the reference/increased subsidy scenario, and US$167/year in Chitwan/Terai and US$193/year in Lamjung/Hill in the improved production efficiency/integrated scenario. Thus, when all the potential households install biogas plants (integrated scenario), the total theoretical carbon credit earning potential of the domestic biogas sector in Terai and Hill combined is about US$357 million/year, which justifies the notion of increasing the subsidy amount to extend biogas technology to all potential households as assumed in the increased subsidy and integrated scenarios in this study.

The mitigation potential per plant is lower in Lamjung/Hill compared with Chitwan/Terai in the reference and increased subsidy scenario but higher in the improved production and integrated scenarios. In the reference and increased subsidy scenarios, the consumption of emission-intensive fuels, mainly fuelwood, was higher in Lamjung/Hill to fulfill the energy deficit due to low availability of biogas and hence resulted in lower GMP. Increased biogas production after the co-digestion of crop residues with dung, on the other hand, is expected to fulfil most of the domestic energy needs for cooking, replacing all of the fuelwood. Since the quantity of fuelwood consumed per household was higher in Lamjung/Hill, increased biogas production after co-digestion of crop residues with dung results in higher GMP.

8.5.4 Transformation analysis

The transformation analysis refers to the process of conversion of primary energy fuels into final energy, energy transmission and distribution and resource extraction (SEI, 2013). It calculates energy imports, exports and primary resource requirements, and tracks costs and environmental loadings from the energy conversion process (SEI, 2010). In this study, transformation module analyses transformation activities, mainly electricity generation and biogas production through anaerobic digestion that produces energy outputs to meet the demand. Total energy requirement by feedstock fuel and environmental emissions associated with the transformation activities are projected in this module.

Electricity generation

The electricity generation requirement projection in the four scenarios is shown in Table 8.21, which comprises electricity generation from the existing hydropower plants, thermal (diesel) plants and electricity import. Merit order dispatch rule[57] was computed and the process efficiency was taken as100% for hydro, 49% for thermal plants and 75% for import (NEA, 2013; SEI, 2013). The energy loss during transmission was assumed to be 15% for all scenarios (NEA, 2013). The total electricity requirement is projected to increase from about 58 TJ in 2012 to 217 TJ (average annual growth of 4.8%) in the reference scenario in 2040. The total electricity requirement is higher in other scenarios: 313 TJ in the increased subsidy scenario (6.2% growth/year), 1000TJ in the improved production efficiency scenario (10.7% growth/year), and 1620TJ in the integrated scenario (12.6% growth/year) in 2040. The sharp increase in total electricity

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[57] The merit order rule ranks available sources of energy based on increasing order of price and amount of energy generated so that lower cost energy are generated first to meet demand and thus minimises the cost of energy production (SEI, 2010).

requirements in the improved production efficiency and integrated scenario is due to the use of electricity to supplement for energy deficit from available biogas.

Table 8.21: Electricity generation requirement in the four scenarios (TJ)

Source	2012	Reference		Improved efficiency		Increased subsidy		Integrated	
		2020	2040	2020	2040	2020	2040	2020	2040
Existing hydro	45	79	174	195	802	85	251	234	1300
Thermal	5	9	24	22	111	10	35	26	179
Import	8	14	19	34	87	15	27	41	142

Biogas production requirement

Biogas is produced from anaerobic digestion of animal waste (dung) in the reference and increased subsidy scenarios, whereas crop residues are co-digested with animal waste to produce biogas in the improved efficiency and integrated scenarios. Since co-digestion increases the production efficiency of biogas plant (Section 6.4), the biogas output is higher in the improved production efficiency and integrated scenarios than the other two scenarios (see Section 8.4). The average annual growth of biogas requirement from 2012-2040 is higher in the improved production scenario (7%) and integrated scenario (8.9%) compared with the reference scenario (4.8%) and increased subsidy scenario (6.5%), mainly due to the increased biogas consumption in the former two scenarios. In 2040, total biogas requirement is projected to increase from 1.9 PJ in 2012 to 7.0 PJ in the reference scenario, 12.5 PJ in the improved production efficiency scenario, 11.2 PJ in the increased subsidy scenario and 20.8 PJ in the integrated scenario (Figure 8.12).

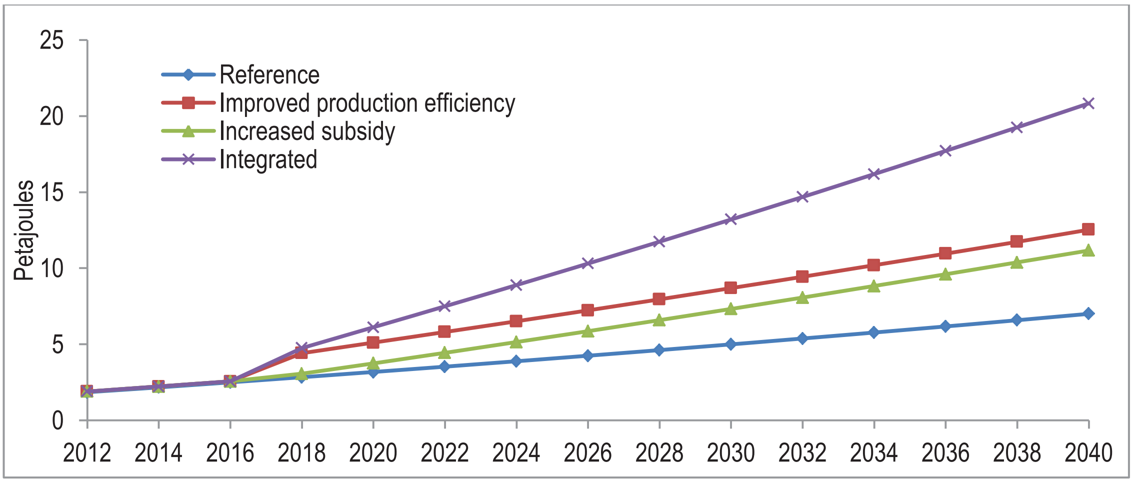

Figure 8.12: Biogas production requirement projections in the four scenarios

Environmental loading of transformation process

Emissions directly associated with transformation activities such as burning of bottled LPG, imported kerosene, fuelwood and crop residues were already allocated to demand categories. So, emissions associated with the transformation process include electricity generation and biogas production. Since the anaerobic co-digestion process does not involve any emission, the major emission is from thermal electricity generation. The GHG emissions increase with increase in electricity generation requirements for all the scenarios (Table 8.22), and the annual average growth rate is higher for improved production efficiency (10.7%) and integrated scenario (12.6%) compared with reference (4.8%) and subsidy scenario (6.2%), since electricity requirement is higher in the former two scenarios.

Table 8.22: GHG emissions projections from electricity generation in the four scenarios (1,000 tonnes CO_2 equivalent)

Scenarios	2012	2020	2025	2030	2035	2040	Average annual growth (%)
Reference	0.75	1.31	1.67	2.04	2.42	2.81	4.8
Improved production efficiency	0.75	3.24	4.98	7.15	9.78	12.92	10.7
Increased subsidy	0.75	1.41	1.98	2.6	3.29	4.04	6.2
Integrated	0.75	3.89	6.82	10.59	15.26	20.89	12.6

8.5.5 Cost benefit analysis

A cost-benefit calculation, including demand cost of energy and externality costs from emission of pollutants, was performed and then compared between the scenarios. The costs of energy used for this analysis was taken from the calculations of total energy costs based on the responses of the surveyed households (Chapter 7).

Cost-benefit summary

A comparative overview of the costs and benefits of each scenario relative to reference scenario is presented in Table 8.23. The total cumulative costs for each scenario were discounted at 10% to year 2012. The cumulative benefits from saving of fuels and cost of avoiding GHG emissions in the integrated scenario relative to the reference scenario is about US$13.54 million in Chitwan, US$2.31 million in Lamjung, US$213.71 million in the Terai and US$93.40 million in the Hill from 2012-2040 (Table 8.23). The benefit in the integrated scenario relative to the no biogas case is much higher at US$40.27

million in Chitwan, US$6.75 million in Lamjung, US$623 million in the Terai and US$213 million in the Hill.

Table 8.23: Comparative cumulative benefits from saving on fuels and cost of avoiding GHGs (2012-2040) relative to reference scenario (million US$)

District/ Region	Improved production efficiency	Increased subsidy	Integrated	No biogas
Chitwan	6.46	4.0	13.54	- 26.73
Lamjung	2.04	0.23	2.31	- 4.44
Terai	95.45	65.64	213.71	- 409.06
Hill	53.50	17.34	93.40	- 119.39

Note: All cost-benefits discounted at 10% to year 2012.
Negative values represent the costs relative to the reference scenario.

Cost of energy

A cost of energy is the total cost of energy demand in the *Demand* branch. The data for the analysis was entered in terms of annual cost per household for each technology branch (SEI, 2013). LEAP calculates the demand cost by using the formula given in Equation 8.4 (SEI, 2010).

$$(\text{Cost})_{s,t} = (\text{Cost per activity})_{s,t} \times (\text{Activity level})_{s,t} \qquad \text{Equation 8.4}$$

Where *s* is scenario and *t* is year. In Chitwan, for example, the demand cost of energy without biogas (US$16.27 million) is much higher than in reference scenario (US$11.35 million) and integrated scenario (US$4.21 million) in 2040. Despite a higher number of biogas plants, the cost of energy in the integrated scenario is lower than other scenarios, mainly due to the replacement of costly fuels such as fuelwood and LPG by cheap and efficient fuels such as biogas and electricity (Table 8.24).

Table 8.24: Demand cost projection for the four scenarios in selected years (million US$)

District/ Region	2012	Reference		Improved efficiency		Increased subsidy		Integrated		No biogas		
		2020	2040	2020	2040	2020	2040	2020	2040	2012	2020	2040
Chitwan	11.35	10.98	10.05	9.99	7.96	10.71	7.93	9.48	4.21	14.55	15.02	16.27
Lamjung	1.83	1.82	1.81	1.41	1.36	1.81	1.71	1.39	1.26	2.44	2.52	2.73
Terai	242	226	182	212	146	221	150	203	85	285	295	319
Hill	104	102	97	92	83	89	89	89	64	123	127	138

The average saving on cost of energy per household relative to non-biogas is estimated at about US$100/year in Chitwan and US$57 in Lamjung in the reference scenario in 2040, which is projected to increase to US$195/year in Chitwan and US$91/year in Lamjung in the integrated scenario in the same year (Figure 8.13). The average saving of the two districts is US$143, which would be sufficient to cover the additional subsidy paid over as assumed in the subsidy scenario. The higher expected saving in Chitwan is due to the higher price of fuelwood. This finding matches with the finding in Chapter 7 that use of biogas reduces the cost of energy significantly, and saving on the total cost of energy is higher when biogas production is increased through co-digestion of crop residue with dung.

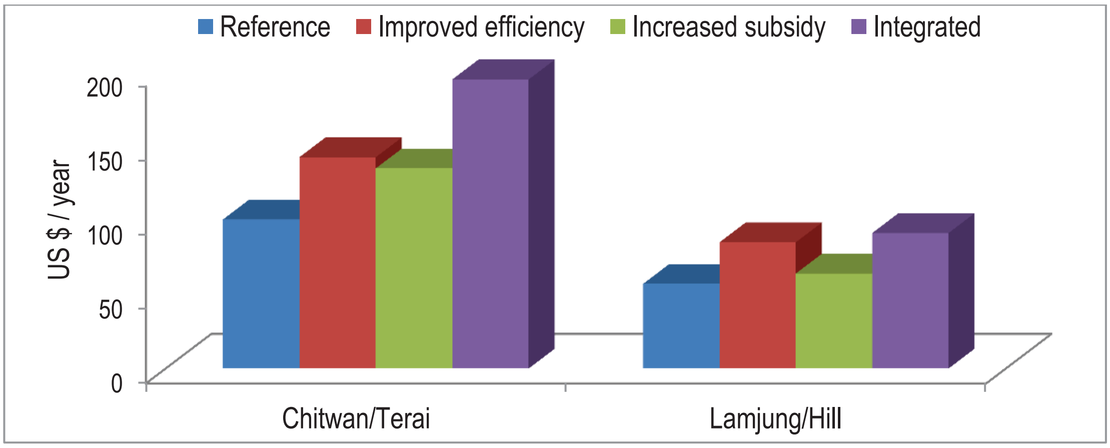

Figure 8.13: Average annual saving on total cost of energy per household in the studied districts relative to without biogas in the four scenarios in 2040

Externality costs or social damage costs of pollutants

An externality is a cost or benefit imposed on third party, such as a society that did not choose to incur the cost or benefit (Endres, 2011). Externality can be both positive and negative; environmental emission is a negative externality that imposes cost to the society (Endres, 2011). The externality costs arising from the avoided emissions of pollutants is projected to decrease significantly in 2040 for all districts/regions and scenarios, but the annual average rate of reduction is much higher for the integrated scenario compared with other scenarios (Table 8.25). The reason for the decrease in the externality cost is less emission due to reduced consumption of highly polluting traditional fuels. The annual average rate of reduction in the Terai from 2012-2040, for example, is projected at 15.4% in the integrated scenario, much higher than in the reference scenario (1.9%).

Table 8.25: Externality costs of avoiding GHGs (energy-related) in two districts and regions for the four scenarios (million US$)

District/ Region	2012	Reference		Improved efficiency		Increased subsidy		Integrated	
		2040	Annual drop rate (%)	2040	Annual drop rate (%)	2040	Annual drop rate (%)	2040	Annual drop rate (%)
Chitwan	25.2	18.7	1.1	13.2	2.3	10.3	3.1	0.2	15.4
Lamjung	6.5	5.6	0.6	2.8	3	4.4	1.4	0.1	16.1
Terai	566	332	1.9	231	3.2	188	3.9	5	15.8
Hill	438	343	0.9	199	2.8	253	1.9	2	16.9

CHAPTER NINE

DISCUSSION

9.1 Introduction

In this chapter, the findings of the study conducted in two districts of Nepal, Chitwan representing the warmer plains of the Terai region and Lamjung representing the colder, mountainous Hill region (Section 4.4) are highlighted, discussed and compared with other relevant research findings. The discussion is focused on the research objectives. The influence of socio-economic characteristics on biogas plant installation is discussed first, followed by the feedstock availability for biogas production. It then discusses the impacts of biogas on energy use patterns, and the gender impacts of biogas technology, with particular focus on women's time saving and reduced workload. The biogas demand and production deficit aspects are presented to explore whether conventional biogas production practice is sufficient to provide energy security to rural households. The potential of improving biogas production efficiency through co-digestion of mixed feedstocks and its cost-effectiveness compared with non-biogas households and current energy use practices are discussed next. Finally, the impacts of increased biogas production through co-digestion to reduce energy consumption and corresponding GHG emissions are discussed at the end of the chapter.

9.2 Influence of Socio-economic Characteristics on Biogas Plant Installation

A number of studies have demonstrated that a decision to install a biogas plant and the size of the plant are influenced by the socio-economic characteristics of the households (e.g., P. C. Ghimire, 2005; Kabir, Yegbemey, & Bauer, 2013; Karki et al., 2005; Mwirigi et al., 2014; Mwirigi, Makenzi, & Ochola, 2009; Raha, Mahanta, & Clarke, 2014; M. Singh & Maharjan, 2003). The findings from this study also agree that socio-economic characteristics, mainly family size, caste/ethnic group, occupation/income, landholding size and number of livestock influence households' decision to install a biogas plant and the size of the plant. A more detailed description on linkages of biogas plants and these characteristics is presented in Chapter Five. Higher caste households, who in general have higher education, income and comparatively larger landholding size and livestock numbers compared with marginalised *Janajatis* and *Dalit*s have tended to install biogas plants. Similarly, the size of the plant is mostly determined by the family size and the number of livestock, i.e., the bigger the family size and number of livestock, the bigger the size of the plants, in general. These findings are consistent with the findings of other similar studies (e.g., Amgai, 2013; NESS, 2011; M. Singh & Maharjan, 2003). This implies that biogas programmes should be prioritised to those households who are illiterate, lack regular cash income, and own less land and livestock numbers.

9.3 Feedstock for Biogas Production

This study found that only dung and human excreta (in toilet attached plants) were used as feedstock to operate biogas plants and about 75% of the plants in Chitwan and 80% of the plants in Lamjung were under-fed. The average quantity of dung fed into the digesters daily was 26.9 kg (92% of total daily dung available) in Chitwan and 23.6 kg (74% of total daily dung available) in Lamjung. The prescribed quantity of feedstock for the hydraulic retention time of 70 days as in the case of household-level biogas plants in Nepal, is 6 kg/m^3 plant size (BSP-Nepal, 2012b), which is 15% more than the presently available average quantity of feedstock and 23% more than the average quantity fed into the digesters. This finding matches the finding of Amjid, et al. (2011) who estimated that only 79% of dung was being fed in biogas digesters in Nepal. About 9% of plants in Chitwan and 15% in Lamjung, mostly bigger size plants, received even less than 40% of the daily prescribed quantity of dung. The households produced less than the daily prescribed quantity of dung because of less numbers of livestock raised, or reduced the number as a result of decline in household labour from out-migration of youths to overseas or urban areas for a job or study, and/or changes in other socio-economic condition of the households. Others, despite having sufficient production of dung, did not feed all of the produced dung into the digester, but used it for making compost, believing that compost makes better fertiliser.

These under-fed plants were the major reason for lower biogas production. The plant owners were less aware about the effects of under-feeding on biogas production. Although biogas users' surveys in Nepal (AEPC, 2013b; NESS, 2011) also reported production and feeding of insufficient dung, it seems that neither the BSP-Nepal nor the biogas companies realise this is a problem, perhaps being only concerned with achieving the installation targets. Clearly, the monitoring and support offered to purchasers to help optimise gas production after sale has not been effective. Studies conducted in other countries also reported the problem of under-fed plants, the feedstock deficit ranging from 36-47% of the daily prescribed quantity (Dung et al., 2009; P. C. Ghimire, 2005, 2007; Gosens, Lu, He, Bluemling, & Beckers, 2013;

Parawira, 2009b). However, measures to supplement feedstock deficit to optimise biogas production at household level plants were not reported in any of those studies, as had been attempted in this study (see Chapter 6).

9.4 Impacts of Biogas on Energy Use Patterns

The introduction of biogas has changed energy use patterns by replacing fuelwood and other biomass sources in many rural households in Nepal (CBS, 2012a). However, available biogas was not sufficient to fulfil the cooking energy demand throughout the year in most of the user households (Section 5.5.1), and households continued using conventional fuels to supplement the energy deficit. This has also been the case in other developing countries in Asia and Africa (G. Austin & Blignaut, 2007; P. C. Ghimire, 2005, 2007; Gosens et al., 2013; IDE, 2011; Pathak et al., 2013). However, as a result of biogas production, the share of fuelwood to total energy consumption has decreased from 95% to 20% in the Terai district and 98% to 41% in the Hill district, which is comparable with the findings of IDE (2011), Gosens, et al. (2013), Pathak, et al.(2013), and Ghimire (2005, 2007). Kerosene was used for cooking in only a few households, so the impact of biogas on kerosene reduction was not common, but use of biogas replaced the burning of crop residues significantly (about 70%). The saved crop residues could then be utilised as feedstock for producing biogas (see Chapter 6). These findings support the argument that biogas technology has a high potential of reducing consumption of inefficient, unhealthy, expensive and environmentally-unfriendly fuels (Bajgain & Shakya, 2005; BSP-Nepal, 2012b; Gosens et al., 2013; Limmeechokchai & Chawana, 2007; Riek, Rücker, Schall, & Uhlig, 2012).

The impacts of biogas on household energy consumption were analysed using the LEAP model with a time horizon of 2012-2040 generating four scenarios: (a) reference scenario - an extension of the current energy use pattern and policies, (b) improved biogas production efficiency scenario with implications of co-digestion of mixed feedstocks on biogas production, (c) increased subsidy scenario assuming increase in subsidy to increase poor's access to biogas systems, and (d) integrated scenario with cumulative effects of improved biogas production efficiency and increased subsidy scenarios assuming that all potential households have installed biogas plants (Section 8.4). If the current energy use pattern continues, biogas is projected to decrease energy consumption, mostly from saving on fuelwood burning, by 31.8 GJ/household in the Terai and 19.3 GJ/household in the Hill from 2012-2040 compared with a non-biogas household. This is equivalent to an average annual reduction of 1.9% of total energy consumption in the Terai and 0.9% in the Hill. The reduction in total energy consumption is about 40% compared with non-biogas households. The higher rate of reduction in energy consumption in the Terai is due to higher gas production than in the colder Hill region (Section 8.5.1).

Despite being expensive, consumption of LPG increased because of its increased availability in the local market, convenience in use and decreased availability of fuelwood[58]. Users were accustomed to cooking with biogas, an efficient and convenient fuel, and hence chose LPG as a substitute for cooking quick food (tea/snacks) when biogas was not enough. However, studies in other Asian countries reported decreases in LPG use ranging from 23% to 84% (P. C. Ghimire, 2005, 2007; Gosens et al., 2013; Pathak et al., 2013). Gosens, et al. (2013) argued that biogas replaced LPG because these two are perfect substitutes in terms of convenience and efficiency, and LPG is expensive. Use of electricity for cooking has slightly increased after the introduction of biogas across the region. However, cost was the limiting factor to completely replace fuelwood by LPG and electricity, because fuelwood was much cheaper than these fuels and its collection did not involve any cash payment. The geographic location affected households' access to energy sources and prices, as also suggested by Jiang and O'Neill (2004) and Goesns, et al. (2013), and cooking habits and practices (e.g., heating milk and cooking animal feed), also reported by Gupta and Kohlin (2006), influenced the households' decision about fuel choices and consumption level. Besides this, the rural households were less aware of the negative environmental and health effects of burning fuelwood, which gave them incentive to continue its use, as reported by Bajgain and Shakya (2005), Demurger and Fournier (2010) and Baland, et al. (2013).

9.5 Gender Impacts of Biogas Production and Utilisation

Biogas technology by changing energy use patterns can have positive impacts on saving time and reducing workload of users, particularly of female members in daily household activities such as cooking, cleaning of utensils and fuelwood collection. Although feeding a biogas plant was an additional work allocation each day, the average daily time saved per household for all members after the installation of biogas was about 4.5 hours/day in the Terai district and 4.9 hours/day in the Hill district (Section 5.4). The higher time saving in the Hill district is mainly because of the hilly

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[58] Fuelwood availability was decreased due to physical loss of forests from over-exploitation or restricted access to forest products under community forest management rules as in the case of the Hill region of Nepal (Adhikari, 2012).

terrain that took more time walking for fuelwood and water collection. The average time saved by female members in a household was 3.2 hours/day. A household can save up to 50 minutes/day in cooking, 40 minutes/day in utensil cleaning and over 2 hours/day in fuelwood collection. This finding is consistent with the findings of Ghimire (2005, 2007), PASA (2007), BSP-Nepal (2012b), Chand, et al. (2012), Riek, et al. (2012) and AEPC (2013b) that use of biogas has reduced time required for some household activities. The average daily time saved per household found in this study however was slightly higher than reported in other Asian and African countries (P. C. Ghimire, 2005, 2007; Riek et al., 2012), mainly because of the differences in fuelwood collection time. In most of the households of rural areas in Nepal, family members collected fuelwood by themselves, and the average time spent on its collection before the use of biogas was 2.7 hours/day in Chitwan and 3.0 hours/day in Lamjung, higher than reported by Ghimire (2005, 2007) and Reik (2012) .

Although biogas technology might not change the deep-rooted traditional gender patterns of the division of labour in the developing countries as suggested by Bajgain and Shakya (2005) and Riel et al. (2012), it has certainly encouraged the social and economic empowerments of women in rural areas and thus addressed some strategic gender needs. Women and men have different roles in the provision of energy within a household, as also reported by IRADe (2009). Women typically spend more time on managing household energy systems and carry out non-market economic activities that are usually undervalued due to their low status and absence in decision-making roles (P. C. Ghimire, 2005; Mahat, 2003; Sidh & Basu, 2011). In this context, women benefit disproportionately by the installation of biogas technology through the reduced drudgery of fuelwood collection, educational and social/community work opportunities from time saved, improved health conditions and economic advantages by utilising saved time (Section 5.4), although full benefits of the technology in relation to income-generating opportunities were not always assessed as reported by Gurung and Thakali (2014) and Raha, et al. (2014). However, women's saved time was usually reallocated to other household chores for family benefits. Whether biogas really reduced the drudgery of women with such reallocation of their saved time to other household chores needs further research.

9.6 Biogas Demand and Production Deficit

The existing biogas production in Nepal was not sufficient to meet the cooking energy needs all year round in more than 15% of households in Chitwan and 4% in Lamjung.

About 62% of households in Chitwan and 31% in Lamjung reported sufficient gas in summer only. Biogas deficit was not characterised within a particular caste/ethnic group or other socio economic factors, but technical factors such as insufficient feedstock, as discussed earlier, lower temperature, technical problems such as gas leakages (Section 5.6.2) and poor performance of the plants (Section 5.6.3) were contributing to it. Although the average share of biogas in energy balance as found in this study (73.5% in Chitwan and 64% in Lamjung) (Section 5.5.1) was similar to other Asian and African countries (P. C. Ghimire, 2005, 2007; Gosens et al., 2013; Pathak et al., 2013; ter Heegde & Sonder, 2007), insufficient gas supply could make the biogas projects less attractive as reported by Zhang and Wang (2014) in the case of rural China. The consequences of the remaining more than 1.6 million potential households in Nepal not being interested in installing biogas plants for insufficient gas production could be huge. This calls for an immediate action towards increasing biogas production to meet household cooking energy needs to continue the successful development of biogas technology in Nepal.

Lower temperature during winter or in colder regions is considered as another factor for lower gas production. Potential higher cost of energy prevents the users from adopting digester heating practices. The energy they would have to spend on heating the digester might be sufficient to fulfill the energy deficit as a result of low gas production, although assessment of biogas production with digester heating and its cost-effectiveness requires further research. Gas loss due to leakages from the plant is another important reason for lower gas availability (Section 5.6.2). Devkota (2003) estimated an average of 40.63 kg/year methane leakage from a biogas plant installed in Nepal. Such leakage not only reduces gas availability for cooking but also contributes to GHG emissions (Section 8.5.2). Biogas companies therefore need to focus on minimising the leakage through effective quality control monitoring during plant construction and post-construction support services.

Under-performance of the plants in operation was identified as another important factor for insufficient biogas supply. The average efficiency of the plants - the percentage of biogas output to theoretical potential of feedstock input - in terms of their size was just over 50%, whereas, based on the existing quantity of digester feeding was 73%. Although the performance was higher than reported in the domestic biogas plants in Pakistan (Ghimire, 2007) and Bangladesh (Ghimire, 2005), the average required efficiency to meet the current energy demand is estimated to be about 93%. Increasing the size of the plants or increasing the quantity of dung to produce more biogas, however, may not always be an efficient option, which is also associated with increased installation and operation costs.

This study therefore, proposes the co-digestion of mixed feedstocks, such as crop residues and dung, and human excreta in toilet attached plants, as a measure to increase biogas production through improved production efficiency of the plants. Crop residues are a potential co-feedstock for biogas production due to their nutrient and carbon characteristics values (Tripathi et al., 1998; T. Zhang et al., 2013). Using agricultural residues as feedstock for co-digestion with animal dung had a good potential in Nepal (Lungkhimba et al., 2011). On average, about 3.4 tonnes crop residues such as rice straw, corn stover and wheat straw are produced in Nepal every year, about half of which is used for animal feed and the remainder could be available for use as digester feedstock to enhance biogas production. Co-digested biogas digesters could solve the problem of insufficient feedstock and perform better even in lower temperature/colder areas.

9.7 Improving Biogas Production Efficiency Through Co-digestion

This study suggests that co-digestion of mixed feedstocks could be the best solution for underfed domestic biogas plants to increase biogas production. Co-digestion of crop residues with dung and human excreta could increase biogas yield by approximately 50-150% depending on the proportion of the co-substrates and temperature (Section 6.4.4). This finding is consistent with Moller, et al. (2004), Asam, et al. (2011), Sahito, et al. (2013) and Omar, et al. (2008), who reported an increase in biogas yield of 50-200% more than single feedstock digestion, depending on plant operating condition and co-substrates used. Co-digestion of dung with human excreta only, as currently practised in Nepal, however, has no significance on improving biogas production. Above 50% increase in gas production would increase the share of biogas in total energy balance by at least 90%, reducing the dependency over traditional fuels. Moreover, co-digestion technology could improve plant performance even in lower temperatures; increasing biogas yield by 6.5-12.5% in Chitwan and 4.2-10.2% in Lamjung during winter. The higher increase rate in Chitwan could be due to the higher average winter temperature in the district.

Integration of co-digestion technology and increase in subsidy for biogas plant installation is assumed to motivate all potential households to install biogas plants (Section 8.4.5) that will fulfill most of the household cooking energy needs. Increased biogas production from co-digestion is projected to reduce the total annual energy consumption by about 46.2 GJ/household in the Terai and 57 GJ/household in the Hill in 2040 compared with non-biogas households mostly from saving on fuelwood burning. The higher reduction in energy consumption in the Hill is due to the higher consumption of fuelwood before the use of biogas (Section 5.5.1). These findings demonstrate the contribution of co-digested biogas systems in conserving forests and reducing households' workload and drudgery on fuelwood collection. Although specific studies on the impact of biogas on reducing energy consumption could not be found, this study's finding is consistent with the finding of other studies on renewable energy technologies, that use of efficient energy sources reduces the consumption of inefficient traditional fuels and hence total energy consumption (e.g., Limmeechokchai & Chawana, 2007; Lin et al., 2006; Malla, 2013; S. Pokharel, 2007a).

However, domestic biogas users were unaware that co-digestion technology could improve biogas production efficiency. They had little knowledge about possible alternative feedstocks except dung and human excreta, which has also been reported in other developing countries in South Asia and Africa (P. C. Ghimire, 2005, 2007; Jingura & Matengaifa, 2009; Raha et al., 2014). Such a lack of awareness and knowledge gap have deprived biogas households of utilising other organic materials such as crop residues that are being wasted otherwise, to produce biogas.

Despite the benefits and opportunities of co-digestion technology, technical suitability of the Chinese-dome type domestic plant design to handle digestion of crop residues is still questionable (KC et al., 2013; P. Lamichhane, 2012). Less has been reported previously about this, not only in Nepal but also in other countries where livestock dung is used as major feedstock in household level biogas digesters (P. C. Ghimire, 2005, 2007; Gosens et al., 2013; Pathak et al., 2013; Thu et al., 2012). Absence of a slurry mixing feature and a mechanism to remove digested inert materials accumulated at the bottom of the plant, as suggested by Lamichhane (2012) and KC, et al. (2013) could limit co-digestion capability of the existing plants. So, this study proposes that the BSP-Nepal, AEPC or biogas companies examine the capability of the existing plants in handling digestion of lignocellulosic materials. The proportions of co-digestion mixtures discussed in this study (Section 6.4.2) can be used for the experiments. Depending upon the results of the experiment, the suitability of the plants for co-digestion of crop residues with dung would be determined. If not suitable, the BSP-Nepal or AEPC, whoever is relevant, should prioritise modification of the plant design to suit co-digestion of lignocellulosic materials with dung. Promoting community awareness on the importance of co-digestion and sharing knowledge with biogas users about the suitability of other organic matters as feedstock to produce biogas is equally important, because users are usually reluctant to adopt new practices without them demonstrating visible benefits (Pant, 2012).

This study could be one of the pioneer studies in exploring the potential of improving biogas production efficiency of the household-level biogas digesters through co-digestion of crop residues, dung and human excreta under different ambient temperatures**.** There is a knowledge gap about how much biogas could be increased after co-digestion of crop residues with dung in a household-level biogas plant and what could be the suitable proportion of the feedstocks for co-digestion. Although the suitability of the existing domestic biogas plant design to handle digestion of crop residues is still to be determined, the findings of this study could serve as a guideline for the suitability assessments.

9.8 Cost-effectiveness of Biogas Production through Co-digestion

Co-digestion of crop residues with dung not only increases biogas production, but also is a cheaper cooking energy option in terms of total cost of energy of a household. The average total annual cost of energy of a biogas household after co-digestion could be up to 45% cheaper compared with a no-biogas household (if fuelwood collected), and up to 37% cheaper than the existing total annual cost of energy (biogas production without co-digestion), depending on the size and location of the digester (Section 7.6).

The potential of co-digestion technology on reducing total annual cost of energy at household level was not reported previously; most of the available literatures reporting on co-digestion were of large-scale wastewater treatment plants or large-scale farm-level plants (B. Jacobsen, Frederik, & Dubgaard, 2011; Lantz & Borjesson, 2014; Lassner, 2011; Rural Futures, 2010). Thus, this finding is believed to fill the prevailing knowledge gap on cost-effectiveness of co-digestion practice on domestic biogas systems. Such information could help scaling up of co-digestion technology in the domestic biogas sector, since information on cost-effectiveness is vital to a household's decision to install a biogas plant or adopt the co-digestion practice (Bajgain & Shakya, 2005; IDE, 2011; Kabir et al., 2013; Pant, 2012).

Fuelwood, which shared above 90% of the total annual energy cost in a non-biogas household, was reduced by almost 80% in the Terai region and 63% in the Hill region after the use of biogas, with an average saving on fuel expenditure between US$19-117 in the Terai district and US$20-28 in the Hill district depending on the size of the plants. The higher saving in the Terai district was due to the higher local price of fuelwood, which implies that the saving largely depends on the price of fuelwood. This finding matches with the findings of Li, et al. (2007) and Rajendran (2012) that a biogas plant could benefit by about US$100/year. Gosens et al. (2013) reported up to 39% (US$97/year/plant) savings on fuel expenditure in rural China, which was almost equal to the annual cost of biogas plant operation. Monthly average saving on fuel cost after the use of biogas was calculated to be about US$18/plant in Bangladesh (IDE, 2011), whereas Govidasamy and Hsu (2008) found an average annual reduction in the cost of fuelwood by US$61 and kerosene by US$38 in India's remote villages. Gosens, et al. (2013) also found biogas about 5-12 times cheaper than LPG.

Nevertheless, the annual cost of other fuels to supplement energy deficit from available biogas was still high ranging between 59-67% of the total energy cost in the Terai region and 55-61% of the cost in the Hill region, depending on the plant size. The cost was at least 40% and 22% higher than the annual cost of biogas itself in the Terai and Hill regions, respectively. This further justifies the need to increase biogas production efficiency (through co-digestion) in order to minimise the existing higher cost of conventional fuels to supplement for energy deficit from available biogas.

In the hilly district of Nepal where forest resources are comparatively abundant and the price is less, the cost of purchased fuelwood is almost similar to the cost of labour for its collection (Section 7.2.1). The households still preferred to collect fuelwood because of lower opportunity cost of their time and lack of regular cash required to purchase it. In this context, purchasing a biogas system could be difficult for the poor households without subsidy. This study therefore strongly supports the government subsidy policy for biogas promotion (MSTE, 2013b) and recommends further increasing the subsidy amount to poor households. The subsidy can be managed through the earnings of carbon credit by the biogas plants under the CDM (Section 8.5.3), as also suggested by (Somanathan et al., 2014), assuming that long-term international arrangements for climate change mitigation like CDM continue even after the completion of the Kyoto protocol in 2020 (Garnuat, 2012).

9.9 Impact of Biogas on GHG Emissions Reduction

This study showed that domestic biogas systems have good potential to reduce GHG emissions by replacing burning of emissions-intensive fuels with efficient fuels/stoves as well as reducing non-energy emissions such as avoiding decomposition of dung and reducing deforestation by saving fuelwood. The LEAP model was used to analyse the impact of biogas on GHG emissions reduction. The total GHG emissions reduction in the Terai and Hill combined from the reduced burning of emission-intensive fuels compared to no biogas case is 445,000 tCO_2e in the reference scenario, which is projected to increase to 1.02 million tCO_2e in the integrated scenario in 2040. Considering both energy and non-energy sources, biogas has total GHG mitigation potential of about 12.58 million tCO_2e in the Terai and Hill combined in the reference scenario, which is projected to increase to 35.6 million tCO_2e in the integrated scenario in 2040 when all the potential biogas households have access to biogas. This is equivalent to about 16.7 tCO_2e/plant in the Terai and 19.3 tCO_2e/plant in the Hill in 2040 in the integrated scenario (Section 8.5.3). The average annual rate of GHG emissions reduction after improving plant efficiency through co-digestion of mixed feedstocks in the Hill (9.8% per year) is higher than in the Terai (8.6% per year) because increased biogas production is projected to replace more fuelwood in the Hill. These findings are comparable with the findings of Gosens, et al. (2013), but are slightly higher than reported by BSP- Nepal (2006), Shakya and Shrestha (2006), Pokharel (2007b), Chaulagain and Laudari (2010), Dhakal and Raut (2010), and Ghimire et al. (2014), because they did not take into account the improved production efficiency of the plants and non-energy sector emissions.

The LEAP results showed that utilisation of dung to produce biogas could reduce the GHG emissions by about 220 kg CO_2e/year/plant for both regions compared with non-biogas households (Section 8.5.2). This finding is consistent with the findings of Pathak (2013). Similarly biogas slurry substituting chemical fertiliser could reduce GHG emissions by 540 kg CO_2e/year/plant. However, only about 5% of the households reported using slurry to replace chemical fertilisers and hence the reduction in the emissions, in practical terms, would be less than the projection. Thus, promotion of effective application of bio-slurry needs to be prioritised not only for increasing agricultural productivity and reducing the associated GHG emissions, but also to encourage households to use available dung to feed digesters instead of making compost. This would increase the availability of feedstock for biogas production, at the same time avoiding GHG emissions from the decomposition of dung (Section 8.5.2).

However, methane leakage from a biogas plant (about 1.02 tCO_2e/year) is significant. This implies that methane leakage offsets the CO_2 avoidance from burning of traditional fuels substituted by biogas. The total GHG emissions from the leakage (about 2 million tCO_2e) in the Terai and Hill combined in 2040 (Section 8.5.2) is almost double the CO_2 avoidance from the fuelwood burning. This highlights the need to upgrade plant construction/fittings and address technical issues in a timely manner to avoid gas leakages. The emissions from the leakages are however much lower compared with the total GHG avoidance from both energy and non-energy sector sources (16.7 tCO_2e/year in the Terai and 19.3 t CO2e/year in the Hill in the integrated scenario), still making biogas an environment-friendly technology.

Thus a biogas plant, considering an assumed price of US$ 10/tCO_2e, could generate carbon credit of up to US$167/year in the Terai and US$193/year in the Hill, which would be sufficient to cover most of the capital cost of biogas plant installation. The biogas revenue could even be higher if the avoided cost of illness due to improved health and sanitation conditions and social cost of reduction in workload and drudgery is considered. This implies that biogas subsidy could be increased to a near-100% of the installation cost with financial break-even over the life period of the plant, as assumed in the increased subsidy or integrated scenario (Section 8.4) and also suggested by Somanathan, et al. (2014), and that could provide a great opportunity to promote biogas technology as a profitable activity to mitigate climate change.

Potential of household level biogas plant with co-digestion technology in reducing energy consumption and GHG emissions considering a long time horizon under different energy intensity and policy conditions was not reported previously. Although a few studies have analysed the impact of biogas on energy consumption and GHG emissions (Limmeechokchai & Chawana, 2007; Pathak et al., 2013; Shakya & Shrestha, 2006), they were mostly based on the assumption that biogas replaces all other fuels, which may not be a practically valid assumption. This study clearly demonstrated the benefits of the proposed policy conditions/assumptions in terms of energy consumption, GHG emissions and costs, and provided evidence that a proposed increase in subsidy could be recovered through the outcomes of the programme implementation (i.e., income generated from carbon credit). It further analysed the impacts of co-digestion technology in GHG emissions from non-energy sector sources, particularly from reduced deforestation, which were not specifically reported previously. The current study thus adds to the body of literature the contribution of biogas technology (with and without co-digestion of mixed feedstocks) on reducing GHG emissions from non-energy sector sources. Moreover, this is one of the very few studies to look at the energy transformation activities for analysing total energy (biogas, electricity) requirements by feedstock fuels and environmental emissions associated with the transformation activities, whereas other biogas studies were mainly confined within the demand sector.

CHAPTER TEN

CONCLUSIONS AND RECOMMENDATIONS

10.1 Introduction

This study was conducted in two districts of Nepal, Chitwan from the Terai region and Lamjung from the Hill region. The two districts represent two distinct regions in terms of temperature, energy use practices, fuel cost, feedstock availability, biogas subsidy policy, and remoteness that have influence on biogas production and utilisation. This chapter first presents the research conclusions. Implications and recommendations based on the research findings are then described. The implications and recommendations made from this study can have strong relevance for the Government of Nepal’s Alternative Energy Promotion Centre, the BSP-Nepal, donor agencies, biogas construction companies, existing/potential biogas user households and other relevant agencies that support the wider replication of biogas technology as a simple, reliable and cost-effective solution to provide energy security to rural households. This study's findings can also be relevant to other developing countries where biogas can be a part of solution to provide energy security, gender equality and climate change mitigation.

10.2 Key Findings

- Installation and size of biogas plants in both the surveyed districts were linked with family size, size of landholdings and number of livestock owned. Bigger family size, larger landholdings and larger number of livestock owned greatly influenced the decision to install a biogas plant and own a bigger sized plant.

- The average daily feeding materials produced (animal dung and human excreta) by a biogas household was 32.2 kg in Chitwan and 31.7 kg in Lamjung, of which 92% in Chitwan and 74% in Lamjung was fed into a biogas digester.

- Feeding of insufficient feedstock was identified as one of the major reasons for lower biogas production. About 56% of biogas plants in Chitwan and 66% of plants in Lamjung were fed less than 80% of the daily required quantity of feedstock. Bigger sized plants were more under-fed than smaller sized plants; the average quantity of feedstock fed being just 58% of the daily prescribed quantity in 10 m^3 plants compared with 92% in 4 m^3 plants.

- Biogas was mainly used for cooking, and introduction of biogas had changed the energy use patterns, successfully replacing traditional biomass energy sources. Use of biogas reduced the consumption of fuelwood by 76% in Chitwan and 61% in Lamjung, saving nearly 3 tonnes fuelwood per year per household.

- The gender impact of biogas technology in terms of saving time and reducing workload of users, particularly of women, in daily household chores due to changes in the energy use patterns was significant. A household saved an average of 4.8 hours/day, with females benefitting the most by daily time saving of 3.2 hours and reducing drudgery of fuelwood collection and cooking in a smoke-free kitchen.

- The impacts of biogas on household energy consumption reduction were analysed using the LEAP model, generating four different scenarios with a time horizon of 2012-2040. If the current energy use practices continued (i.e., the reference scenario) introduction of biogas could reduce the total annual energy consumption of a household by 22.1 GJ in Chitwan/Terai and 26.5 GJ in Lamjung/Hill compared with a non-biogas household, mainly due to the replacement in burning of inefficient fuelwood by efficient cooking fuel (biogas).

- The existing biogas production was usually not enough to fulfill cooking energy needs of a household all year round. Biogas deficit was higher during winter due to lesser gas production in colder temperatures. On average, biogas fulfilled 87% and 79% of the cooking energy needs of a household in summer and 60% and 49% of the demand in winter in Chitwan and Lamjung, respectively. Such insufficient biogas production has been identified as the major constraint for wider replication of domestic biogas technology.

- The biogas plants were performing poorly both in terms of their optimum production capacity based upon their size (56% in Chitwan and 50% in Lamjung) and actual quantity of feedstock fed (73% in both districts). The required efficiency of the plants to meet the energy demand was estimated to be 93% in both districts, which seemed difficult to achieve under the existing digester feeding practices. Co-digestion of dung with other organic materials, such as crop residues was therefore considered for improving production efficiency of the plants.

- Crop residues are a potential co-feedstock for biogas production. The average annual quantity produced was about 3.4 tonnes/household; about half was used for animal feed and the remainder could be available for use as digester feedstock to enhance biogas production.

- Co-digestion of crop-residues with dung and human excreta could increase volumetric methane production by approximately 50-150% compared to the single digestion of dung depending on composition of the feedstocks. Digestion of dung with human excreta only as currently practised in Nepal, however, has no significance on improving biogas production. Considering a 50% increase in production, biogas could fulfill at least 90% of the cooking energy demand of a household even in winter across all sized plants. From the resulting C/N ratio of the co-digestion mixture point of view, up to 25% of crop residues (air-dried) by weight is suitable.

- Temperature has a significant effect on methane production in co-digested plants as well. The increase in methane yield after co-digestion of mixed feedstocks could range from 11-17.2% in summer and 6.5-12.5% in winter in Chitwan, and 8.6-14.9% in summer and 4.2-10.2% in winter in Lamjung depending on the feedstock type and co-digestion mixture proportions.

- Increased biogas production through co-digestion and access to biogas for all the potential households (i.e., the integrated scenario) is projected to increase the saving on total annual energy consumption of a household to 46.2 GJ in Chitwan/Terai and 57.1 GJ in Lamjung/Hill by substituting all of the traditional and petroleum fuels.

- The average annual cost of energy of a household after the installation of biogas plants, if fuelwood were collected, was less by US$3-14 in Chitwan and US$22-34 in Lamjung compared to the non-biogas households depending on the size of the plants, where bigger sized plants saved more on energy costs. The saving on the cost would be much higher at US$99-117 in Chitwan but slightly lower at US$20-28 in Lamjung if purchase of fuelwood is considered. The large difference in the average saving of energy cost between the two districts is due to the lower fuelwood price in Lamjung (US$ 0.035/kg) than in Chitwan (US$ 0.063).

- The estimated saving on average annual total energy cost as a result of co-digestion (free crop residues) over the existing dung only digestion practice is between US$56-85 in Chitwan and US$42-76 in Lamjung depending on plant size, the saving being higher for bigger sized plants. This implies that if a household has sufficient crop residues for co-digestion, bigger sized plants are more cost-effective. But for a household that needs to purchase crop residues, the saving is higher for smaller plants due to lower cost of crop residues, and thus plants up to 6 m^3 size is cost-effective. However, the decision about the size of a plant also depends on the biogas need of the household.

- Existing biogas production has a potential to reduce total GHG emissions of about 445,000 tCO_2e in the combined Terai and Hill regions by reducing the burning of emission-intensive fuels, compared with non-biogas households, in 2040. This is projected to increase to 1.02 million tCO_2e in the integrated scenario with increased access to biogas for all potential households and improved biogas availability through co-digestion.

- The GHG emission mitigation potential of a co-digested biogas plant from both energy and non energy sector sources, such as avoiding deforestation for fuelwood, decomposition of dung and bio-slurry replacing fertilisers in 2040 is projected to be about 16.7 tCO_2e in Chitwan/Terai and 19.3 tCO_2e in Lamjung/Hill. However, only about 5% of households reported using slurry to replace fertilisers and hence the reduction in emissions would be less than the projection.

- The GHG emissions due to the methane leakage from biogas plants are significant at about 1.02 tCO_2e/year/plant. This is higher than the GHG avoidance from burning of traditional fuels substituted by biogas, but is much lower compared to the GHG avoidance from both energy and non-energy sector sources.

- Assuming a price of US$10 per tCO_2e and considering both energy and non-energy sector emissions, a biogas plant has a carbon credit earning potential of US$167/year in Chitwan/Terai and US$193/year in Lamjung/Hill. Thus, if all the potential households installed biogas plants, the total theoretical carbon credit earning potential of the domestic biogas sector in the Terai and Hill combined would be about US$357 million/year, which would be sufficient to increasing the subsidy to near-100% of the installation cost.

- The cumulative benefits from saving of fuels and cost of avoiding GHG emissions in the integrated scenario relative to the reference scenario is about US$13.54 million in Chitwan, US$2.31 million in Lamjung, US$213.71 million in the Terai and US$93.40 million in the Hill from 2012-2040. The benefit relative to a no biogas case is much higher at US$40.27 million in Chitwan, US$6.75 million in Lamjung, US$623 million in the Terai and US$213 million in the Hill.

10.3 Recommendations

The results of this study point out a number of policy-related implications and recommendations.

- Given the theoretical nature of this research, although the findings were validated by comparing with experimental data reported in literature and the results agreed reasonably well, validation of the findings - particularly the volumetric methane production potential of the individual feedstocks and under co-digestion - through an experimental programme at the lab or in a pilot-scale level could improve the applicability of the results and thus the quality of this research. However, such an experimental facility lacks in Nepal. Such a pilot-scale research project (e.g., as a post-doctoral study) at a resourceful institution like Massey University could ultimately provide assistance to the rural poor people of Nepal, hard-hit by energy crisis and the recent earthquakes, in achieving energy security.

- Considering the multiple benefits of co-digested biogas plants over the existing plants and lack of knowledge about the suitability of the existing plants to co-digestion, the BSP-Nepal/biogas companies should examine whether the existing plant design can handle the digestion of crop residues. Modification of the plant design needs to be investigated and promoted for wider replication of biogas technology as a reliable and cost-effective source of energy in rural households. Co-digestion compatible plants could also be suitable for low temperature areas.

- Co-digestion of crop residues with dung for domestic biogas production has not been practised in Nepal yet, and users lack knowledge in regards to co-digestion.

Extending awareness and training on co-digestion to potential users is important for the adoption and smooth operation of co-digested plants. Agencies working for biogas development in Nepal, such as BSP-Nepal, AEPC and biogas companies, should design and facilitate such educational programmes and the Government of Nepal and related donor agencies should provide financial support for the execution of such programmes.

- Feedstock insufficiency has been identified as one of the major reasons for lower biogas production. Biogas companies/BSP-Nepal should therefore carefully assess the feedstock availability beforehand to ensure that a newly constructed plant will not be under-fed. Post-construction support/monitoring is equally important to ensure smooth operation of the plants.

- Installation of biogas technology has helped to meet practical gender needs to some extent by reducing the drudgery of fuelwood collection and improved health conditions from reduced drudgery and cooking in smoke-reduced kitchens, but strategic gender interests still need to be addressed. Utilisation of saved time on educational and social/community activities and economic advantages by utilising the saved time could help attain women's equal position in society. The Government of Nepal/Department of Women and Children in coordination with the BSP-Nepal, biogas companies and other relevant government/non-government agencies should prepare strategies and action plans/programmes about how the saved time can be utilised towards achieving strategic gender needs. The plans/programmes should be disseminated/implemented through the district based Women Development Offices and local biogas companies as a package programme of biogas technology promotion and support.

- This study’s findings showed that the total annual cost of energy from co-digested biogas plants is cheaper than the existing cost of energy (without co-digestion) and much cheaper than that of a non-biogas household. This information needs to be disseminated to the potential users effectively in order to encourage them to adopt biogas technology. Moreover, the per unit costs of energy after biogas with co-digestion is the lowest for 4 and 6 m^3 plants due to the lower cost of feedstock purchase, and thus installation of smaller size plants should be prioritised for domestic use. Bigger size plants should only be considered if the households have sufficient feedstock including crop residues in the case of co-digested digesters.

- Considering the carbon credit generation potential of biogas plants, this study demonstrated that biogas subsidy can be increased to near-100% of the installation cost. If the energy sector goal is to provide energy security to rural households that are reliable and cost-effective, the Government of Nepal should consider increasing the biogas subsidy to meet at least 75% of the installation cost as proposed in this study for wider replication of the technology in all potential households.

- Anaerobic digestion of dung reduces the GHG emissions by reducing its decomposition for making compost in heaps as practised in rural Nepal, and bio-slurry replacing the chemical fertilisers. The biogas users lack knowledge and awareness about the importance of slurry application on reducing environmental emissions and increasing soil nutrition. The BSP-Nepal and biogas companies in coordination with the agricultural development agencies should carry out firmer efforts to train users on slurry application and handling to raise their level of awareness. Such training activities should also be included as a part of the post-installation support programme. Determining the nutrient value of the co-digested slurry, however, could be a subject of another research.

This study's findings have supported the hypothesis. Moreover, in light of the devastating earthquake (24/4/2015), these recommendations will further assist improving the energy supply situation in many affected rural households in Nepal and may be in some urban households too.

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Annexes

Annex 1: The Ethical Reports

(Information Sheets, Participant Consent Form and Confidentiality Agreement)

Annex 1.1: Information Sheet for an Individual Household

School of Engineering and Advanced Technology
Massey University, Palmerston North, New Zealand

You are kindly invited to participate in the research project entitled "**Domestic Biogas Production and Use in Nepal – A Simple, Reliable and Cost-Effective Solution to Provide Energy Security to the Rural Households**". This research aims to critically evaluate the biogas production efficiency and utilisation under the conditions that exist in Nepal, particularly in terms of feedstock availability and temperature; and looks at how the end uses of biogas can be made more efficient, hence reducing the demand for the biogas. The research is expected to be completed by April 2014.

The researcher, Shanti Kala Adhikari, is a doctoral student at the School of Engineering and Advanced Technology, Massey University, New Zealand. This research project is conducted in order to fulfil one of the requirements for the Doctor of Philosophy degree in Energy Management. The researcher is under the supervision of Prof Ralph E. Sims, Dr Phil Murray and Dr Rochelle Stewart-Withers.

The biogas user households have been selected for this research with the purpose of analysing biogas production efficiency, and examining demand and consumption pattern of biogas in rural households. Please be aware that the households for this research have been selected randomly using a simple random sampling design from the list of biogas user households in the district. A total of 165 households will be interviewed in each of the two districts as per the research sampling design.

You are kindly requested to participate voluntarily in the interview for not more than 1.5 hours. You are requested to provide information on your socio-economic characteristics such as household demography, land ownership, livestock, wealth and income, energy demand and consumption, biogas production and consumption, use and availability of feedstock, and role of biogas on reducing workload. At the end of the interview, you will be given the opportunity to edit, retract, or add to any of the comments you have made.

You are under no obligation to accept this invitation. If you decide to participate, you have the rights to:

- decline to answer any particular question;
- withdraw from the study at any time;
- ask any questions about the study at any time during participation;
- provide information on the understanding that your name will not be used unless you give permission to the researcher;

- be given access to a summary of the project findings when it is concluded.

The information provided by you will be used for analysis and interpretation to answer the research questions. A summary of key findings (in Nepali) will be communicated to you through relevant organisations (e.g., BSP-Nepal or Biogas Companies) after the completion of the research.

If you have any query with regard to this research, please contact the researcher or his supervisors in the address below:

Researcher's address in New Zealand
School of Engineering and Advanced Technology College of Sciences, Massey University Private Bag 11 222, Palmerston North New Zealand Tel.: +64 6 356 9099 ext. 7439 Email: S.Subedi@massey.ac.nz

Supervisors' address in New Zealand		
Prof Ralph E. Sims	**Dr Phil Murray**	**Dr Rochelle Stewart-Withers**
School of Engineering and Advanced Technology Massey University Private Bag 11 222 Palmerston North, New Zealand Tel.: +64 6 350 5288 Email: R.E.Sims@massey.ac.nz	School of Engineering and Advanced Technology Massey University Private Bag 11 222 Palmerston North, New Zealand Tel.: +64 6 350 5701 Email: P.Murray@massey.ac.nz	School of People, Environnent and Planning Massey University Private Bag 11 222 Palmerston North, New Zealand Tel.: +64 6 356 9099 extn 2464 Email: R.R.Stewart-Withers@massey.ac.nz

This project has been evaluated by peer review and judged to be low risk. Consequently, it has not been reviewed by one of the University's Human Ethics Committees. The researcher(s) named above are responsible for the ethical conduct of this research.

If you have any concerns about the conduct of this research that you wish to raise with someone other than the researcher(s), please contact Professor John O'Neill, Director, Research Ethics, telephone 06 350 5249, email: humanethics@massey.ac.nz.

Annex 1.2 Information Sheet for Key Informant

(Government/Non-Government Agency)

School of Engineering and Advanced Technology
Massey University, Palmerston North, New Zealand

You are kindly invited to participate in the research project entitled "**Domestic Biogas Production and Use in Nepal – A Simple, Reliable and Cost-Effective Solution to Provide Energy Security to the Rural Households**". This research aims to critically evaluate the biogas production efficiency and utilisation under the conditions that exist in Nepal, particularly in terms of feedstock availability and temperature; and looks at how the end uses of biogas can be made more efficient, hence reducing the demand for the biogas. The research is expected to be completed by April 2014.

The researcher, Shanti Kala Adhikari, is a doctoral student at the School of Engineering and Advanced Technology, Massey University, New Zealand. This research project is conducted in order to fulfil one of the requirements for the Doctor of Philosophy degree in Energy Management. The researcher is under the supervision of Prof Ralph E. Sims, Dr Phil Murray and Dr Rochelle Stewart-Withers.

Please be aware that the key informants for this research have been selected from the organisations involved in the development and promotion of domestic biogas technology in Nepal, who can provide information regarding overall prospect of biogas development in Nepal, research outcomes, biogas related policy and plans, and opportunities and challenges for replication of biogas technology to the rural poor households. A total of about 20 key informants will be interviewed from different organisations. The key informants are selected randomly.

You are kindly requested to participate voluntarily in the interview for not more than 2 hours. You are requested to provide information on overall prospect of biogas development in Nepal, priorities that are intended to promote biogas technology to the rural poor people from the policy perspective, and opportunities and challenges for replication of biogas technology. You will be further requested to provide information on the roles and mechanisms of your organization on the development and replication of domestic biogas technology. At the end of the interview, you will be given the opportunity to edit, retract, or add to any of the comments you have made.

You are under no obligation to accept this invitation. If you decide to participate, you have the rights to:

- decline to answer any particular question;

- withdraw from the study at any time;
- ask any questions about the study at any time during participation;
- provide information on the understanding that your name will not be used unless you give permission to the researcher;
- be given access to a summary of the project findings when it is concluded.

The information provided by you will be used for analysis and interpretation to answer the research questions. A summary of key findings will be communicated to you after the completion of the research.

If you have any query with regard to this research, please contact the researcher or his supervisors in the address below:

Researcher's address in New Zealand

School of Engineering and Advanced Technology
College of Sciences, Massey University
Private Bag 11 222, Palmerston North
New Zealand
Tel.: +64 6 356 9099 ext. 7439
Email: S.Subedi@massey.ac.nz

Supervisors' address in New Zealand

Prof Ralph E. Sims	**Dr Phil Murray**	**Dr Rochelle Stewart-Withers**
School of Engineering and Advanced Technology	School of Engineering and Advanced Technology	School of People, Environnent and Planning
Massey University	Massey University	Massey University
Private Bag 11 222	Private Bag 11 222	Private Bag 11 222
Palmerston North, New Zealand	Palmerston North, New Zealand	Palmerston North, New Zealand
Tel.: +64 6 350 5288	Tel.: +64 6 350 5701	Tel.: +64 6 356 9099 extn 2464
Email: R.E.Sims@massey.ac.nz	Email: P.Murray@massey.ac.nz	Email: R.R.Stewart-Withers@massey.ac.nz

This project has been evaluated by peer review and judged to be low risk. Consequently, it has not been reviewed by one of the University's Human Ethics Committees. The researcher(s) named above are responsible for the ethical conduct of this research.

If you have any concerns about the conduct of this research that you wish to raise with someone other than the researcher(s), please contact Professor John O'Neill, Director, Research Ethics, telephone 06 350 5249, email: humanethics@massey.ac.nz.

Annex 1.3 Participant Consent Form - Individual

Massey University
School of Engineering and Advanced Technology
Massey University, Palmerston North, New Zealand

I have read the Information Sheet and have had the details of the study explained to me. My questions have been answered to my satisfaction, and I understand that I may ask further questions at any time.

I agree to participate in this study under the conditions set out in the Information Sheet.

Signature: .... **Date:** ....

Full Name ....

Annex 1.4 Confidentiality Agreement

MASSEY UNIVERSITY

School of Engineering and Advanced Technology
Massey University, Palmerston North, New Zealand

I ……………………………………………………………………… agree to keep confidential all information concerning the project "Domestic Biogas Production and Use in Nepal – A Simple, Reliable and Cost-Effective Solution to Provide Energy Security to the Rural Households"

I will not retain or copy any information involving the project.

Signature: ……………………………………………… **Date:** ……………………………

Annex 2: Field Visit Schedule

SN	Activities	May-12	Jun-12				Jul-12				Aug-12				Sep-12				Oct-12				Nov-12				Dec-12				Jan-13				Feb-13				Mar-13		
		4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3
1	Travel to Nepal, Familiarization Meeting with officials from BSP-Nepal	■																																							
2	Visit to family and friends		■																																		■				■
3	Meetings with district-based biogas construction companies for final planning and preparation of field visit			■																																					
4	Data collection																																								
	Pre-testing of survey questionnaires				■																																				
	Questionnaire finalisation, translation into Nepali and printing				■																																				
	Biogas user household survey (summer)					■	■	■	■	■	■	■	■	■	■	■	■																								
5	Final checking of completed questionnaire and data entry (summer)																		■	■	■	■																			
6	Biogas user household survey (winter)																						■	■	■	■	■	■	■	■	■	■	■	■							
7	Sharing of the initial findings with BSP-Nepal and biogas construction companies																	■																	■						
8	Key informants interviews																	■	■	■															■	■					
9	Data entry (winter)																																					■	■	■	
10	Travel back to Massey																																								■

Annex 3: Example of Biogas User Household Database from the BSP-Nepal

DISTRICT:CHITWAN

Fiscal Year	Company	Plant Code	Ward	VDC / Municipality	Size (m^3)	Subsidy Amount (Rs.)
2051/2052	BUB	BUBBHA510001	9	Bharatpur N.P.	10	7000
2051/2053	BUB	BUBBHA510002	13	Kailash Nagar	10	7000
2051/2054	BUB	BUBBHA510003	5	Gunjanagar	10	7000
2051/2055	BUB	BUBBHA510004	13	Bharatpur N.P.	10	7000
2051/2056	BUB	BUBBHA510005	6	Bharatpur N.P.	8	7000
2051/2057	BUB	BUBBHA510006	12	Bharatpur N.P.	10	7000
2051/2058	BUB	BUBBHA510007	12	Bharatpur N.P.	10	7000
2051/2059	BUB	BUBBHA510008	13	Bharatpur N.P.	10	7000
2051/2060	BUB	BUBBHA510011	2	Sukranagar	10	7000
2051/2061	BUB	BUBBHA510018	2	Bharatpur N.P.	10	7000
2051/2062	BUB	BUBBHA510022	8	Panchakanya	8	7000
2051/2063	BUB	BUBBHA510033	3	Patihani	10	7000
2051/2064	BUB	BUBBHA510034	4	Panchakanya	8	7000
2051/2065	BUB	BUBBHA510036	13	Bharatpur N.P.	10	7000
2051/2066	BUB	BUBBHA510039	12	Bharatpur N.P.	10	7000
2051/2067	BUB	BUBBHA510044	14	Bharatpur N.P.	10	7000
2051/2068	BUB	BUBBHA510045	6	Panchakanya	10	7000
2051/2069	BUB	BUBBHA510048	2	Ratnanagar N.P.	10	7000
2051/2070	BUB	BUBBHA510049	4	Panchakanya	8	7000
2051/2071	BBI	CGGBHA510001	9	Gitanagar	10	7000
DISTRICT: LAMJUNG						
2051/2052	GGC	GGCDUM510002	8	Chakratirtha	8	10000
2051/2052	GGC	GGCDUM510004	9	Chakratirtha	8	10000
2051/2052	GGC	GGCDUM510019	9	Besishahar	10	10000
2051/2052	GGC	GGCDUM510020	9	Besishahar	10	10000
2051/2052	GGC	GGCDUM510021	9	Besishahar	10	10000
2051/2052	GGC	GGCDUM510022	9	Hiletaksar	10	10000
2051/2052	GGC	GGCDUM510023	9	Hiletaksar	10	10000
2051/2052	GGC	GGCDUM510027	7	Gaunshahar	8	10000
2051/2052	GGC	GGCDUM510028	6	Gaunshahar	8	10000
2051/2052	GGC	GGCDUM510029	7	Gaunshahar	8	10000
2051/2052	GGC	GGCDUM510030	7	Gaunshahar	6	10000
2051/2052	GGC	GGCDUM510031	7	Gaunshahar	8	10000
2051/2052	GGC	GGCDUM510032	7	Gaunshahar	8	10000
2051/2052	GGC	GGCDUM510033	7	Gaunshahar	6	10000
2051/2052	GGC	GGCDUM510034	7	Gaunshahar	6	10000
2051/2052	GGC	GGCDUM510035	7	Gaunshahar	8	10000
2051/2052	GGC	GGCDUM510036	7	Gaunshahar	8	10000
2051/2052	GGC	GGCDUM510037	7	Gaunshahar	8	10000
2051/2052	GGC	GGCDUM510038	7	Gaunshahar	8	10000
2051/2052	GGC	GGCDUM510039	7	Gaunshahar	6	10000
2051/2052	GGC	GGCDUM510040	6	Besishahar	10	10000
2051/2052	GGC	GGCDUM510041	7	Gaunshahar	6	10000

Annex 4: List of the Sampled Households

Household ID	Plant Code	VDC	Ward No.	Village name
District: Chitwan				
13759	RGGCHI660022	Ayodhyapuri	5	Kharkatta
6112	RGGBHA580077	Ayodhyapuri	8	Krishnanagar
9622	NKGCHI620012	Ayodhyapuri		Govindabasti
8118	HEDCHI 610024	Bachauli	7	Jankali
973	KGYTAD 530012	Bachauli	7	Bachauli
10437	HEDCHI 630044	Bachauli	9	Taraili
3480	BBIBHA 650132	Bachauli	6	Bachauli
4984	JGGBHA570112	Bachauli	8	Bachauli
9309	HEDCHI620015	Bachauli	9	Jhuwani
5674	GGCBHA 580010	Bagauda	9	Nayapipara
11315	GGCCHI 640029	Bagauda	9	Inarbaruwa
10374	GGCCHI 630053	Bagauda	8	Brahmmapuri
1976	NKGBHA540150	Bagauda	4	Sitalpur
14072	BBICHI 670022	Bhandara	9	Bagar
2164	RGGBHA 540122	Bhandara	1	Bhandara
785	GGCBHA 530088	Bhandara	8	Bhandara
12631	RGGCHI 650028	Bhandara	8	Dhaduwa
3982	NKGBHA 560021	Bhandara	1	Bhandara
5172	RGGBHA570023	Bhandara	7	Bhandara
3038	NKGBHA 550101	Bharatpur Municipality	11	Bharatpur
284	GGCBHA520003	Bharatpur Municipality	5	Bharatpur
8306	JGGCHI 610054	Bharatpur Municipality	5	Laxmipur
2289	RGGCHA540295	Bharatpur Municipality	6	Sano Yagyapuri
8870	RGGCHI610291	Bharatpur Municipality	8	Gauriganj
6865	RGGBHA590052	Bharatpur Municipality	8	Gauriganj
12505	NKGCHI650004	Bharatpur Municipality	2	Jaldevi Tole
8682	RGGCHI610092	Bharatpur Municipality	13	Anandpur
10938	RGGCHI630154	Bharatpur Municipality	8	Healthpost Chowk
5110	NKGBHA570159	Bharatpur Municipality	12	Sarvodaya Tole
8557	NKGCHI610093	Bharatpur Municipality	11	Pragati YC tole

Household ID	Plant Code	VDC	Ward No.	Village name
14762	RGGCHI670138	Bharatpur Municipality	13	Anandpur
10813	RGGCHI630026	Bharatpur Municipality	9	Sharadpur
7053	RGGBHA590256	Bharatpur Municipality	5	Sikhartole
8494	NKGCHI610030	Bharatpur Municipality	7	Annapurnachowk
2665	HGGBHA550024	Bharatpur Municipality	6	Tribhuvan Chowk
8933	RGGCHI 610362	Birendranagar	4	Bajarhatti
1788	KGYTAD 540001	Birendranagar	5	Birendranagar
5924	JGGBHA 580063	Chainpur	7	Lahari
10061	RGGCHI620315	Chainpur	3	Ramkola
5611	BUBBHA 580057	Chainpur	1	Baderi
14574	NIACHI 670117	Darechowk	3	Kurintar
7930	BBICHI610181	Divyanagar	9	Rodigaun
8369	JGGCHI610137	Divyanagar	8	Rodigaun
9058	BBICHI620064	Divyanagar	9	Khatraili
4232	RGGBHA560193	Gardi	3	Bhairavpur
13822	RGGCHI660087	Gardi	4	Bankatta
33	GGCBHA 510008	Gardi	8	Gardi
3668	HGGBHA560008	Gitanagar	5	Pulhar
3104	PGCCHI550019	Gitanagar	5	Ammarbasti
9873	RGGCHI620125	Gitanagar	4	Devnagar
5736	HGGBHA580006	Gitanagar	8	Indrapuri
9810	RGGCHI620062	Gitanagar	4	Devnagar
12819	RGGCHI650223	Gitanagar	6	Kesharbag
8181	HGGCHI610034	Gitanagar	2	Champanagar
8745	RGGCHI610156	Gitanagar	5	Ammarbasti
6489	HGGBHA590016	Gitanagar	1	Ujwalnagar
15012	RGGCHI680033	Gitanagar	6	Kataharbag
2227	RGGBHA 540222	Gitanagar	8	Gitanagar
6677	JGGBHA590097	Gunjanagar	4	Bhimnagar
10562	JGGCHI630120	Gunjanagar	3	Purba Bhimnagar
5862	JANBHA580058	Gunjanagar	8	Lagauti
12129	BUBCHI650012	Jagatpur	2	Jagatpur
4922	JGGBHA570049	Jagatpur	2	Kumarichowk

Household ID	Plant Code	VDC	Ward No.	Village name
3856	JGGBHA560042	Jagatpur	2	Jagatpur
1224	RGGBHA530159	Jutpani	5	Jamunapur
1663	JANBHA540046	Jutpani	6	Suryapur
5298	RGGBHA570179	Jutpani	4	Saguntole Bhateni
12192	JGGCHI 650012	Jutpani	5	Jamunapur
11377	JGGCHI640028	Jutpani	6	GaBiSa Chowk
12693	RGGCHI650095	Kalyanpur	5	Kirtanpur
1161	RGGBHA530086	Kalyanpur	8	Gopalnagar
14950	BBICHI680116	Kalyanpur	1	Basantapur
10186	BBICHI630107	Kalyanpur	4	GaBiSa Chowk
3292	RGGBHA550223	Kalyanpur	5	Kalyanpur
12004	BBICHI 650063	Kalyanpur	4	Kalyanpur
13007	BBICHI 640044	Kalyanpur	1	Basantapur
11879	RGGCHI640255	Kalyanpur	3	Kirtanpur
14511	JGGCHI 670204	Khairani	5	Laltinnagar
11126	BBICHI 640037	Khairani	5	Sutarna
13383	JGGCHI660094	Khairani	8	Sasauli
2540	BUBBHA550061	Khairani	7	Khairahani
13320	JGGCHI660010	Khairani	7	Tulsipur
4546	BUBBHA570119	Khairani	8	Khaireni
14323	HEDCHI 670032	Komroj	7	Sishani
13257	HEDCHI 660029	Kumroj	2	Simarahani
8619	RGGCHI610027	Mangalpur	2	Rampur
848	JANBHA530015	Mangalpur	8	Vijaynagar
10500	JGGCHI630035	Mangalpur	6	Dandaghari
6927	RGGBHA590117	Mangalpur	8	Vijaynagar
14448	JGGCHI670134	Mangalpur	6	Dhandadhari
1036	NKHBHA530005	Mangalpur	5	Prempur
6050	PGCCHI580076	Mangalpur	5	Mangalpur
9497	JGGCHI620133	Mangalpur	4	Fulichowk
4796	JANBHA570055	Mangalpur	5	Brahmapur
9434	JGGCHI 620029	Mangalpur	5	Bhahampapur
6614	JGGBHA590024	Pithuwa	7	Madhavpur

Household ID	Plant Code	VDC	Ward No.	Village name
14887	RGGCHI670276	Meghauli	5	Patani
7366	HGGCHI600093	Padampur	3	Pokhariya Naya Padampur
9685	NKGCHI 620075	Padampur	2	Jitpur
10750	NKGCHI 630092	Padampur	3	Road, No.1
221	RGGBHA 510104	Panchakanya	8	Panchakanya
7241	BUBCHI600051	Parbatipur	8	Parilotar
472	NKGBHA520021	Parbatipur	6	Ratanpur
7805	BBICHI610054	Parbatipur	8	Parilotar
10249	BBICHI630171	Parbatipur	6	Ratanpur
9246	BUBCHI 620081	Parbatipur	8	Paharilotar
597	RGGBHA20084	Parbatipur	6	Parbatipur
409	KGYTAD 520026	Parsakhaireni	7	Parsakhaieni
7617	RGGCHI600066	Patihani	5	Barauji
4170	RGGBHA560127	Patihani	4	Sunderbasti
7554	PGCCHI600033	Patihani	8	Ganganagar
14824	RGGCHI670208	Patihani	4	Sundarchowk
8243	JANCHI610039	Phulbari	7	Ganeshganj
2916	JGGBHA550150	Phulbari	6	Mahendrachowk
5047	NKGBHA570048	Phulbari	5	Mahendrachowk
14010	RGGCHI660289	Phulbari	5	Mahendrachowk
13884	RGGCHI660153	Phulbari	6	Ganeshganj
2853	JGGBHA550081	Phulbari	7	Phulbari
11691	RGGCHI 640032	Piple	7	Kailashpuri
11001	RGGCHI630217	Pithuwa	6	Madhavpur
4358	BBIBHA 570103	Pithuwa	7	Pithuwa
9121	BBICHI620162	Pithuwa	5	Dobato
14135	BBICHI 670106	Pithuwa	2	Dobato
96	GGCBHA510104	Pithuwa	7	Pithuwa
12067	BBICHI 650127	Pithuwa	5	Bramatol
13633	NIACHI 660072	Pithuwa	5	Parijat
6238	BBIBHA590005	Pithuwa	5	Dhamalatol
14699	RGGCHI 670071	Pithuwa	8	Madhabpur

Household ID	Plant Code	VDC	Ward No.	Village name
13195	BBICHI 660440	Pithuwa	3	Madhabpur
2477	BBIBHA 550185	Pithuwa	9	Pithuwa
1725	JGGBHA540037	Pithuwa	8	Pithuwa
14198	BBICHI 670182	Ratnanagar	10	Jirauna
12255	JGGCHI 650091	Ratnanagar	10	Jirauna
4420	BBIBHA 570167	Ratnanagar	13	Ratnanagar
3229	RGGBHA550136	Ratnanagar	9	Gheghauli
1600	HGGBHA540017	Ratnanagar	8	Ratnanagar
158	KGYTAD510005	Ratnanagar Minicipality	1	Shantichowk
6802	PGCCHI590046	Ratnanagar Minicipality	10	Jirauna
6426	BUBBHA590058	Ratnanagar Minicipality	8	Kailash
6301	BBIBHA590068	Ratnanagar Minicipality	9	Salghari
13947	RGGCHI 660225	Saktikhor	2	Safriya
11941	RGGCHI 640319	Shardanagar	2	Rampur
12881	RGGCHI650288	Shardanagar	2	Shardanagar
1537	GGCBHA540065	Shardanagar	2	Shardanagar
4044	PGCCHI560016	Shardanagar	3	Shardanagar
6363	BBIBHA590131	Shivanagar	2	Jaynagar
13696	NKGCHI660057	Shivanagar	9	Hanumannagar
5548	BBIBHA580097	Shivanagar	5	Shivanagar
9998	RGGCHI620251	Shivanagar	8	Shantipur
9560	JGGCHI620217	Shivanagar	2	Jaynagar
11440	JGGCHI640102	Shivanagar	1	Bhagawanpur
12380	JGGCHI650226	Shivanagar	2	Jaynagar
10625	JGGCHI630193	Shivanagar	8	Bhimsennagar
14386	JGGCHI670046	Sukranagar	1	Sankarchown
7429	JGGCHI600003	Sukranagar	2	Amritnagar
7993	BUBCHI610020	Sukranagar	1	Bisalchowk
5360	RGGBHA570256	Sukranagar	2	Sukranagar

Household ID	Plant Code	VDC	Ward No.	Village name
District: Lamjung				
3722	KAMLAM 590051	Archalbot	5	Nimote
8084	SUGLAM 680008	Archalbot	9	Sankhara
6380	NIPLAM 650007	Archalbot	5	Dhale Chautara
2972	RGGDUM570504	Archalbot	8	Archalbot
3176	KAMLAM 570138	Archalbot	4	Alam
1745	KAMLAM 560046	Archalbot	8	Archalbot
3210	KAMLAM 580172	Archalbot	8	Khalte
3926	RGGDUM 590001	Bajhakhet	7	Dandagaun
2052	RGGDUM 560185	Bajhakhet	8	Bahakhet
6175	SUGLAM 640049	Bajhakhet	7	Bhotephant
4540	LGGLAM 610006	Bajhakhet	7	Dandagaun
1336	JGGLAM 550017	Bajhakhet	8	Dandagaun
7709	PGGTAH670679	Bangre	1	Banrebeshi
961	GGGLAM540001	Beshisahar	3	Baluwatar
1472	RGGDUM550013	Beshisahar	2	Campus Chowk
5971	RGGTAH 640166	Beshisahar	6	Upallobari
2188	RGGDUM560412	Beshisahar	6	Beshisahar
3994	RGGDUM590126	Beshisahar	6	Dhanbanse
6482	RGGTH650022	Beshisahar	9	Tallopakhathok
280	RGGDUM 510049	Beshisahar	2	Beshisahar
1506	RGGDUM 550118	Beshisahar	4	Beshisahar
3415	RGGDUM 580058	Beshisahar	7	Kolbete
1132	NGGDUM 540042	Bhalayakharka	3	Sailitar
7913	RGGTAH 670427	Bhalayakharka	3	Sailitar
1643	BBIGOR 560063	Bhalayakharka	1	Sailitar
518	RGGDUM 520064	Bhalayakharka	3	Sailitar
1132	NGGDUM 540042	Bhalayakharka	3	Sailitar
7402	RGGTAH 660348	Bhalayakharka	6	Bogatigaun
7982	SUGLAM 670044	Bhalayakharka	9	Dambardhunga
5119	NIPLAM 620003	Bharte	5	Lamiswara
1779	KAMLAM 560088	Bharte	5	Bharte

Household ID	Plant Code	VDC	Ward No.	Village name
4505	GGCTAH 610004	Bhorletar	6	Bhorletar Bazar
4505	GGCTAH 610004	Bhorletar	8	Charsaya
382	GGCPOK520134	Bhorletar	6	Bhorletar Bazar
143	HGGBHA 510042	Bhorletar	6	Bhorletar
7879	RGGTAH 670391	Bhorletar	6	Tallotar
5630	RGGTAH630126	Bhorletar	6	Tallotar
3653	GGCPOK 590140	Bhorletar	6	Bhorletar bazar
4131	RGGDUM 590427	Bhorletar	6	Bhorletar Bazar
3279	LGGLAM 580011	Bhotewodar	3	Akalachowk
620	RGGDUM, 520053	Bhotewodar	4	Akalachowk
6141	SUGLAM 640015	Bhotewodar	9	Pahire
552	NGGLAM520042	Bhotewodar	9	Bhotewodar
3006	RGGDUM 570557	Bhotewodar	9	Siudibar
4301	NPLAM 600048	Bhotewodar	8	Bagaichha
4710	NIPLAM 610045	Bhotewodar	9	Phulbari
6346	MBGTAH 650103	Bhotewodar	5	Dhokeswara
6687	SUGLAM 650017	Bhotewodar	9	Phedikuna
7607	MKGKAS 670055	Bichaur	6	Marhathatol
1268	BBIGOR 570023	Chakratirtha	6	Kumalgaun
8118	SUGLAM 680043	Chakratirtha	9	Boragaun
211	NGGLAM 510018	Chakratirtha	1	Chakratirtha
2290	BBIGOR570023	Chakratirtha	1	Chakratirtha
4948	RGGTAH 610345	Chakratirtha	8	Tinpiple
7061	MBGTAH 660057	Chandisthan	1	Sera
314	RGGDUM 510095	Chandisthan	3	Chandisthan
5869	NIPLAM640038	Chandisthan	9	Chanaute
5937	RGGTAH 640098	Chandisthan	2	Golthok
2904	RGGDUM 570424	Chandreshwor	9	Duradanda
3517	RGGDUM 580250	Chandreshwor	9	Okhlepani
7368	RGGTAH 660313	Chandreshwor	6	Swara
1370	JGGLAM 550051	Chiti	3	Tilahar
1029	JGGLAM 540057	Chiti	3	Tilahar

Household ID	Plant Code	VDC	Ward No.	Village name
348	RGGDUM 510161	Chiti	8	Chiti
4608	LGGLAM 610075	Chiti	3	Tilahar
450	JGGLAM 520050	Chiti	8	Chiti
1063	JGGLAM 540091	Chiti	2	Chiti
2597	LGGLAM 570036	Chiti	7	Chiti
3313	LGGLAM 580044	Chiti	8	Hatiyatol
4233	LGGLAM 600026	Chiti	1	Basnetgaun
5051	LGGLAM 620003	Chiti	7	Ramchowk Beshi
5528	NIPLAM630032	Chiti	7	Ramchowk Beshi
6959	EGCMAN 660138	Chiti	4	Gairthok
7573	MBGTAH 670082	Chiti	7	Ramchowk Beshi
4914	RGGTAH 610271	Dhamilikuwa	2	Dhamilikuwa
859	NGGDUM 530061	Dhamilikuwa	3	Majhhatiya
7266	RGGTAH 660124	Dhamilikuwa	5	Dhamilikuwa
927	RGGDUM530110	Dhamilikuwa	7	Salphedi
6584	RGGTAH 650239	Dhamilikuwa	7	Salphedi
4812	RGGTAH 610111	Dhamilikuwa	1	Bagargaun
1575	RGGDUM 550237	Dhamilikuwa	4	Dhamilikuwa
41	GGCDUM510072	Dhamilikuwa	8	Dhamilikuwa
2393	KAMLAM570080	Dhamilikuwa	8	Dhamilikuwa
3074	KAMLAM 580026	Dhodeni	1	Majhgaun
3108	KAMLAM 580060	Dhodeni	1	Dhodeni
3688	KAMLAM 590017	Dhodeni	1	Saranchowk
1541	RGGDUM 550176	Dhuseni	9	Dhuseni
5426	HEDLAM 630030	Dhuseni	9	Dhauseni
6278	HEDLAM 650021	Dhuseni	9	Dhuseni
6652	RGGTAH 650369	Dhuseni	6	Katunje
4437	RGGTAH 600203	Duradanda	6	Archelyani
6550	RGGTAH 650204	Duradanda	5	Milanbasti
7300	RGGTAH 660170	Gaunshahar	8	Dhand
2563	LGGLAM 570002	Gaunshahar	6	Bhakunde
3449	RGGDUM 580131	Gaunshahar	8	Pakhathok
416	JGGLAM 520016	Gaunshahar	7	Gaunsahar

Household ID	Plant Code	VDC	Ward No.	Village name
1234	RGGDUM 540193	Gaunshahar	6	Gaunsahar
757	JGGLAM 630080	Gaunshahar	7	Gaunsahar
7095	MBGTAH 660091	Gaunshahar	1	Thumkadanda
7	GGCDUM 510023	Hiletaksar	9	Takasara
109	GGCDUM 510170	Hiletaksar	9	Hiletaxar
1881	LGGLAM 560009	Hiletaksar	9	Hiletaxar
7675	MUCLAM670171	Ilampokhari	5	Tarja gaun
8016	SUGLAM 670078	Ilampokhari	7	Ghardhunga
3483	RGGDUM 580165	Isaneshwor	2	Laxmi bazar
6039	RGGTAH 640285	Isaneshwor	9	Aryang
5323	RGGTAH 620257	Isaneshwor	3	Chisanku
4642	MBGTAH 610036	Jita	6	Gairigaun
2461	KAMLAM 570154	Jita	7	Jita
4403	RGGTAH 600152	Khudi	1	Tarapu
5255	RGGTAH620114	Khudi	1	Tarapu
2495	KAMLAM 570190	Kolki	3	Kolki
6993	EGCMAN 660188	Kolki	9	Archale
7470	EGCMAN 670007	Kolki	9	Bhansar
3619	RGGDUM 580398	Kunchha	7	Bhaluwafedi
3585	RGGDUM 580334	Kunchha	7	Khamariot
5153	NIPLAM 620039	Nauther	5	Jitaure
7504	EGCMAN 670069	Nauther	2	Bagkaule
5732	SUGLAM 630028	Nauther	2	Ramailophant
6857	EGCMSN 660015	Neta	5	Bhanjyang
5766	HEDLAM 640016	Neta	3	Neta
4846	RGGTAH 610173	Parewadanda	5	Bertole
246	NGGLAM 510055	Parewadanda	2	Parewadanda
5664	RGGTAH 630218	Parewadanda	2	Hadetar
6891	EGCMAN660052	Parewadanda	5	Khadkagaun
4335	RANLAM 600031	Parewadanda	9	Parewadanda
825	KAMLAM530023	Rainasmohoriyakot	8	Mohoriyakot
4744	RANLAM 610025	Rainasmohoriyakot	3	Dandabari
1847	KAMLAM 560160	Rainasmohoriyakot	8	Ramkot

Household ID	Plant Code	VDC	Ward No.	Village name
1302	JGGDAM55OO25	Ramgha	9	Ramgha
4199	JGGTAH 600037	Ramgha	7	Thulo Kumalgaun
1677	JGGDAM 560011	Ramgha	9	Ramgha
5017	SUGLAM610021	Shreebhanjyang	8	Handikhola
3790	KAMLAM 590138	Shreebhanjyang	2	lamagaun
5221	RGGTAH 620049	Simpani	7	Bagarphant
1438	NGGLAM 550010	Sundarbazar	4	Sundarbazar
3892	NGGLAM 590068	Sundarbazar	6	Phedikuna
1166	NGGLAM 540037	Sundarbazar	4	Sundarbazar
2018	RGGDUM 560126	Sundarbazar	6	Sundarbazar
5835	MUCTAH 640063	Sundarbazar	9	Sahakale
3381	NGGLAM 580037	Sundarbazar	9	Tarkutar
2256	RGGDUM560487	Sundarbazzar	8	Sundarbazzar
7164	MUCLAM 660086	Sundarbazzar	8	Sundarbazzar
2154	RGGDUM 560360	Sundarbazzar	5	Sundarbazzar
1984	RGGDUM 560070	Sundarbazzar	4	Sundarbazzar
6448	PGGTAH650502	Suryapal	9	Suryapal
5562	PGGTAH 630298	Suryapal	6	Mohoriyatol
2086	RGGDUM 560248	Suryapal	6	Suryapal
2767	RGGDUM 570147	Suryapal	9	Suryapal
7198	MUCLAM 660171	Tarkughat	5	Harrabot
2358	KAMLAM 570006	Tarkughat	1	Majhigaun
2836	NGGLAM 570060	Tarkughat	5	Pangrephant
5596	RGGTAH 630062	Tarkughat	2	Harrabot
4097	RGGDUM 590367	Tarkughat	2	Katahrbari
1950	RGGDUM 560022	Udipur	2	Gaikhuri
6789	SUGLAM 650137	Udipur	8	Nayagaun
2801	RGGDUM 570208	Udipur	1	Udipur

Annex 5: Household Survey Questionnaire

Interviewee: Household ID:
Date of interview: Address: District: VDC: Ward No.:
Start time: End time: Village:
Data checked by: Elevation: Mean Temperature
Data entry by: Summer Winter:

Household Characteristics

1 Family size ....
2 Ethnicity ....
3 Number of livestock
    Cow/cattle ....
    Buffalo ....
    Goat/sheep ....
    Pig ....
    Chicken ....
    Other (specify, ...) ....

4 Landholding size (ha) ....
5 Major occupation/income source ....

6 Access to electricity (Yes/No) ....

7 Electricity Source ....

8 Electricity price per kWh ....

9 Distance from forest (km) ....

10 Distance from local market (km) ....

Energy Use Pattern

11 What energy source do you use for cooking (except biogas)?

	Before Biogas	After Biogas	(per unit price or labour cost for collection)
Fuelwood (kg/month)	....	....	....
Kerosene (litre/month)	....	....	....
Agricultural residues (kg/month)	....	....	....
Dung cake (kg/month)	....	....	....
LPG (cylinder/month)	....	....	....
Electricity (kWh/month)	....	....	....
Solar power	....	....	
Other (specify, ...)	....	....	

12 What energy sources are used for lighting (except biogas)?

	Before Biogas	After Biogas	(per unit price)
Kerosene (litre/month)	....	....	....
Electricity (kWh/month)	....	....	....

Solar light	....	....	....
Candle	....	....	....
Other (specify, ...)	....	....	....

13 What is the daily energy use pattern (on hourly basis)?

Hour 5:00 - 6:006:00 - 7:00		7:00 - 8:008:00 - 9:00	9:00 - 10:0010:00-11:00 11:00 - 12:00
Energy type	Firewood		
Use	Tea		
Appliances	Pan		
Time (min)	20 min		
Total energy	....		

Hour 12:00-13:0013:00-14:00	14:00-15:0015:00-16:00	16:00-17:0017:00-18:0018:00-19:00
Energy type		
Use		
Appliances		
Time (min)		
Total energy		

Hour19:00-20:0020:00-21:00	21:00-22:0022:00-23:00	23:00-00:0000:00-01:0001:00-02:00
Energy type		
Use		
Appliances		
Time (min)		
Total energy		

Biogas Plant

14 Type and size of biogas plant ....

15 Year constructed ....

16 Use of biogas ....

17 No. of biogas stove

18 No. of biogas lamps

19 System of digester heating or insulation ....

20 Soil type (of digester location) ....

21 Is toilet attached with the biogas digester? ....

Feedstock Availability for Biogas

22 Total quantity of feedstock needed (kg/day) Summer .... Winter ....

23 Daily feedstock available/fed into the digester (kg/day)

	Available SummerWinter	Fed into digester SummerWinter	Cost (if bought)
Cattle dung	....	....	....
Buffalo dung	....	....	....
Goat/sheep dung	....	....	....
Poultry manure	....	....	....
Kitchen waste	....	....	....
Human waste	....	....	....
Others (................................)	....	....	....

24 What is the proportion of water used in the substrate (% or volume)? ....

25 Are you using or are there any other organic materials available to use as feedstock? ....

If yes, what are they, how much is available and what would be the cost?

Type of material	Quantity (kg/day) SummerWinter		per unit cost or labour hours
....	....	....	....
....	....	....	....

26 Do you store feedstock when it is surplus? (Yes/No) If yes, what and how do you store it?

Type of material	Storing process	Quantity (kg)
....	....	....
....	....	....
....	....	....

27 How are the agricultural residues used now?

Type	quantity (kg/day)	Use
....	....	....
....	....	....
....	....	....

28 If agricultural residues are used as feedstock, what would be the implications on previous or other potential uses?

....
....

Anticipated Biogas Demand

29 Biogas demand for cooking <u>Colder Season (Oct - Feb)Warm Season (Mar - Sep)</u>
Number of burners available <u>1 23123</u>
Specific gas consumption per burner ....
Required cooking time (hour) ....
Total daily gas demand for cooking ....

30 Biogas demand for lighting <u>Colder Season (Oct - Feb)Warm Season (Mar - Sep)</u>
Number of lamps in use <u>1 23123</u>
Specific gas consumption per lamp ....
Actual duration of lamp operation (hour) ....
Total daily gas demand for lighting ....

Actual Biogas Availability

31 Daily biogas availability for cooking <u>Colder Season (Oct - Feb)Warm Season (Mar - Sep)</u>
Number of burner in use <u>1 23123</u>
Type of burner (stove) in use ....

Specific gas consumption per burner	....	....	....	....	....	....
Duration of burner operation (hour)	....	....	....	....	....	....
Total daily biogas available for cooking	....			....		

32 Average daily biogas available for consumption for lighting

		Colder Season (Oct - Feb)		Warm Season (Mar - Sep)		
Number of lamps in use	1 23123					
Type of lamp in use	....	....	....	....	....	....
Specific gas consumption per lamp	....	....	....	....	....	....
Duration of daily lamp operation (hour)	....	....	....	....	....	....
Total daily biogas available for lighting	....			....		

Biogas Surplus/Deficit and Measures to Increase Biogas Production

	Responded	Calculated	Difference
33 Total annual biogas surplus/deficit for cooking			
During warm season	....	....	....
During cold season	....	....	....
Total surplus/deficit	....	....	....
34 Total annual biogas surplus/deficit for lighting			
During warm season	....	....	....

During cold season	....	....	....
Total surplus/deficit	....	....	....

35 What could be the reasons for low biogas production?

....

....

36 Have you applied any measures to increase biogas production? Yes / No

If yes, what are they? ....

....

If not, why not? ....

....

37 Have you applied any solution options to increase temperature of the digester during winter? Yes / No

If yes, what are they? ....

....

If not, why not? ....

....

38 Are you facing any technical problem related to low biogas production (e.g.,leakage, blockage, ineffective appliances, plant size, colder climate) Yes / No

If yes, what are they? ....

....

39 Is there any difference in performance of biogas plant in terms of gas production with its age? Yes/ No

If yes, what are the differences (e.g., lower/higher gas production) ....

....

Economic Assessment of Biogas and Alternative Energy Systems

		Biogas	Solar cooker	Solar light
40	System Type	Biogas	Solar cooker	Solar light
41	Life cycle period/ Age of system	....	....	....
42	Total costs of the system			
	(a) Subsidy	....	....	....
	(b) Installation costs (cash + labour)	....	....	....
	(c) Annual maintenance and repair Costs	....	....	....
	(d) Annual operation cost (labour+material)	....	....	....
	(e) Other cost (e.g., cost due to change in animal husbandry practice)	....	....	....
43	Total income from the system			
	Energy related revenues (value of displaced fuels)	....	....	....
	Income from utilisation of saved time (e.g., cooking time, fuelwood collection)	....	....	....
	Income from replacing chemical fertiliser and increased agriculture productivity	....	....	....

Other income (specify, ...) ....

Biogas for Reducing Women's Workload

44 Time allocation before and after biogas plant installation

	Before biogas			After biogas		
	Adult male	Adult female	Child	Adult male	Adult female	Child
Livestock caring	....	....	....	....	....	....
Fetching water	....	....	....	....	....	....
Feeding biogas plant				....	....	....
Collecting fuelwood/dung cake/ ag Residue	....	....	....	....	....	....
Cooking	....	....	....	....	....	....
Washing utensils	....	....	....	....	....	....
Fodder collection	....	....	....	....	....	....

45 How do you utilise any saved time? ....

46 If used in income generating or productive activities, what are they?

....

....

THANK YOU FOR YOUR TIME AND CONTRIBUTION

Annex 6: Relevant organisations and number of key informants interviewed

Organisation	Number	Energy relevant program focus
BSP-Nepal	3	Develops and promotes appropriate rural and renewable energy technologies, particularly biogas; effective in improving livelihood of the rural people.
Alternative Energy Promotion Centre (AEPC)	2	Acts as an intermediary institution between the private promoters of renewable energy and the policy decision levels in relevant ministries; and is responsible for energy policy formulation, planning and facilitating the implementation of the policies/plans; manages and operates the credit fund.
SNV-Nepal	1	Focuses on increasing access to renewable energy solutions for rural and remote communities through programmes like improved cookstoves, biogas and improved watermills.
KfW (German Development Bank)	1	Provides financial support, which mainly backs the subsidies for the biogas plants.
Winrock International Nepal	1	Works to increase financing in clean energy working with the government and other national level household energy programmes to mobilize micro-finance institutions and provides credit for rural energy technologies.
UN-Habitat	1	Provides financial support for solid waste management, including biogas from municipal solid waste.
National Biogas Promotion Association (NBPA). Kathmandu	1	An umbrella organization by and for the biogas construction companies, aimed for the sustainability of the biogas development programme, and is active in the promotion, coordination, R&D, and training of biogas technology.
Centre for Energy Studies, Institute of Engineering, Lalitpur	1	Building capacity of energy systems planning and analysis for developing sustainable energy policies; studies on biogas storage system, efficiency of biogas stoves and biogas from hospital waste.
World Wildlife Fund (WWF)	1	Promotes alternative energy sources including biogas to reduce deforestation and lower carbon emissions.
Alternative Energy Programme, DDC Lamjung	1	Aims to improve the living conditions of the rural population by enhancing their access and affordability to rural energy solutions that are environment friendly.
Nepal Urja Bikas Company Pvt. Ltd., Kathmandu	1	Manufacturing, supply, installation and maintenance of renewable energy sources such as solar photovoltaic systems, solar inverters, renewable energy system batteries.

Organisation	Number	Energy relevant program focus
Biogas construction companies (Rastriya Gobar Gas Company, Tanahun and Chitwan; Marsyangdi Gobar Gas Company, Lamjung; Lamjung Gobar Gas Company, Lamjung; Janata Urja Bikas Company, Chitwan; Biogas tatha Urja Bikas Company, Chitwan)	6	Construction of biogas plants and provision of after-sale services.
Micro finance company (Jyoti Mahila Bikas Saving and Credit Cooperative Society Ltd., Chitwan)	1	Financing domestic biogas plants through micro-credit programme (work under the AEPC credit fund scheme).

Annex 7: Checklists for key informants interview

Checklist for Central Level Organisations

1. The organisations' role in the development and replication of domestic biogas technology.
2. Reasons for insufficient biogas production to meet the energy demand of a rural household for cooking and lighting.
3. Plan or strategy to increase biogas production efficiency in cold climate regions or during winter.
4. Factors for low performance of biogas plants: is insufficient feedstock or mono-digestion of cattle dung a factor? If so, how can the performance be improved?
5. Potential of co-digestion of other organic materials with animal dung to meet the feedstock requirement and increase biogas production efficiency.
6. Facility (and associated costs) to store the surplus biogas produced (if any) in rural poor households.
7. Efficiency of biogas appliances compared with other similar appliances (e.g., biogas vs LPG stove).
8. Any plan or strategy for integrating other renewable energy sources (e.g., solar lighting, solar cooker) with biogas system to reduce the demand for biogas.
9. Opportunities and constraints of biogas technology replication to rural poor households, who cannot purchase a biogas system even with the subsidy.
10. Current policies and strategies for the development and replication of biogas technology: are they sufficient to provide benefits to the poor households? If not, what changes are necessary?

Checklists for Field Level Organisations

1. The organisations' role in the development and replication of domestic biogas technology.
2. Coping with insufficient biogas production: how the rural households cope with insufficient biogas production to meet their energy demand for cooking and lighting?
3. Measures or local practices to increase biogas production efficiency in cold climate regions or during winter.
4. Feedstock availability: major feedstock available in rural households, required amount of feedstock and actual amount fed to the digester.
5. Potential of other organic materials to use as feedstock for co-digestion with cattle manure.
6. Use of other renewable energy sources (e.g., solar lighting, solar cooker) in biogas households to reduce the demand for biogas, and opportunities and challenges of their replication.
7. Challenges of biogas plant construction at field level. Are there any policy or financial constraints?
8. Loan sanctioning process, particularly to the poor households who cannot produce collateral. Has the loan provided any negative impact on the livelihood of poor farmers?
9. Subsidy scheme: is the subsidy a significant reason for biogas installation? What happens if subsidy will not be provided?

Checklists for Renewable Energy System Installation Companies

1. Types of alternative energy systems available/offered, and their suitability to rural households
2. Capacity and uses of the system
3. Technical service life of the system
4. Costs of the system
5. Subsidies to the poor
6. Benefits from the system (financial, environmental and social/health related benefits)
7. Constraints for installation of such a system in rural households

Annex 8: List of key informants interviewed

Reference	Position	Organisation	Data
KI-1	Executive Director	BSP-Nepal	May, October 2012
KI-2	Assistant Director	BSP-Nepal	May, October 2012
KI-3	Treasurer	BSP-Nepal	May 2012
KI-4	Executive Director	AEPC	February 2013
KI-5	Assistant Director	AEPC	February 2013
KI-6	Senior Renewable Energy Advisor	SNV Nepal	February 2013
KI-7	Project Manager	KfW	February 2013
KI-8	Director	Winrock International Nepal	January 2013
KI-9	Programme Manager	UN Habitat	January 2013
KI-10	Executive Director	NBPA	January 2013
KI-11	Executive Director	Centre for Energy Studies, Institute of Engineering	January 2013
KI-12	Alternative Energy Officer	WWF Nepal	February 2013
KI-13	Technical Advisor	District Development Committee – Lamjung	August 2012
KI-14	Manager	Nepal Urja Bikas Company Pvt. Ltd., Kathmandu	May 2012
KI-15	Director	Rastriya Gobar Gas Nirmal tatha Sewa Pvt. Ltd., Chitwan	August 2012
KI-16	Manager	Janata Urja Bikas Company, Chitwan	August 2012
KI-17	Manager	Marsyangdi Gobar Gas Company, Lamjung	June 2012
KI-18	Branch Manager	Rastriya Gobar Gas Nirmal tatha Sewa Pvt. Ltd., Dumre, Tanahun	June 2012
KI-19	Managing Director	Lamjung Gobar Gas Company	July 2012
KI-20	Managing Director	Biogas tatha Urja Bikas Company, Chitwan	August 2012
KI-21	Chairperson Secretary	Jyoti Mahila Bikas Saving and Credit Cooperative Society Ltd., Chitwan	September 2012

Note: The label 'KI' was used for the key informants

Annex 9: Characteristics of animal dung and agricultural residues available to use as feedstock for biogas production

Feedstock	Buffalo dung	Cattle dung	Rice straw	Wheat straw	Corn stover	Human excreta
Total solid (TS) (%)	19.5, 24, (19) [f, l, m]	9.3, 12.3, (16.7), 18.5,12.0, 10.8 [a, b, c, d, e, k]	97.9, 92.1, 92.2, (84) [f, g, d, h]	90.5, 90.5, (88.9), 92.9 [d, b, g, f]	(84.9), 84.9, 94.0, 94.7, 93.2 [d, i, j, a, h]	20 [p]
Volatile solid (VS) (% TS)	(71.8), 70.7 [f, l]	70, 88.4, 89.5, 71.3, 74.8, (80) [a, k, b, c, d, e]	83.4, (79.5), 81.6, 69.3, 76.4 [f, g, d, n, h]	77.9, 95.9, 79.6, 86.8, (83.5) [d, h, n, f, h]	(76.9), 76.9, 87.4, 75.2, 91.2, 87.2 [d, i, j, n, a, h]	(75), 88, 70 [p, q, r]
C (% TS)	(38.6), 37.8 [f, l]	38.9, 43.5, (37.6), 28 [a, c, d, e]	37.6, 34.8, 39.7, 41.8, 36, (41) [f, g, d, n, o, h]	39.9, 45.5, 46.7, (42.7) [d, h, n, f]	43.2, 43.2, (46.2), 43.7, 46.8, 43.7 [d, i, j, n, a, h]	(40), 40 [p, q]
H (% TS)	4.3 [f]	5.2, 5.5, (5.1), 4.8 [a, b, d, e]	4.8, 4.6, (5.4), 4.6, 5.3, 5.4 [f, g, d, n, o, h]	(5.7), 6.0, 6.3, 5.1 [d, h, n, f]	5.9, (5.9), 5.6, 5.6 [i, d, n, h]	5.4 [p]
O (% TS)	40.1 [f]	23.1, (42.9), 28.9, 49.2 [a, c, d, e]	37, 38.2, (38.2), 36.6, 43.1, 36.6 [f, g, d, n, o, h]	(39.6), 34.1, 41.2, 35.8 [d, h, n, f]	40.2, 44.4, 43.3, (43.3) [d, i, o, h]	38.8 [p]
N (% TS)	1.6 [d]	3.5, (1.8), 2.8, 1.8 [a, c, d, e]	1.0; 0.5, 0.9, 0.7, 0.6, (0.7) [f, g, d, n, o, h]	0.4, (0.5), 0.4, 1.7 [d, h, n, f]	0.8, 0.8, (0.7), 0.6, 0.6 [d, g, j, n, h]	5.0 [p, q]
Carbohydrate (% VS)	45.6 [f]	44.5, (43.5), 43.5, 57.7, 63.4 [a, b, c, d, k]	(79.0), 77.8, 60.8 [d, h, s]	, 85.9, 83.6, (72.3), 62.8 [b, d, h, k]	78.8, 85.6, 77.8, 72.1, (78.0) [a, d, h, i, j]	52.0 [r]

Feedstock	Buffalo dung	Cattle dung	Rice straw	Wheat straw	Corn stover	Human excreta
Protein (% VS)	16.4 [f]	27.6, 15, (17), 14.7,16.7 [a, b, d, e, k]	5.6 [d]	(3.8), 2.5, 3.2 [b, d, k]	4, (5), 5 [a, d, i]	17.6 [r]
Lipid (% VS)	6.2 [f]	9.4, (6.9), 5.5, 6.5 [a, b, e, k]	5.9 [s]	(2.3), 2.6 [b, k]	5.1 [a]	5.6 [r]
VFA (%VS)	2.7 [f]	3.6 [c]	0 [d,i]	0 [b, d,i]	0 [d,i]	2.9 [p]
Lignin (% VS)	8.9 [f]	12.1, 17.4, 17.4, (7.9), 11.7 [b, c, d, e, k]	(10.8), 17.8, 5.6, 9.8 [d, f, g, s]	7.8, 7.6, (11.8), 7.5, 15.8 [b, d, f, h, k]	(10.3), 8.3, 8.7 [d, i, j]	6.4 [r]

a = Zhang, et al., 2012; b = Moller, et al., 2004; c = Omar, et al., 2008; d = Li, Zhang, et. al., 2013; e = Steffen, et al.,1998; f = Sahito et al, 2013; g = Zhang and Zhang, 1999; h = Chandra et al., 2012b; i = Li, Liu et al., 2013; j = Zhong et al., 2011; k = Demirbas, 2006; l = Prateek et al., 2009; m = Kall and Menon, 1984; n = Acaroglu, 1999; o = Grover, 2002; p = Meher et al., 1994; q = Daisy and Kamarai, 2011; r = Fuchigami, et al., 2001; s = Watanabe, et al. (1993).

Note: Figures in parenthesis are the best fit values. The values are the data points that fell on or closest to the best-fit line drawn in a scatter diagram of individual feedstock characteristics values.

Annex 10: Benefit cost analysis of the existing biogas plant operation with and without subsidy

(Unit: US$/year/household)

Plant size	Installation cost (with subsidy)	Annual R&M and operation cost	Traditional fuel cost	Annual revenue from			Discount rate[59]	Capital cost with subsidy	Yearly Cash flows (Year 1 - 20)	With subsidy			Without subsidy		
				Saving on traditional fuels	Utilisation of saved time	Replacing chemical fertiliser				NPV	FIRR	B/C ratio	NPV	FIRR	B/C ratio
Chitwan															
4 m³	325	30.8	95	154	59	1	16%	-325	88	171	27%	5	52	18%	3
6 m³	369	35	78	182	50	1.5	16%	-369	121	298	33%	6	178	24%	4
8 m³	376	37.1	86	186	57	1.5	16%	-376	121	296	32%	6	182	24%	4
10 m³	442	42.7	92	165	88	2.9	16%	-442	121	238	27%	5	233	27%	5
Lamjung															
4 m³	362	32.2	63	100	81	1.1	16%	-362	87	132	24%	4	40	18%	3
6 m³	367	33	70	114	76	1.2	16%	-367	88	134	24%	4	43	18%	3
8 m³	405	34	84	144	96	9	16%	-405	131	320	32%	6	242	26%	5
10 m³	458	39.4	76	183	42	5.6	16%	-458	115	194	25%	4	189	25%	4

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[59] The rate of interest that a bank/micro-finance institution charges on loan is up to 16%, which is used as discount the discount rate in this study.

Annex 11: Benefit cost analysis of biogas plant operation with co-digestion of crop residues with dung

Unit: US$/year/household

Plant size	Installation cost (with subsidy)	Annual R&M and operation cost	Traditional fuel cost plus crop residue cost	Annual revenue from			Discount rate (%)	Capital cost with subsidy	Yearly cash flows	With subsidy			Without subsidy		
				Saving on traditional fuels	Utilisation of saved time	Replacing chemical fertiliser			Year 1-20	NPV	FIRR	B/C ratio	NPV	FIRR	B/C ratio
Chitwan															
4 m^3	325	30.8	34	154	59	1	16%	-325	149	482	46%	8	368	32%	6
6 m^3	369	35	41	182	50	1.5	16%	-369	158	487	43%	7	372	31%	6
8 m^3	376	37.1	67	186	57	1.5	16%	-376	140	393	37%	6	285	28%	5
10 m^3	442	42.7	75	165	88	2.9	16%	-442	138	325	31%	5	325	31%	5
Lamjung															
4 m^3	362	32.2	30	100	81	1.1	16%	-362	120	301	33%	6	213	26%	5
6 m^3	367	33	48	114	76	1.2	16%	-367	110	247	30%	5	159	23%	4
8 m^3	405	34	94	144	96	9	16%	-405	121	269	30%	5	197	24%	4
10 m^3	458`	39.4	84	183	42	5.6	16%	-458	107	153	23%	4	153	23%	4