Department of Mechanical and Aerospace Engineering

Routes to Low-Cost Yield Improvement for Small-Scale Biogas Digesters

Author: Russell Stuart Pepper

Supervisor: Professor Joseph Clarke

A thesis submitted in partial fulfilment for the requirement of the degree

Master of Science

Sustainable Engineering: Renewable Energy Systems and the Environment

2015

Copyright Declaration

This thesis is the result of the author's original research. It has been composed by the author and has not been previously submitted for examination which has led to the award of a degree.

The copyright of this thesis belongs to the author under the terms of the United Kingdom Copyright Acts as qualified by University of Strathclyde Regulation 3.50. Due acknowledgement must always be made of the use of any material contained in, or derived from, this thesis.

Signed: Date: 02/09/2015

Acknowledgements

Thanks to my supervisor, Professor Joseph Clarke, who gave me the advice and assistance I needed to complete this project. Additionally Dr Paul Strachan has been an excellent course director for RESE, always very helpful and informative.

Thanks also to Matthew Geraghty, Andrew Roscoe, Maureen Cloonan and Jean Currie for giving me permission to use their modelling tool in this study.

My parents John and Wendy are always there for me and have always given me the help and assistance I need to follow my ambitions; my master's year here in Glasgow would not have been possible without them.

And finally thanks to my partner, Karolina, who encouraged me to take this course and moved to Scotland with me so I could take it. She's supported me and given me a lot of help and advice in completing this thesis – this last year would not have been easy without her.

Abstract

Biogas digesters (BDs) have the potential to reduce greenhouse gas (GHG) emissions through burning methane released from manure and landfill, rather than allowing it to escape into the atmosphere. If used in developing countries, they reduce the demand for solid fuel which is the main source of cooking and heating energy which contributes to deforestation as well as releasing GHGs.

Whilst large-scale plants are gaining popularity in more developed countries, they are less accessible in developing countries due to cost, skill and infrastructure limitations. The aim of this study was therefore to explore ways in which small-scale plants – quite common in developing countries – could become more profitable, with minimal additional investment.

In achieving this, a rudimentary small scale plant was modelled. A systematic assessment of the addition of components to this plant was then performed using performance and financial variability factors which were derived from a literature review. The impacts of these additions were measured, and from the increase in profit, a "maximum acceptable investment" value was derived for a range of acceptable payback periods.

It was found that the addition of a second digester increased payback period by 50%. Additionally, it was found that heating provided the highest yield increase – 22, 44 and 66% for heating at temperatures of 25, 30 and 35ºC respectively. The addition of a shredder gave a 38% increase and a second digester 11.7%. For combinations of two or more components, those combinations including heating always provided the highest yields. It was therefore recommended that the primary focus of future work be on finding low-cost heating solutions, and secondarily, shredders.

Table of Contents

List of Figures

List of Tables

List of Abbreviations

AD	Anaerobic digestion
BD	Biogas digester
BPEX	British Pig Executive
BSP	Biogas Support Programme
CHP	Combined heat and power
DM	Dry matter
GHG	Greenhouse gas
GWP	Global warming potential
HRT	Hydraulic retention time
IEA	International Energy Agency
IFORSE	International Network for Sustainable Energy
IPCC	Intergovernmental Panel on Climate Change
ISAT	Information and Advisory Services on Appropriate Technology
ISO	International Organisation for Standardisation
KTBL	Kuratorium für Technik und Bauwesen in der Landwirtschaft
LEAD	Livestock, Environment and Development Initiative
MSW	Municipal solid waste
OLR	Organic loading rate
TDBP	Tanzania Domestic Biogas Programme
UNESCO	United Nations Educational, Scientific and Cultural Organisation
WHO	World Health Organisation

List of Symbols

CH_4	Methane
CO_2	Carbon dioxide
ºC	Degrees centigrade
C_p	Specific heat capacity (kJ/kg°C)
EUR	Euros
GBP/£	Pounds Sterling
h	Hour
H_2	Hydrogen
H_2O	Water
kg	Kilogramme
kW	Kilowatt
kWh	Kilowatt-hour
l	Litre
m	Mass (kg)
mm	Millimetre
m^3	Cubic metre
NO_2	Nitrous oxide
Q	Energy required to heat substrate (kWh/year)
ΔT	Change in temperature (°C)
t	Metric tonne (1000kg)
yr	Year

1. The Role of Biogas Digesters in CO_2 Reduction

The signing of the Kyoto Protocol in 1997 by the majority of the world's developed countries resulted in a higher awareness of the potentially damaging effects of greenhouse gases upon our environment. Reducing the emission of these gases has since been a requirement for the signatories of the protocol.

One sector where there is a great potential to reduce emissions is the livestock sector which is responsible for over 18% of anthropogenic greenhouse gases measured in CO_2 equivalent – this is a higher percentage than total emissions from transport worldwide. Additionally the sector emits 37% of anthropogenic CH_4 - with a Global Warming Potential (GWP) of 23 times that of CO_2 (IPCC, 2001) - most of which is from enteric fermentation by ruminants and 65% of anthropogenic NO_2 (with a GWP of 296 times that of CO_2), the majority of which is from manure (LEAD, 2006).
Studies (Flessa, H., et al., 2002; Schils, R.L.M. et al., 2005; Gibbons, J.M. et al., 2006; Olesen, J.E. et al., 2006) have shown that CH_4 and NO_2 are the dominating gases being emitted.

This is a growing problem that needs to be addressed, especially in developing countries with increasing meat and dairy consumption; global meat consumption is expected to more than double on 1999 figures by 2050 from 229 to 465 million tonnes and milk consumption is expected to almost double from 580 to 1043 million tonnes (LEAD, 2006). Emissions from this sector must therefore halve per unit of production simply to remain at present day levels.

With policy changes and proper management, there is the potential to reduce these figures greatly; intensification of farming (reducing deforestation and increasing efficiency), improved diets to reduce methane emissions by enteric fermentation, farming methods to sequester carbon, proper manure management and biogas digesters could all be part of the solution (LEAD, 2006).

Biogas digesters (BDs) can address this problem twofold:

One – they are a proper means of disposal for manure. The digester prevents the manure from releasing CH_4 and NO_2 into the environment by storing it and collecting these gases to be burned, releasing CO_2 and H_2O. This is far less polluting than if the manure were left to sit and release these gases as before - up to 50% less in cool climates and up to 75% in warmer climates (LEAD, 2006).

Two - they reduce the need to burn wood which releases CO_2, and contributes to deforestation which exacerbates the problem. According to the International Energy Agency (IEA, 2015), approximately 2.7 billion people worldwide use solid fuels such as coal, wood, agricultural waste (corn stalks, rice husks etc.) and dung-cake fires to heat their homes and cook with. The burning of such fuels leads to incomplete combustion, which, as well as carbon dioxide, releases pollutants such as methane and black carbon which contribute significantly to climate change (IPCC, 2001). The number of people using solid fuels is ever-increasing and is expected to reach 2.9 billion by 2030 (IEA, 2002).

Additionally, BDs have the potential to solve the growing problem of waste disposal in developing nations; the majority of municipal solid waste (MSW) in these countries is composed of biodegradable matter (Troschinetz and Mihelcic, 2008; Wilson et al., 2012), which can pose considerable health and environmental risks if left untreated (Scheinberg et al., 2010). If used correctly, BDs can process this waste and produce a harmless digestate - suitable for a range of purposes - in addition to producing biogas fuel. They can be very simple and cheap to build, and are especially well suited to warmer climates. This study therefore recognises the potential of BDs to tackle these growing problems

Whilst household-scale BDs have been proven to work at a low cost (Bond and Templeton, 2011), it may be possible to improve the performance (i.e. biogas yield and consistency of production) at a proportionally acceptable cost increase.

The aim of this project, therefore, was to examine the possible improvements to a small-scale BD and the corresponding performance and cost increases for these improvements.

With this in mind, the project had the following objectives:

- derive factors for performance and cost variance if components pertinent to biogas yield are used;
- modify an existing large-scale BD modelling tool the tool to include these factors;
- validate the tool, using data from case studies ;
- modify the tool so that it may be used to assess small scale biogas digesters i.e. by using the tool to “switch off” all components not required, recording the BD performance and cost;
- methodically “switch on” components, recording the corresponding cost and performance increases;
- use the data gained to generate a cost/performance matrix; and
- make associated recommendations for possible routes to performance improvement at relatively acceptable cost increases.

2. Possible Improvements to Rudimentary Biogas Digesters

There are many different BD systems available, but they all have the same basic premise. They utilise anaerobic digestion (AD), which, as the name implies, is a process whereby organic material is broken down by bacteria in an oxygen-free environment.

Any biodegradable organic material – farmyard manure is especially common - is a suitable input feedstock/substrate for a biogas digester; this is broken down by bacteria in the digester, the type of which is dependent on the temperature inside the digester (Sasse, L., 1998). At 20-45°C the bacteria present will be mesophiles (growing best in moderate temperatures), and at temperatures of 45-70°C they will be heat loving thermophiles (Song et al., 2004). Temperature stability is also important here.

The bacteria within a BD produce biogas; a mixture of approximately 50-70% methane and 30-50% carbon dioxide (as well as other trace gases including nitrogen, hydrogen, hydrogen sulphide and oxygen) and slurry waste, which can be used as fertiliser (Sasse, L., 1998).

This proportion of methane will increase (tapering off) if the substrate is allowed to digest for longer – this length of time is known as the hydraulic retention time (HRT). The longer the HRT of a system, the more pathogens are removed from the substrate; human waste requires a considerably longer HRT than food waste for example.

Other important aspects include pH; this should be between 6.4 and 8.2 for a BD to function effectively, Carbon: Nitrogen ratio; if too high this can cause gas yields to reduce, and organic loading rate (OLR) which is the rate at which substrate is fed into the BD. If this is too fast then the substrate cannot be processed and a build-up of material which inhibits biogas yield will result (Cenex, 2009).

The biogas can then be used immediately for cooking, heating or lighting, or can be used in a gas generator to generate electricity (and heat if required). It can also be purified for sale as methane, e.g. for use in methane powered vehicles.

There are four main stages to AD:

1. Hydrolysis: During this stage, bacteria transform particulate proteins, carbohydrates and fats into liquid amino acids, monosaccharides and fatty acids respectively

2. Acidogenesis: Acidogenic bacteria transform the products of the first stage into short chain volatile acids, ketones, alcohols, hydrogen and carbon dioxide. The principal acidogenesis stage products are propionic acid (CH_3CH_2COOH), butyric acid ($CH_3CH_2CH_2COOH$), acetic acid (CH_3COOH), formic acid ($HCOOH$), lactic acid ($C_3H_6O_3$), ethanol (C_2H_5OH) and methanol (CH_3OH), among others. From these, hydrogen, carbon dioxide and acetic acid will go directly to the fourth stage to be utilised by the methanogenic bacteria

3. Acetogenesis: The remainder of the products from the acidogenesis stage (propionic acid, butyric acid, formic acid, lactic acid, ethanol and methanol) will be transformed by acetogenic bacteria into hydrogen, carbon dioxide and acetic acid

4. Methanogenesis: During the final stage, methanogenic bacteria transform the hydrogen and acetic acid into methane and carbon dioxide, the final products of AD (Angelidaki et al., 2000).

A simple schematic of a generic system is shown below in *Figure 1*:

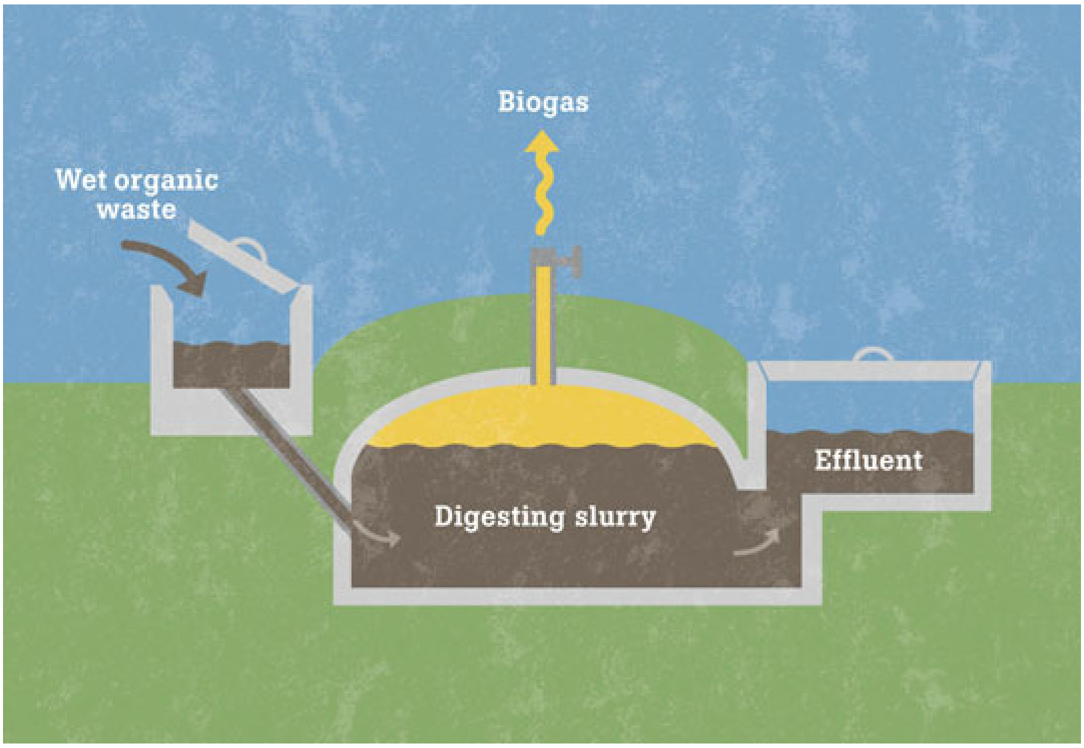

Figure 1 - Generic biogas digester (https://www.ashden.org/biogas)

This shows the flow of organic material through a BD; from the input it is gravity-fed into the digestion chamber where biogas is formed and stored, then moving on to the effluent pit for removal.

A BD system can be as simple as a single cylindrical drum, or can be complex with multi-stage digesters with moving parts and sensors, which will increase the efficiency of the system (Sasse, L., 1998).

In developed countries such as in Europe, biogas plants are mainly used to generate electricity and heat (IEA, 2014). They are often complex systems, involving features such as pre-heating of inputs, temperature controls, mechanised mixers in digestion chambers, multi-stage digestion, CHP engines and many other sophisticated components.

All of these additions to the generic system are designed to maximise reliability and volume of gas production, as well as profitability (Karim et al., 2005, Abdel-Hadi, and Abd El-Azeem, 2008, Alkhamis et al., 2000, Schievano et al., 2012). Such additions, however, will increase the requirement for input capital, reliability of infrastructure and availability of a skilled workforce; all factors which are in considerably shorter supply in developing countries than they are in more developed countries (UNESCO, 2012).

It is therefore uncommon to find more complex BDs in developing countries; instead small scale household BDs similar to the generic system shown in *Figure 1* are often used. For example, in Nepal, approximately 280,000 similar units have been built since 1992 (BSP Nepal, 2012). Approximately 9000 similar plants (a modified version of the BDs used in Nepal) were built 2009-2012 in Tanzania (TDBP, 2015) and since China's implementation of "biogas use in every rural family", over 7 million BDs have been constructed (He, 2010). Construction on such a scale shows that these small scale plants can be both practical and profitable.

It was found that whilst potentially valuable, research into improvements to such systems was scarce; it may indeed be possible to improve biogas yield through the addition of components with an acceptable cost to the end user. Therefore the improvement to such systems through the systematic addition of components formed the basis of this study, the analysis of which required a computational tool.

3. Performance Assessment

3.1. Tool Requirements and Selection

In order to perform to take an analytical approach in observing the effects various BD configurations would have upon biogas yield and cost, a modelling tool was required. Therefore a literature review was conducted to obtain a model or tool for use in this study that had the ability to:

a) model a small-scale BD and

b) be altered to remove and add components, and show the corresponding variances in biogas output and cost.

The majority of the models available were either online tools - very narrow in their scope - or documents giving guidelines and advice on the implementation of a BD.

For example, the "Anaerobic Digestion Feasibility Tool" (Colorado State University, 2015) which is an online tool simply asking the user their method of manure collection and availability to wastewater; the economic feasibility part of this tool is a simple decision tree.

Other document-based decision-support tools, such as the "Feasibility assessment tool for urban anaerobic digestion in developing countries" by Lohri et al. (2013) concentrated more on the non-technical criteria which affect the operational success of a BD. Cenex (2009) provide a document entitled "A guide to the production and use of biomethane as a road transport fuel", which is

"designed to give local authorities and others information about what is needed to produce and use biomethane as a vehicle fuel"

and Methanogen Ltd. (2010) developed "A Toolbox Guide for Assessing the Feasibility of an Anaerobic Digestion Project Developed for the Benefit of a Community or for a Single Farm".
Additionally, Karellas et al. (2010) developed a financial feasibility tool in document form.

All of these tools, whilst excellent aides to the decision making required in the development of a BD, did not fit the requirements for this study.

3.2. Description of Selected Tool

The tool chosen for use in this study was developed by Geraghty, Roscoe, Cloonan, and Currie (2004), and is a set of Excel spreadsheets designed to calculate energy balances for single and two-stage mesophilic biogas digester plants. It was chosen for its ease of alteration, and for its scope to model both large and small-scale BDs.

The inputs include:

- local waste collection area – calculated by maximum distance/radius travelled by collection trucks (shown in in *Table 1)*;
- local demographics for the area - this includes human and animal population (shown in in *Table 1)* as well as local commercial waste available. The tool uses these to calculate possible waste streams available; and
- plant specifications; including required HRT, digestion temperature, component efficiencies and energy requirements. This is shown in *Table 2*.

Table 1 - Demographic inputs for tool

Demographics

Catchment zone characteristics

Inner zone (urban)

Effective inner radius of central zone	3	km
Fixed population inside central zone for:-		
Human sewage sludge	600	People
Generic food waste, domestic collection	900	People
Dairy cattle manure	0	Cows
Beef cattle manure	0	Cows
Laying hens	0	Hens
Broiler chickens	0	Chickens
Pig slurry	0	Pigs
Horse manure	20	Horses

Outer zone (rural)

Outer radius of scheme	6	km
Homogeneous population in outer zone for:-		
Human sewage sludge	0	People/ha
Generic food waste, domestic collection	0	People/ha
Dairy cattle manure	0	Cows/ha
Beef cattle manure	0	Cows/ha
Laying hens	0	Hens/ha
Broiler chickens	0	Chickens/ha
Pig slurry	0	Pigs/ha
Horse manure	0	Horses/ha

Deduced demographics

Inner zone area	2827.4	ha
Inner zone average collection distance	2.0	km
Outer zone area	8482.3	ha
Outer zone average collection distance	4.7	km
Outer zone population for :-		
Human sewage sludge	0.0	People
Generic food waste, domestic collection	0.0	People
Dairy cattle manure	0.0	Cows
Beef cattle manure	0.0	Cows
Laying hens	0.0	Hens
Broiler chickens	0.0	Chickens
Pig slurry	0.0	Pigs
Horse manure	0.0	Horses
Total population for:-		
Human sewage sludge	600.0	People
Generic food waste, domestic collection	900.0	People
Dairy cattle manure	0.0	Cows
Beef cattle manure	0.0	Cows
Laying hens	0.0	Hens
Broiler chickens	0.0	Chickens
Pig slurry	0.0	Pigs
Horse manure	20.0	Horses

Table 2 - Plant parameter inputs for tool

Parameters - Plant

Digestion plant specifications			
Feed density	1.04	tonnes/m^3	
Feed specific heat capacity	4.17	kJ/kgK	
Feed temperature in the input buffer	5	C	
Required Input buffer storage	3	days	
Pasteurisation time	0.08	days	
Pasteurisation feed temperature	71	C	
Pasteurisation temperature	70	C	
Pasteurisation vessel height:diameter ratio	1		
Pasteurisation vessel insulation conductivity	0.04	W/mK	
Pasteurisation vessel insulation thickness	100	mm	
Pasteurisation vessel U-value	0.4	W/m^2/K	
Pasteurisation vessel ambient temperature	18	C	
HRT,1st phase	0	days	
1st phase temperature	38	C	
1st phase vessel height:diameter ratio	1		
1st phase insulation conductivity	0.04	W/mK	
1st phase insulation thickness	100	mm	
1st phase vessel U-value	0.4	W/m^2/K	
1st stage vessel ambient temperature	5	C	
HRT, 2nd phase	8	days	
2nd phase temperature	38	C	
2nd phase vessel height:diameter ratio	1		
2nd phase insulation conductivity	0.04	W/mK	
2nd phase insulation thickness	100	mm	
2nd phase vessel U-value	0.4	W/m^2/K	
2nd stage vessel ambient temperature	5	C	
Digestate density	1.02	tonnes/m^3	
Digestate storage	20	days	
Digestate vessel height:diameter ratio	1		
Heat exchanger effectiveness			
1st exchanger (2nd stage digester output)	70.0%		
2nd exchanger (Pasteuriser output)	70.0%		
3rd exchanger (Engine cooling water)	70.0%		
1st digester (Engine cooling water)	70.0%		
2nd digester (Engine cooling water)	70.0%		
Electrical loads, kWh consumed in one day, per (tonne/day) capacity and digester size (m^3)			
Primary shredder	0.66	(kWh/day)/(tonnes/day)	(of feed)
Secondary shredder	0.53	(kWh/day)/(tonnes/day)	(of feed)
Reception tank mixer	0.80	(kWh/day)/(tonnes/day)	(of feed)
Reception tank discharge pump	0.13	(kWh/day)/(tonnes/day)	(of feed)
Input buffer tank mixer	0.23	(kWh/day)/m^3	(vessel size)
Input buffer tank discharge pump	0.13	(kWh/day)/(tonnes/day)	(of feed)
Pasteurisation mixer	0.10	(kWh/day)/m^3	(vessel size)
Pasteurisation discharge pump	0.13	(kWh/day)/(tonnes/day)	(of feed)
1st stage digester mixer	0.10	(kWh/day)/m^3	(vessel size)
1st stage discharge pump	0.13	(kWh/day)/(tonnes/day)	(of feed)
2nd stage digester mixer	0.10	(kWh/day)/m^3	(vessel size)
2nd stage discharge pump	0.13	(kWh/day)/(tonnes/day)	(of feed)
Digestate mixer	0.02	(kWh/day)/m^3	(vessel size)
Biofilter air fan	0.008	(kWh/day)/(m^3/day)	(of biogas)
Gas holder air fan	0.012	(kWh/day)/(m^3/day)	(of biogas)

Based on the volume of feedstock available, the plant digesters are sized by the tool. Then, feedstock types and volume are analysed to give an estimate of the biogas output available– the tool did not analyse the effects of HRT, temperature or co-digestion; when feedstocks are digested simultaneously, the methanogenic communities can experience an increase in the amount of methane they produce, due to complex interactions between the different substrates (Callaghan, F.J. et al. 1998, Tian, H. et al. 2014).

.

Table 3 - Biogas output from tool

Biogas/methane power outputs				
		Estimates		
	Lowest	Middle	Highest	
Total biogas per day	30.4	63.8	139.8	m^3
Methane content range of biogas	52.8%	60.0%	65.9%	%
Total methane per day	16.1	38.3	92.2	m^3
kWh per day @ 11.04 kWh/m^3	177.3	422.6	1017.7	kWh
kW average power (methane)	7.4	17.6	42.4	kW

From the biogas available, the tool then calculates the methane content and according the calorific value of methane, the energy available (shown in *Table 3).* From this, a CHP engine is sized and gross heat and electrical energy available is calculated, taking into account component efficiencies and heat loss. Plant component heat and electrical energy requirements are then used to gain a final output of net electrical and heat energy available (shown in *Table 4).* For all outputs, a low, medium and high estimate is given.

No need was seen to validate the tool as this had already been conducted thoroughly by the developers.

Table 4 - Results summary output from tool

Results summary

Input feed properties		Estimates		
	Lowest	Middle	Highest	(Biomass)
Total tonnes per day	42.4	47.2	52.0	tonnes
Dry solids content range of feed	14.8%	21.6%	29.2%	%
Total dry solids per day	6.3	10.2	15.2	tonnes
VS content of dry solids	71.5%	71.4%	71.4%	%
Total volatile solids per day	4.5	7.3	10.8	tonnes
Carbon:Nitrogen ratio	16.19	16.23	16.15	
Digester properties				
Input buffer diameter	0.00	0.00	0.00	m
Input buffer height	0.00	0.00	0.00	m
Pasteuriser diameter	1.61	1.67	1.72	m
Pasteuriser height	1.61	1.67	1.72	m
1st stage diameter	3.73	3.87	3.99	m
1st stage height	3.73	3.87	3.99	m
2nd stage diameter	3.73	3.87	3.99	m
2nd stage height	3.73	3.87	3.99	m
Digestate buffer diameter	10.19	10.56	10.91	m
Digestate buffer height	10.19	10.56	10.91	m
Temperatures				
Pasteuriser	70.9	70.9	70.9	C
1st stage digester	42.4	42.4	42.4	C
2nd stage digester	41.9	41.9	42.0	C
Energy				
Total energy yielded, of which	518.2	901.3	1237.6	kW
Process heat required	24.8	27.6	30.4	kW
Process electrical required	7.6	9.1	10.5	kW
Engine heat lost	64.7	94.1	114.8	kW
Generator heat lost	8.3	15.0	20.9	kW
Surplus electricity for export	150.9	275.3	387.0	kW
Surplus heat (available for CHP export)	261.8	480.2	674.0	kW
Check energy sum	518.2	901.3	1237.6	kW
Surplus CHP water temperature	78.1	80.6	81.5	C
Surplus CHP water at mass flow rate	0.86	1.52	2.11	kg/s

3.3. Tool Adaptation

The tool was adapted and used according to *Figure 2* below:

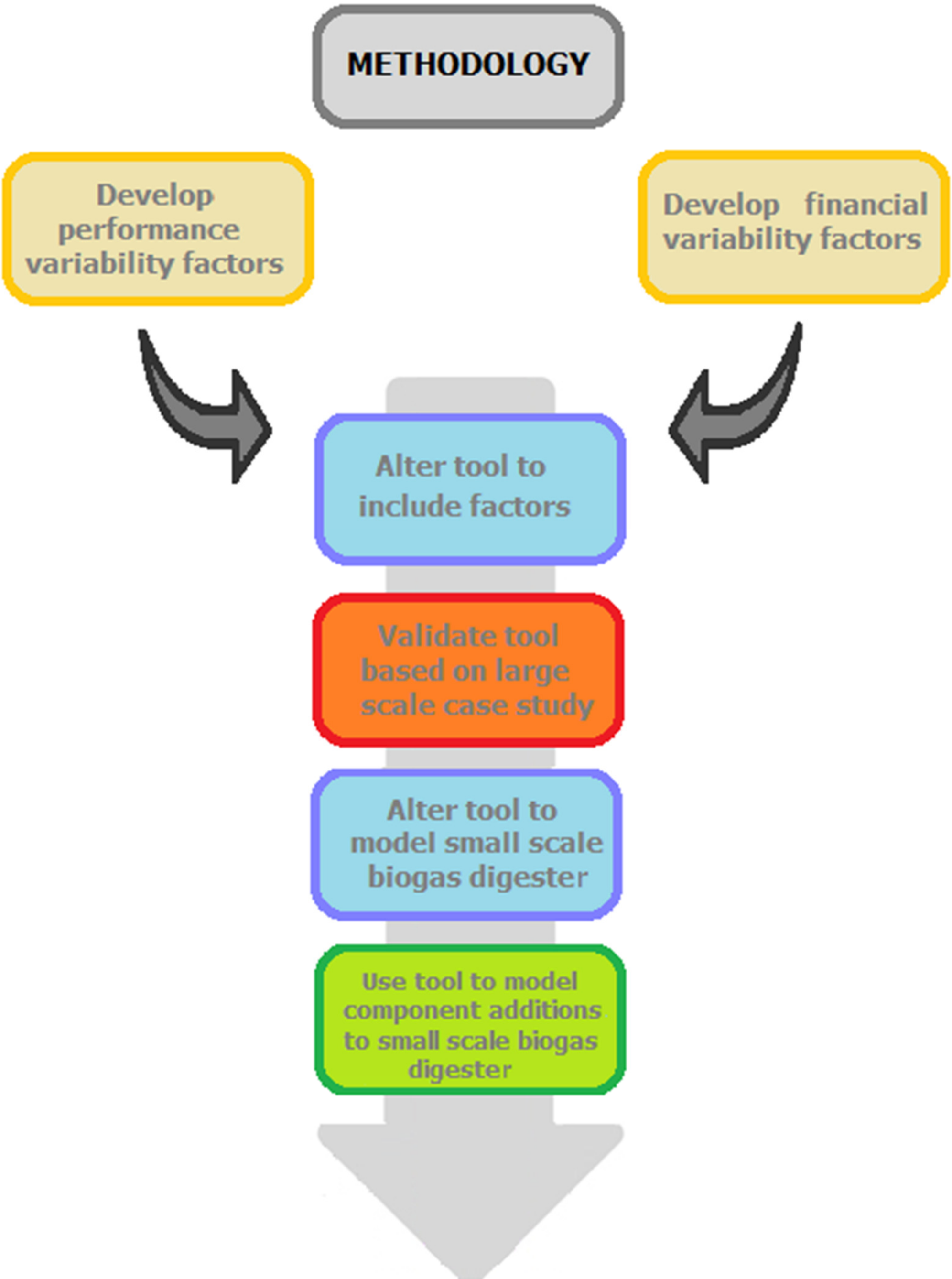

Figure 2 - Diagram showing methodology process

As the aim of this study was to examine possible routes to acceptable cost increases in biogas plant through system improvement, it was vital that the tool was able to calculate:

a) the variability in performance when components are added; and
b) the financial impact of these additions

The tool was, however missing these features; as such it was modified, described in sections 3.4 and 3.5 respectively.

To make these alterations effectively, all components within the tool had to be separated into those pertinent to biogas production and those not – below are the components pertinent to biogas production.

- Reception tank mixer
- Input buffer tank mixer
- 1st stage digester mixer
- 2nd stage digester mixer
- Primary shredder (mechanical pre-treatment)
- Secondary shredder (mechanical pre-treatment)
- 1st stage digester (unheated/heated)
- 2nd stage digester (unheated/heated)

A detailed literature review was conducted to determine the individual effects of these components upon biogas production and cost. From this were derived factors for the variability in performance and cost if the components were used, compared to if they were not. These factors were then built into the tool so that they would alter biogas production and financial viability of a potential biogas plant.

It was considered outwith the scope of this study to consider composite effects, as this would require laboratory work.

Additionally, the possible operational effects, as well as financial impacts of the addition of other components were considered outwith the scope of this study. These are as follows:

- Reception tank discharge pump
- Pasteurisation mixer
- Pasteuriser (heated)
- Input buffer
- Input buffer tank discharge pump
- Pasteurisation discharge pump
- 1st stage digester discharge pump
- 2nd stage digester discharge pump
- Heat exchanger 1 (exit from 2nd stage digester)
- Heat exchanger 2 (exit from pasteuriser)
- Heat exchanger 3 (exit from engine coolant)
- Digestate mixer
- Digestate buffer
- Bio filter air fan
- Gas holder air fan
- CHP gas engine

To validate the tool, data from a case study were input to compare the output with recorded performance data. The case study chosen was SBW Lelbach, a system in Germany – chosen because it is a two-stage mesophilic BD which could be analysed effectively by the tool.

Where data for input into the tool was incomplete, assumptions were made – these are listed as well as all the pertinent data for the case study. For the tool to be deemed "valid" it was decided that estimated figures should be of the same order of magnitude as actual figures, and lie within 50% of them. This was because due to various estimates, figures could lie within a reasonably large range.

Once the tool was validated, it was "stripped down" so it was able to model a household-scale biogas plant.

A case study of a BD in Cameroon - of a similar design to those used in Nepal – was then analysed for biogas yield improvements and cost increases associated with the addition of components pertinent to biogas yield.
Recommendations for improvements in biogas yield with acceptable cost increase were then made based on these findings.

3.4. Derivation of Performance Variability Factors

For the derivation of all of these factors, a literature review was conducted regarding the specific components considered. The figures found within the literature review were then analysed and processed to derive a "performance variability factor"; which was a ratio by which biogas production varied when a component was used compared to when it was not. These factors were then built into the tool - as explained in section 3.6.

3.4.1. Single-stage vs. two-stage digestion – biogas yield

In single-stage digestion, the hydrogen produced during the acidogenic stage of digestion is used by bacteria in the methanogenic stage. However, in two-stage digestion this hydrogen is captured, and forms a component within the end biogas product. Not only does this provide additional chemical energy within the biogas, but it can also facilitate a higher methane yield in the acidogenic stage (Schievano et al., 2012). The exact mechanisms behind this are not fully understood and further work is required in this field.

Testing for four different organic feedstocks, Schievano et al. (2012) found that overall energy yield (H_2 and CH_4) for two-stage systems was significantly higher (8-43%) than for single stage (CH_4) systems in the large majority of experiments performed, and never significantly lower (1-13.8%). This was, however, mainly due

to the increase in methane production; the proportion of final energy content made up of hydrogen in the two-stage process was in the range of 3.9-15.7%, with an average of 9.4% for all experiments performed. This relatively low value, coupled with the fact that the tool is only designed to take account of methane yield, led to the decision to exclude hydrogen output from the scope of this study.
Additionally, methane yield from feedstock is a more mature and well understood field, with more readily available information, as can be seen from the following studies:

Maspolim et al. (2014) found that, for municipal sludge, the methane yield of a two-stage system was higher than a single stage system by 23%, 16% and 40% for HRTs of 30, 20 and 12 days respectively.

In a study using thin stillage – wastewater from the production of bioethanol – as a feedstock, Luo et al. (2011) found that for an HRT of 15 days, methane production was 5.7% higher for a 2 stage when compared to a single stage system. It was suggested that the relatively small increase was due to a short HRT time of the second stage of only 12 days; Nasr et al. (2012) found a 27% increase in methane production using thin stillage after 28 days.

Liu et al. (2006) found a 21% increase in methane production, using household waste as a feedstock – this was for an HRT of 15 days for the single stage and 17 days (2 days for the first and 15 for the second stage) for the two-stage process.

Pakarinen et al. (2009) found an overall improvement in methane production of 8.4% when using grass silage as a feed stock. This was for HRTs of 56 days for the single and 71 days (14 days for the first and 57 for the second-stage) for the two-stage process. When the silage was spilt into solid and liquid fractions, however, it was found that for the solid fraction methane yield increased by 64% whilst for the liquid fraction, yield decreased by 27%. It was therefore determined that optimal performance would be gained from splitting the silage into solid and liquid fractions and putting the solid fraction through two-stage and the liquid stage through single stage digestion if possible. These results are shown below in *Table 5*.

Table 5 - Yield improvements due to two-stage digestion

Study	Feedstock	% improvement in CH_4 yield two-stage has over single-stage process, with HRT (days)						Mean improvement (%)
		12	15	20	28	30	56	
Maspolim et al. (2014)	municipal sludge	40	n/a	16	n/a	23	n/a	26.3
Luo et al. (2011)	thin stillage	n/a	5.7	n/a	n/a	n/a	n/a	5.7
Nasr et al. (2012)	thin stillage	n/a	n/a	n/a	27	n/a	n/a	27
Liu et al. (2006)	household waste	n/a	21	n/a	n/a	n/a	n/a	21
Pakarinen et al. (2009)	grass silage	n/a	n/a	n/a	n/a	n/a	8.4	8.4
								Mean value = 17.7 %

From *Table 5* it can be seen that a wide variance in yield improvement due to two-stage digestion has been observed across a range of studies (from 8.4 – 27%). This could be down to a range of factors – temperature, HRT, substrate used, mixing regime and substrate particle size are but some of the major factors involved.

To derive an accurate value for yield improvement due to two-stage digestion it would therefore be necessary to perform a range of laboratory-based tests, for a large range of substrates subjected to a large range of variables – this is, however, out of the scope of this study. Whilst acknowledging the inaccuracy of the figure, the mean value of 17.7% was deemed suitable to take as the value for which two-stage digestion improves methane production when compared to single-stage production.

This figure was introduced into the tool and only applied when two-stage digestion was considered; the figures used by the tool to calculate methane production come from experimental data considering single-stage digestion only.

3.4.2. Heated digestion – biogas yield

As discussed in Chapter 2, anaerobic bacteria present in digesters can either be mesophilic - operating at 20-45°C or thermophilic - operating at 45-70°C (Song at al., 2004). The tool under consideration analyses only digesters operating under mesophilic conditions. This, coupled with the fact that the majority of small-scale BDs operate within the mesophilic range, led to the decision to discount thermophilic digesters from scope of this study.

Temperature is a critical parameter for anaerobic digestion since it influences both system heat requirements and methane production (Chae et al., 2008). A significant role is therefore played by digester temperature upon the financial viability of a BD; the tool was therefore altered to take account of this in the following manner:

- a literature review was conducted to find and compare biogas production from substrates at different temperatures;
- as the tool uses values for biogas production at a temperature of 35°C, studies comparing biogas production at different temperatures to this baseline temperature were examined;
- these values were plotted and a line of best fit using r^2 values was drawn; and
- this line was used to calculate a ratio to input into the tool to alter biogas production values based on temperature.

If non-heated digesters are to be considered, in non-tropical climates where temperatures frequently are below 20°C, biogas production may be seriously affected. Whilst it has been shown that it is possible to produce biogas at low temperatures of 10-23°C (Safley and Westerman, 1994), the substantially lower yields obtained at these temperatures would have clearly serious impacts upon the financial viability of a plant. In fact, according to ISAT (1999), at temperatures below 15°C, biogas production is so low that it becomes financially unfeasible.

It would therefore be recommended that heaters be used if ambient temperature is less than 15°C. It would also be advised that before considering operating a non-heated plant, performance of the required substrate at the ambient temperature in the region of operation be known, and finances carefully calculated. Consideration should also be given to affordable heating methods - if, for example, a gas generator unit is to be used, engine coolant can be used to heat the digesters.

Arikan et al. (2015) compared digestion of dairy manure at temperatures of 22, 28 and 35°C. They found that biogas output was 87% and 70% of the yield at 35°C, for 28 and 22°C respectively. It was concluded that:

"Small farm digester systems that may not have access to waste heat from electrical generation, could efficiently operate at these lower temperatures to produce methane and reduce greenhouse gas emissions and odours."

This is of course only relevant to regions with temperatures within these ranges. At higher mesophilic temperatures, Chae et al. (2008) investigated the effects of 3 different temperatures (25, 30 and 35°C) upon methane yield for the anaerobic digestion of swine manure. It was found that, compared to the methane yield at 25°C, there were improvements of 3 and 17.4% for 30 and 35°C respectively.

Bouallagui et al. (2004) found that when digestion of fruit and vegetable waste at 35°C was compared to 20°C, there was a 73% improvement in methane yield.

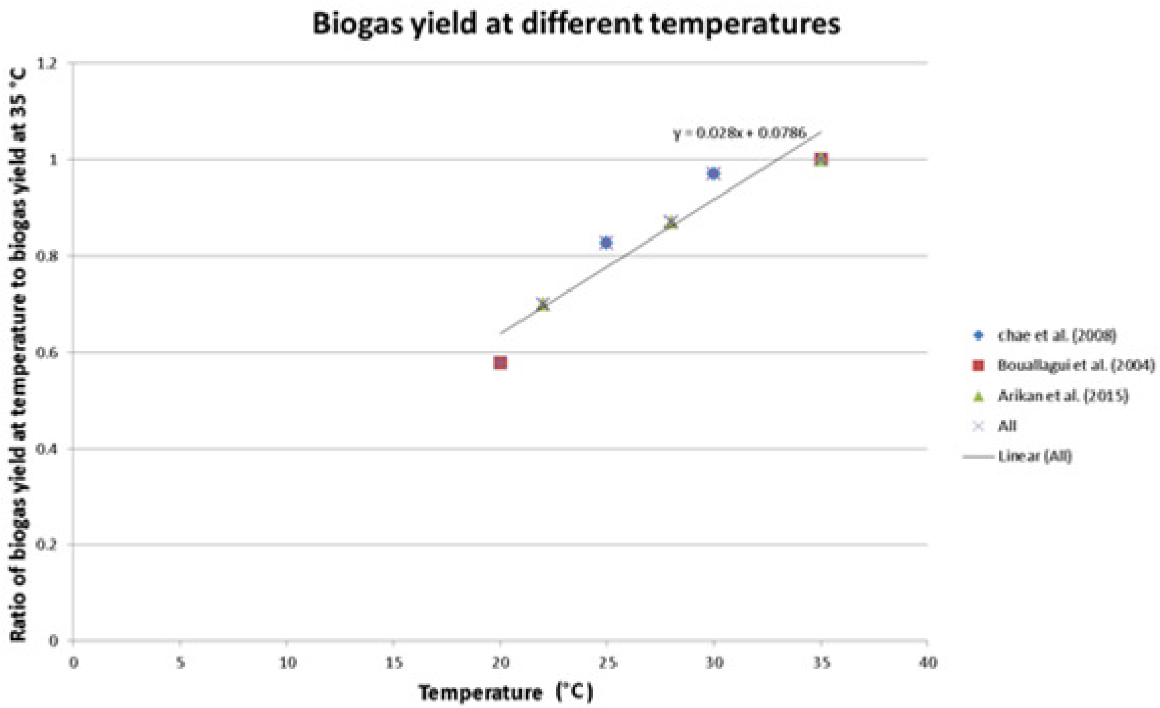

Figure 3 - Biogas yield at different temperatures

Inputting the values from these studies into a scatter graph and drawing an r^2 line of best fit, the graph shown in *Figure 3* was gained; this clearly shows a positive correlation between temperature and biogas yield between 20 and 35°C. Comparing results from Bouallagui et al. (2004), Arikan et al. (2015) and Chae et al. (2008) to the line of best fit shows that the improvement appears to taper off as temperatures increase; this is already known, as the mesophilic bacteria begin to become less effective as the temperature becomes too high for them to operate.

This formula for the r^2 line of best fit is given as:

$$y = 0.028x + 0.0786$$

Where:

y = ratio of gas production : gas production at optimal temperature of 35°C; and

x = temperature of digester(s).

Table 6 lists the following example values which were gained for a reduction in biogas production at temperatures between 20 and 45°C using this formula.

Table 6 - Ratio of biogas yields at 5°C temperature steps

Temperature (°C)	Ratio of biogas yield at temperature to biogas yield at 35°C
20	0.6386
25	0.7786
30	0.9186
35	1.0586
40	1.1986
45	1.3386

This formula was then programmed into the tool with the proviso that temperatures below 15°C would not be recommended due to previous recommendations made regarding the financial impact of operating at such low temperatures. Additionally, heating above 45°C was not considered as this would be out of the mesophilic range and thus out of the scope of this study.

It is, however, appreciated that further research and work could lead to a tool which would take lower and higher temperatures into account. Additionally, whilst it is appreciated that the relationship between temperature and biogas production is not in fact linear, it will serve as a reasonable approximation for the purposes of this study.

3.4.3. Mixers – biogas yield

Biogas digesters often have mixers, also called agitators or stirrers, within the digestion tanks. They are considered necessary to ensure an even distribution of bacteria and enzymes within the tank (Parkin and Owen, 1986; Stenstrom at al., 1983). It has also been shown (Stenstrom et al., 1983; Kaltschmitt et al., 2009; James

at al., 1980; Weiland, 2010) that mixing is important to help avoid the formation of crusts and sedimentation, as well as ensuring a homogenous temperature and distribution of nutrition and trace elements necessary for the bacteria. Finally, mixing encourages the off-gassing of biogas from within the digestate (Ong et al., 2002).
The benefits provided by mixers have been much debated (Karim et al., November 2005) and there is yet to be a consensus reached on the topic; currently there are many studies, but they often hold conflicting arguments.

In an analysis of the digestion of cattle manure slurry, Ong et al. (2002) used continuous mixing, intermittent mixing (½ hour mixing, 5 ½ hour break) and no mixing. They found no difference in biogas production between the intermittent and continuous mixing modes, and actually found that no mixing led to an increase of biogas production of up to 28.4%.

Another study using digesters fed by buffalo dung (Abdel-Hadi and Abd El-Azeem, 2008) examined digesters which were either mixed at room temperature or mixed at an increased temperature; these were compared to a control which was not mixed and at room temperature. This study found that whilst mixing at an increased temperature increased yield by 20% and 61.5% for the horizontal and vertical mixers respectively, biogas yield was 42% lower (for both digesters) when mixed at room temperature, compared to the control.

Additionally, Chen et al. (1990) observed methane yields from municipal solid waste to be 10-20% higher (dependent on HRT and loading rate) for unmixed when compared to a continuously mixed 4.5m^3 digester.

Conversely, Ho and Tan (1985) observed slightly higher (7%) methane production for a continuously mixed digester when compared to a non-mixed digester when using palm oil mill effluent as a feedstock.

Karim et al. (November 2005) performed experiments on mode of mixing and concentration of feedstock (manure slurry) used. They found that whilst unmixed and mixed digesters performed similarly when fed with 5% manure slurry, mixing had an impact on biogas yield when the slurry concentration was increased. They concluded that:

"Digesters fed with 10% manure slurry and mixed by slurry recirculation, impeller, and biogas recirculation produced approximately 29%, 22% and 15% more biogas than unmixed digester, respectively".

Additionally, Hashimoto (1982) showed that continuously mixed digesters fed with cattle waste produced 8-11% more methane than digesters mixed for 2 hours per day. It can be seen that there still remains much work to be completed in this field; it is still unclear which mixing regimes are most appropriate for which feedstocks HRTs and loading rates in regards to biogas production.

For the purposes of this study, it was therefore deemed inappropriate to alter the tool so that biogas output was affected by the use of mixers. They are, however, deemed important, and a large-scale system can fail if improperly mixed (Parkin and Owen, 1986). Wang et al. (2009) also state that a small-scale digester operates far more effectively when mixed; it is therefore recommended that mixers are used when financially possible

3.4.4. Shredders – biogas yield

Shredders are one of a multitude of mechanical pre-treatment methods available for feedstock; others include ultrasonic treatment, lysis centrifuge, liquid shear, collision plate, high pressure homogeniser and grinder - similar to a shredder (Carrère et al., 2010). These methods all serve to reduce substrate size to increase surface area available to microorganisms and their enzymes, resulting in an increase in food availability to bacteria. This process is especially relevant to substrates which are hard to break down due to their lignocellulosic structure – many plants such as maize, switchgrass and elephant grass come under this category (Montgomery and Bochmann, 2014).

According to Palmowski and Muller (1999), reducing the particle size of substrate has two effects: firstly, if the substrate is fibrous with a low degradability, there will be an improvement in gas production, and secondly, there is a reduction in digestion time.

Sharma et al. (1988) investigated the effects of 5 different particle sizes (0.088, 0.40, 1.0, 6.0 and 30.0mm) of 7 agricultural and forest residue feedstocks in batch digesters at 37°C. It was found that the smallest particle sizes of 0.088 and 0.4mm produced the highest gas yields, with a yield improvement of 7% on average when compared to the 6mm particles. It was also found that whilst larger particles (30.0mm) of succulent materials such as leaves could be used, larger particles of lignocellulosic materials such as straw decreased biogas yields significantly.

In a separate study, Sharma et al. (1989) also studied the digestion of the stem of *Ipomoea fistulosa*, and found that 0.4mm particles produced 98% more biogas than 6mm particles.

Reviewing experiments performed on examining the effect of particle size reduction of sewage sludge upon biogas yield; Baier and Schmidheiny (1998) reported an increase in biogas yield of 10%, and Wett et al. (2010) reported a 41% increase in yield when using grinders.

Barjenbruch and Kopplow (2003) found an improvement of approximately 20% and Engelhart et al. (2000) reported an improvement of 60% when studying the effects of high pressure homogenisers.

Whilst studies clearly show that reducing particle size increases biogas yield, figures vary greatly depending on many factors including particle size reduction method, substrate type, and particle size. Using current knowledge, it is therefore impossible to deduce an accurate figure for use in the tool.

Whist acknowledging that further laboratory work would be required to build a greater degree of accuracy into the tool, for the purposes of this study it was deemed reasonable to take a mean value to use in the tool. Discounting the value of 98%

(Sharma et al., 1989), which was assumed to be an outlier in the data, a mean value for the biogas production increase due to shredders of 27.6% was arrived at.

From the above, it would be recommended that shredders be used if the feedstock used has a high lignocellulosic content.

3.5. Derivation of Financial Variability Factors

To derive these factors, a literature review was conducted regarding the specific components considered. The figures found within the literature review were then analysed and processed to derive a "financial variability factor"; which was a value by which cost varied when a component was used compared to when it was not. These factors were then built into the tool – as explained in section 3.6.

3.5.1. Single-stage vs. two-stage digestion – cost

The tool currently calculates the required size of digesters based on the amount and rate of substrate input into the BD. Therefore the cost calculation involved initially finding costs per m^3 of digester volume. Nijaguna (2007) states that the cost of a simple, unheated digester is in the region of $50-60 USD. Similarly, ISAT (2015) suggests a figure of $50—75 USD. An average of $58.75 USD was taken, and converted to GBP at an exchange rate of $1 USD = £0.65 (Xe.com, 2015) to give £38.20.

For two-stage digestion, processing the same rate and amount of substrate as single-stage digestion, the requirement is simply another digester of exactly the same size. This is because all of the substrate is transferred from the first into the second digester. Therefore the cost increase over single stage digestion is £38.20 x digester volume (m^3).

3.5.2. Heated digestion - cost

Heating is already considered by the tool; if heating is required then the appropriate amount of heat produced by the CHP unit is used for heating, and the remainder sold to the district heating network. In this sense, a "CHP" unit can either provide heat and power to the grid, or only power, with engine coolant providing heating to the digester(s). If, however, there is no CHP unit and the system is only to be used to produce gas for sale, then the gas required for heating must be calculated.

If the digesters are to be unheated, there will be a decrease in gas output which is calculated by the tool according to the formula y=0.028x + 0.0786, derived in section 4.1.2. There will also be no requirement for any gas to be used for heating. Therefore 100% of gas produced can be sold and there is no need for the tool to be altered in this case.

Again, for the case of heating between 20-35°C, there will be a reduction in gas production when compared to the baseline optimal temperature of 35°C. This will lead to an overall lower gas production and decreased revenue. For heating from 35-45°C, there will be an increase in gas production.
Additionally, there will be a requirement for a portion of the gas produced to be used to heat the digesters; this can be calculated from the following:

$$Q = mC_p\Delta T$$

Where:
Q = energy required to heat substrate (kWh/year);
m = mass of substrate input to the system (kg/year);
C_p = specific heat capacity of substrate (kJ/kg°C); and
ΔT = change in temperature (°C) (Rogers and Mayhew, 1992).

m - known for each specific system considered.
C_p - assumed to be the same as water at 4.17kJ/kg°C.

Therefore the only unknown is ΔT, which will be calculated as the temperature increase of the digester relative to the ambient temperature. As this will be different for different locations and times of the year, it would be prudent to analyse the case for heating vs. non-heating for different values of ΔT.

Once ΔT is determined, Q can be obtained, and the requirement for gas input into the digester heaters calculated accordingly. This will be done using the calorific value of methane as 11.04kWh/m^3 (ISO 6976, 1995).
Additionally, the gas requirement will increase due to heater efficiency, assumed conservatively to be 85% (if heater efficiency is known then the formula will change accordingly). The final formula is therefore:

$$Gas\ required\ to\ heat\ digestate\ per\ year = \frac{mC_p\Delta T}{11.04 \times 0.85}$$

The methane produced will then be reduced by this amount and thus reduce revenue.

Initial capital costs for the heating system have to also be considered. Due to the wide range of heating options available – one report by MinErgy Pvt. Ltd. (2014) discusses 10 different options for heating small-scale BDs alone - it was decided that heating options would have to be considered and priced on a case by case basis.

3.5.3. Mixers - cost

Mixers consume a large proportion of the energy required to run a biogas plant – in the region of 29-54% (Dachs and Rehm, 2006), dependent on type and operation time. There is therefore scope to significantly reduce the running cost of a BD through research into optimal mixer types and operating schedules; the energy requirement of a specific mixer and operating schedule is an input into the tool and thus if this were known it would be easy to alter a system analysis accordingly.

As recommended above, BDs should use mixers due to the danger of failure. Therefore, whilst removal of a mixer could provide considerable cost savings, this is outwith the scope of this study.

3.5.4. Shredders - cost

As for mixers, the tool calculates shredder energy requirements based on input for specific shredder type and operating schedule. This requirement for energy is then used to calculate the corresponding reduction in net energy production.

Therefore it is left to calculate the capital required, as well as maintenance cost. As there are such a wide range of mechanical pre-treatment options available, it is not possible to quantify an acceptably uniform cost. Additionally, certain methods work better for certain substrates; for example, Baier and Schmidheiny (1998) stated that "Ball milling consistently showed better disintegration results than high speed cutter milling" – this was for experiments using sludge. It was therefore decided that a shredder would be chosen on a case by case basis.

3.6. Tool Alteration to Include Variability Factors

Table 7 - Derived performance and financial variability factors

	Variability Factor	
Component	Performance	Financial
two-stage Digestion	1.177	£38.20 x digester volume (m^3) + maintenance cost
Heating	0.028*temperature+0.0786 (inapplicable below 15°C)	Saleable gas price (£)*$mC_p\Delta T$/11.04*0.85 + capital + maintenance cost
Mixer	n/a	n/a
Shredder	1.276	case by case (capital + maintenance cost)

Table 7 summarises the variability factors derived in sections 3.4 and 3.5; in the case of performance variability factors, they are a factor by which the final biogas output is to be multiplied; this was quite a simple task to input these values into the tool. In the case of the financial variability factors, two-stage digestion gave an additional capital cost for the plant; heating and the addition of a shredder gave additional capital cost as well as a yearly cost.

To input these into the tool was a more complicated task, because as the tool stood, it had no way of calculating the financial viability of the plant.

Therefore a new "Financial Viability" section to the tool had to be built (shown in *Table 8*).

Table 8 - Financial viability screenshot

Financial Viability

Gross Profit from Outputs	Amount			Price(£/unit)
	Lowest	Middle	Highest	
Methane (kWh/yr)	22034658.45	73301561.77	116671496.9	0
Electricity (kWhel/yr)	5588488.46	21452546.53	34850382.81	0.145
Heat (kWhth/yr)	6430401.748	33409397.21	55887120.83	0
Slurry (tonnes/yr)	448811.3	613061.3	777311.3	5
Additional proft (£/yr)	80000	90000	100000	1
TOTAL	3134387.326	6265925.746	9039862.008	

Savings	Amount		
	Lowest	Middle	Highest
Local waste treatment fee (£/tonne)	0	0	0
Waste treated (tonnes/yr)	448811.3	613061.3	777311.3
Grants available (£/yr)			
TOTAL	0	0	0

Yearly Costs	Amount		
	Conservative	Median	Optimistic
Cost of feedstock (£/yr)	232140	232140	232140
Plant maintenance (£/yr)	99794.43675	383081.188	622328.2645
No. of workers	5	4	3
Wages/worker (£/yr)	30000	27500	25000
No. of vehicles	1	1	1
Cost/vehicle (£/yr)	29000	27000	25000
Maintenance/vehicle (£/yr)			
Mileage/vehicle (km/yr)	17000	15000	13000
Fuel cost (£/km)	0.4	0.35	0.3
Vehicle fuel (£/yr)	6800	5250	3900
TOTAL	568403.8638	826683.9391	1046124.34

Financial	Amount		
	Lowest	Middle	Highest
Investment/loan required (£)	1325000	1300000	1285000
Interest on loan (%/100)	0.07	0.065	0.06
Plant life/required payback period (yrs)	22	20	20
Amount to pay back on loan (£/yr)	119787.6495	117983.314	112032.1557
Gross profits (£/yr)	3134387.326	6265925.746	9039862.008
Costs (£/yr)	688191.5133	944667.2531	1158156.495
Net profits (£/yr)	2446195.813	5321258.493	7881705.512

From this we can see that the tool now calculates the possible income streams from the plant outputs – namely methane, electricity, heat, slurry fertiliser and any other possible output. If the plant does not gain revenue from a particular output, then a price of zero is put against that output. It also calculates the possible savings made from not having to pay gate fees for the disposal of the waste used – this is considered an income. Again, if there is no cost for the disposal of the feedstock used, then a price of zero need simply be set.

From these inputs the yearly gross income for the plant is calculated.

Running costs for the plant are then calculated from plant-specific inputs; maintenance costs were set at £0.018/$kWh_{el,\ produced}$ (Hahn, 2011).

Next the financial details: initial investment, interest on loan and required payback period on loan are input. From these, the following formula is used to calculate the yearly loan repayment:

$$Yearly\ loan\ repayment = \frac{Cr(1+r)^n}{(1+r)^n - 1}$$

Where:

C = value of the investment/loan (£);

r = interest on the loan (%/100); and

n = required payback period (years).

This is an additional cost for the plant. The costs associated with the inclusion of two-stage digestion, heating or shredders feeds into the investment/loan required (for two-stage digestion, shredder and heating) or yearly costs (heating and shredder). They are calculated using the part of the tool shown in *Table 9*.

Table 9 - Additional component cost calculator screenshot

2-Stage Digestion Cost?	lowest	middle	highest
1 or 2 stage digestion? (put 1 or 2 below)			
2	1558.119	1734.426923	1910.735
Heating Cost			
No CHP unit and separate heating? 1 below if true			
1			
Methane kwh/year lost to heating	1709.083	1902.472968	2095.863
Estimate of heater cost (£)			
Shredder Cost			
Estimate of shredder cost (£)			

Table 9 shows inputs in which determine if the system analysed utilises two-stage digestion, heating and a shredder. If there is two-stage digestion, then the estimates for digester size (calculated based on substrate input rate elsewhere in the tool) are multiplied by £38.20. These values are then taken and fed into the investment/loan required shown in *Table 8*.

If there is heating (without a CHP unit which would provide it for free), the methane requirement for this is calculated based on the formula in section 3.5.2 and this is subtracted from the methane output section shown in *Table 8*. The heater capital cost is calculated on a case-by-case basis and is fed into the investment/loan requirement shown in *Table 8*.

Finally, shredder cost is calculated on a case-by-case basis. The cost here is added to the investment/loan requirement shown in *Table 8*.

All of these inputs then give a final result of net profits per year; ultimately, whether or not the plant is profitable. If profits are negative, or not high enough, something will have to change – a longer payback period, less workers, higher price for outputs etc.

3.7. Tool Validation - Case Study: SBW Lelbach

Key Information

SBW Lelbach – shown in F*igure4* below - is a two-stage digester located in Lelbach, Germany, and thus requires heating. It has digestion tanks of 1700m³ each and storage tanks for liquid manure (250m³) and digested slurry (5000m³). It utilises simultaneous wet fermentation at pH 7.3-7.8, mesophilic conditions at approximately 40ºC, and a HRT of 60 days. All information regarding the plant is taken from Wiese and Kujawski (2008).

Figure 4 - SBW Lelbach (Maschinenring Waldeck-Frankenberg eV., 2015)

Inputs

Measurements of the input substrates were taken between August 2006 and January 2007 (184 days); these were as follows:

- 3242 tonnes liquid cattle manure: 17.8t/day, 4%DM(dry matter)
- 335 tonnes wheat/rye: 1.8t/day, 85%DM, 120EUR/t
- 5108 tonnes silage: 28.1t/day, 23-32%DM, 24EUR/t; comprised of 1% Sudanese grass, 27% green rye and 72% maize silage

Outputs

The plant is a CHP plant, capable of producing a maximum of 530 kW_{el} (at 35.6% efficiency) which is sold to the electricity grid and 625 kW_{th} (at 45% efficiency) of which approximately 70kW_{th} is used to heat the digesters and machine hall. To increase overall efficiency and revenue, between 350-430 kW_{th} is used to dry woodchips for sale and utilise a prototype latent heat storage unit. Therefore 125-230kW_{th} is wasted.

During the measured time period (184 days) 2,181,325 kWh_{el} was produced by the plant, corresponding to an average generator operating power of 493.95kW; just over 93% of its maximum.

Costs

Total plant costs were approximately EUR 1.8m, which corresponds to EUR 3396/kW_{el} and EUR 2880/kW_{th}.

3.7.1. Assumptions

In validating the tool, the following assumptions were made:

Inputs

- The plant digesters are 95% full on average
- The cattle liquid manure came from 320 cows – this corresponded to a middle estimate by the tool of 17.58t/d; comparable with the actual data of 17.8t/d.
- An insulation thickness of 100mm was assumed for pasteurisers and digester walls, with a k value of 0.04W/mK
- The tool has a number of feedstock inputs available for selection. To best approximate the inputs at Lelbach, “Dairy Cattle Manure” was chosen as the most appropriate feedstock option to represent liquid cattle manure, “Grass Clippings” was chosen for silage, and “Energy Crops” was chosen for wheat/rye

Outputs

- Wiese and Kujawski (2008) state that "the regional demand for biogas liquid manure is high", so it was assumed that the slurry could be sold easily – typical prices for slurry are in the region of £5-£15/tonne (BPEX, 2010), so a conservative estimate of £5/tonne was set. Additionally the manure comes into the plant at no cost so it can be reasonably assumed that a fair sell-back price will be given.
- The retail price of electricity was set at £0.145/kWh (European Commission, 2014).

Plant operation

- Maintenance costs were set at EUR 0.025/$kWh_{el, produced}$ (Hahn, 2011).
- A single 18-tonne truck was used to collect the feedstock and distribute the slurry, as daily manure input is slightly less than this at 17.8t/day. Costs for vehicle operation and maintenance were found in the Road Haulage Association Cost Tables (2006).
- Silage and wheat/rye were delivered to the plant, as they are paid for
- An exchange rate of GBP 1 = EUR 1.4 (Xe.com, 2015)
- Gate fees were set to zero as cattle manure is not waste which requires processing (Regulation (EC) No 1069/2009, 2009), and the silage and wheat/rye is being bought into the plant.
- The plant has between 2 (low estimate) and 4 (high estimate) workers, including driver. A minimum of 2 workers was taken from INFORSE – Europe (2006), which states that 420 employees/TWh/year are required. The plant generates 4.33 GWh/year (actual); 4.33×10^{-3} x 420 = 1.8 workers. It was assumed, therefore, that at least one worker had to be on site and one driver would be required.

3.7.2. Methane production

Inputting these details gave the following estimates for methane production:

Low estimate: 1126.5m^3/day

Middle estimate: 1959.4m^3/day

High estimate: 2690.4m^3/day

There was no recorded data available for the methane production from the plant, but; 2,181,325kWh$_{el}$ was produced in 184 days.
2,181,325/184 = 11855kWh/day.

With an engine converting chemical to electrical energy at an efficiency of 35.6%, and running at 93% of its maximum;

$$0.93 \times \frac{11855}{0.356} = 30969\ kWh/day$$

This is the energy available from the methane supplied, and using 10.19kWh/m^3 methane (ISO 6976, 1995), 30969/10.19 = 3039.2m^3 methane produced/day.

This is close to the estimates given by the tool; 13% above the highest estimate of 2690.39m^3/day.
The fact that the estimated values were below actual values will be partly because the biomass yields from the feedstocks within the tool used to approximate actual feedstocks will be lower. Another reason could be due to the phenomenon of co-digestion.

To increase the accuracy of the tool estimate, measured values for the actual feedstocks used were input these into the tool database. This was taken from data published by the Kuratorium für Technik und Bauwesen in der Landwirtschaft (KTBL); *Table 10* lists the expected biogas and methane output.

Table 10 - Biogas and methane output for plant using KTBL figures

Input	Biogas Yield (m^3/t wet weight)	Methane Yield (m^3/t wet weight)	System Input (t/day)	Biogas Output (m^3/day)	Methane Output (m^3/day)
Wheat Grains	625.8	317.0	0.9	563.2	285.3
Rye Grains	625.8	317.0	0.9	563.2	285.3
Grass Silage	161.6	89.9	2.8	452.5	251.7
Rye Silage	139.5	74.7	7.6	1058.8	567.0
Maize Silage	171.8	90.9	20.2	3475.5	1838.9
Cattle Slurry	12.9	5.7	17.8	229.6	101.5
			TOTAL	**6342.9**	**3329.7**

Taking this value of 3329.7m^3 methane/day and multiplying it by the two-stage digestion and heating factors of 1.17 and 1.1986 respectively gives a now optimistic value of 4669.44m^3 methane/day; 54% over 3039.2m^3.

The real figure for methane production could lie somewhere between the two; the figure of 3039.2m^3 was calculated on engine efficiencies alone, but there of course will be other inefficiencies within the system. If we could reasonably assume the system (excluding the engine) was 90% efficient, which would bring the estimate for methane output using KTBL figures within 33% - within acceptable levels.

Additionally, when Wiese and Kujawski compared theoretical values for the plant with recorded plant data, they also observed that the plant was over-producing when compared to theoretical yields. They suggested this could be because theoretical yields were based on lab results using an HRT of 28 days, whereas the plant has a 60 day HRT; co-digestion could also play a part here in explaining the discrepancy.

Due to the complexity of the processes taking place, it would be necessary to perform laboratory tests to truly determine methane output. Such measures are out of the scope of this study, however; for the purposes of validating this tool it has already been shown to work to an acceptable degree of accuracy in estimating methane output.

3.7.3. Electricity generation

Using the above estimate for methane production of 4669.44m^3/day, the tool estimates that net electricity generation, available for export will be 5,985,975 kWh/year.
Actual (net) electrical output for the plant was 4,327,084kWh/yr. For this plant, Wiese and Kujawski assume that 15% of electricity produced is required for plant operation – comparable to the estimates from 7.5% to 14.5% given by the tool – this is already built into the estimated figure of 5,985,975 kWh/year given by the tool for net export energy available.

In addition, Lelbach plant uses 20% of energy produced to compress and purify biogas. This was not built in to the tool estimate, as it is an additional feature, specific to Lelbach. We can therefore reduce our figure by 20% to gain 4,788,780 kWh/year net electrical output. This is very close to the actual value - only 11% higher. This small difference will have to do with differences in the actual and modelled components, operating schedules and feedstocks.
Again, the tool has been shown to give an optimistic value, but has been shown to work to within an acceptable degree of accuracy in estimating electrical output.

3.7.4. Heat generation

Again, using the corrected values for methane output, the tool estimates 10,458,419 kWh/year will be available for heat export.
There are no figures for actual heat production available, but the CHP unit used is capable of producing 625kW_{th}. As the engine is running at 93% capacity, this will be 581kW_{th}, which is equivalent to 5,091,750kWh/year.

Therefore the estimate is 105% above actual/inferred heat generation, which will again be due to differences in the system used – for this case, whilst within the same order of magnitude, the tool does not predict heat generation to within an acceptable degree of accuracy. This was considered acceptable as heat generation is out of the scope of this study.

3.7.5. Financial viability

Electricity

Wiese and Kujawski state that "The electricity is fed into the local electricity network". From this statement, it was not entirely clear if the electricity was being sold on to local customers at a retail price, or into the grid at a wholesale price. It was therefore necessary to evaluate the difference between the two.

If the electricity were being sold at a retail price, the price would be approximately £0.145 (European Commission, 2014).

If, however, the electricity were being sold at a wholesale rate, then the following feed-in tariff shown below in *Table 11* could be used:

Table 11 - Electricity feed-in tariffs in Germany (Hahn et al., 2010)

Electricity feed-in tariffs in Germany 2009 (€ct/kWh$_{el}$)

€-ct/kWh$_{el}$	Basic tariff (2009)	Bonus for energy crops	Bonus for CHP	Technology bonus	Bonus for manure	Formaldehyde bonus
< 150 kW$_{el}$	11.67	7	3	up to 2	4	1
< 500 kW$_{el}$	9.18	7	3	up to 2	1	1
< 5 MW$_{el}$	8.25	4	3	up to 2	0	0
< 20 MW$_{el}$	7.79	0	3	0	0	0

The CHP plant produces electricity at a power of 494kW, and uses energy crops and manure as inputs. It was unknown whether or not the plant would be eligible for technology or formaldehyde bonuses, so these were discounted. The plant will therefore receive a feed-in tariff of EUR 0.2018 = £0.144. These prices are set for 20 years (Lang and Lang, 2015), the assumed lifetime of the plant, so they were considered to be steady.

The two prices are almost identical; the lower was chosen conservatively.

Additional profit from woodchips

An aspect of this particular plant which is not modelled by the tool is the income made available by drying woodchips. Calculations to estimate an income were based on the following assumptions:

- Woodchips with mc (moisture content) of 50% were bought at £70/tonne (Forest Fuels, 2015).
- The woodchips were then dried to 20% mc and sold at £140/tonne (Forest Fuels, 2015).
- Time to reduce the mc of woodchips was 6 days. This was assumed due to the following statement made by the Biomass Energy Centre:

  "Data suggests that green chip can be dried relatively quickly (2–3 days) to 25–30% with minimal energy input, using fan and ambient air. Further reduction of moisture content to below 20% requires longer drying time if energy input is not to be excessive. Reduction can take place in around 6 days for warmed air."
- Dry density of woodchips was taken conservatively as 400kg/m^3 (Forest Power, 2015). Densities for specific moisture contents was then calculated using the following equation for mc greater that 23%;

$$\rho m = \frac{\rho kT}{\left[(1 - 0.0003\rho kT)\left(1 - X(1 - 0.001\rho kT)\right)\right]}$$

And for mc below 23%;

$$\rho m = \frac{\rho kT}{1 - X}$$

(Forest Power, 2015).

Where:

X = moisture content (%/100)

ρm = wet density of wood (kg/m^3)

ρkT = dry-fresh density of wood (kg/m^3)

- The plant has 4 mobile containers, each with 35m^3 capacity. Loading and unloading of them will take a day each (i.e. 2 days for all 4 to be loaded and emptied).

Using the above assumptions, it is possible to calculate profit from woodchips thus:

- 35m^3 * 4 = 140m^3 total mobile container volume
- 6 days drying + 2 days loading/unloading time = 8 days turnaround/140m^3 of chips
- 365/8 = approximately 45 full loads/year
- 140 * 45 = 6300m^3/year
- Using the formulae in the assumptions, density at 50% mc = 800kg/m^3 and 516.5kg/m^3 for 20% mc
- Cost of buying chips at 50%mc = 6300 * 800 * 70/1000 = £352800
- Price of chips sold at 20%mc = 6300 * 516.5 * 140/1000 = £455553
- Profit = £102753/year

As a check, it is known that 350-430kW (say 390 kWh) is used for drying the chips. Over 6 days, this is 56160 kWh to dry 112000 kg = 0.5kWh/kg. Large installations can have an energy usage in the range of 990kWh/tonne for reducing mc from 55% to 10% (Forestry Commission Scotland, 2011), which is equivalent to 0.99kWh/kg. As this plant has only been assumed to be reducing the mc to 20%, the figure of 0.5kWh/kg seems reasonable.

<u>Final calculation</u>

Inputting all of the assumptions and data from earlier gives a middle estimate of net profit of £449,460/year. This is, however, based upon the optimistic electricity estimate of 4,788,780 kWh/year.

Inputting the actual figure of 4,327,084 kWh/year gives a figure of £238,750/year.

From this we can see that finances are quite tight for the plant. INFORSE – Europe (2006) states that:

"it is difficult to make biogas plants cost-effective with sale of energy as the only income".

Considering this, and the fact that an income of almost £200k/year for this estimate comes from a combination of slurry and woodchip sales, it seems that the estimate is within the right degree of magnitude. However, as there is no data available for the profitability of the plant, it is very difficult to say whether or not this lies within 50% of the actual figure.

3.7.6. Conclusion on tool accuracy

The tool appears to show a reasonable level of accuracy in methane output and electricity generation, but not heat generation – over estimating considerably.

Estimates of methane yield were initially 13% lower than actual figures; once corrected using figures for actual feedstocks used rather than approximations, estimates became optimistic; over-estimating by 54%. Further correcting for system inefficiencies brought estimates down, over-estimating by 33%.

The "actual" methane yield of the plant itself was a calculation based on electricity production, system efficiencies and calorific values of methane, so it is in fact unlikely that these are 100% accurate. Indeed, the figures for estimates also have biogas production factors for two-stage and heated digesters, so increase yield by 34%. It would appear difficult to estimate methane yield accurately without knowing all of the system specifics of Lelbach, but it is likely that the actual figure lies within 50% of estimated values and so the tool was deemed valid for the purpose of estimating methane yield.

Electricity generation was similar; estimated production was only 11% higher than actual figures. This was generation from the corrected methane yield, it is possible that part of the reason for the discrepancy lies there. It will also be due to differences in the systems components and operating schedules – again, impossible to model without knowing exactly the details of Lelbach. Analysing this is, however, out of the scope of this study as the tool has been shown to predict electricity output to within an acceptable level of 50%.

Heat production was over-estimated by 105% and was thus not deemed to be within acceptable levels - likely the only reason for the discrepancy is down to specific details regarding the CHP system, the correction of which is outwith the scope of this study as heat generation is not a focus.

The profitability of the plant was shown to be likely within the correct level of magnitude – it was however, impossible to determine the exact accuracy due to lack of financial detail about the plant.
In all, the tool has shown that it is capable of estimating figures to within an acceptable degree of accuracy.

3.8. Tool Modelling for Small-Scale Biogas Digesters

The tool being used is designed to analyse large-scale plant with several components. However, as discussed in Chapter 2, a BD can be very simple; a small scale household BD can operate with only the following components:

- Input buffer
- Digester (unheated)
- Output buffer

This alternative BD configuration uses only the essential components required for biogas production, and such systems are commonly used in developing countries as they can produce biogas at the lowest cost possible. An example of such a system used in Cameroon is shown in *Figure 5*. This is a household-scale plant, processing manure from 20 pigs in an 8m^3 digester, producing approximately 4-5 hours of biogas for cooking per day.

Whilst such a system has been proven to be functional at low cost (approximately £1000 for the entire unit including labour), improvements may be possible. Adding certain components (an additional digester, heaters, mixers and shredders) to the system would not only increase biogas production, but could also increase biogas production at a proportionally acceptable increase in cost, so that the plant is more profitable and the payback period for the system reduces. Such improvements to a BD could prove attractive to potential end users, and as such was examined.

Figure 5 - Example of a small scale BD in Belo, NW region, Cameroon (2015)

To explore the potential for such improvement, this household scale plant was modelled using the tool. To do so, the tool was first be "stripped back" so that only essential components were considered.

Then, combinations of components which could be used to increase biogas production were systematically added, and changes in biogas output and financial viability recorded. Finally, recommendations were made.

3.8.1. Case study: household-scale BD in Cameroon

Key information

The case study is a single-stage BD with a digestion tank of $8m^3$, and storage buffers for feedstock (swine manure and urine) and digested slurry of $0.5m^3$and $1.5m^3$ respectively. It utilises wet fermentation, mesophilic conditions, without heating, and an HRT of approximately 30 days. It is located in Belo, in the NW highland region of Cameroon, which experiences two seasons a year; a warm sunny dry season and a cooler wet season. Temperatures over the year fluctuate between 15-25ºC.

Inputs

The plant has a channel running from a pig pen behind the plant, downhill to the plant input buffer. This provides the plant with manure and urine from 20 swine; equivalent to approximately 150kg/day.

Outputs

Currently, all of the biogas produced is used within the household as cooking fuel; reportedly between 4-5 hours of cooking time/day. At a rate of approximately 200-450l/h for cooking (Tilley et al., 2014) - dependent on burner and gas pressure; this corresponds to $1\text{-}2.5m^3$/day. Currently the digestate is not sold or used for any purpose.

Finances

The plant costs are broken down as follows (Chiambah, 2014):

Building materials:	£550
Pipework, appliances:	£100
Labour:	£350
TOTAL:	£1000

It is appreciated that this is a simplistic breakdown, but as the vast majority of the building materials and labour work are dedicated to building the digester (of which an additional one will be required for our analysis), it was deemed to be sufficient. A more detailed, itemised breakdown of costs can be found in *Table 17* in Appendix 1.

The plant itself was built to reduce the need for firewood and the associated health and environmental problems which come with it. Prior to cooking on biogas, this household spent approximately £20 on firewood/month. Capital investment of £1000, divided by £20 gives a payback period of 50 months - just over 4 years (Chiambah, 2014).

If the biogas yield improves with the addition of components, then there will simply be more biogas available to the household; payback period will not improve unless biogas is sold - either by piping it to a neighbour or compressing and bottling it - or an electricity generator is fitted and savings made to the household electricity bill, or energy exported.
As such plants are frequently in operation in areas where there is no electric network, considering electricity was out of the scope of this study. Selling the additional biogas via pipeline shall be explored instead; from the financial breakdown, pipework and appliances cost £100. It can be reasonably assumed that a similar cost will be incurred to pipe gas to a neighbour.

3.8.2. Removal of non-essential components

The following components needed to be removed from the tool in order to model a household-scale BD:

- Reception tank mixer
- Input buffer tank mixer
- Digestate mixer
- 1st and 2nd stage digester mixers
- Primary and secondary shredders
- 2nd stage digester
- Reception tank discharge pump

- Pasteurisation mixer
- Pasteuriser
- Input buffer tank discharge pump
- Pasteurisation discharge pump
- 1^{st} and 2^{nd} stage digester discharge pumps
- Heat exchanger 1 (exit from 2^{nd} stage digester)
- Heat exchanger 2 (exit from pasteuriser)
- Heat exchanger 3 (exit from engine coolant)
- Bio filter air fan
- Gas holder air fan
- CHP gas engine
- Heating for 1^{st} and 2^{nd} stage digesters

Dis-enabling the pasteuriser and second-stage digester was done by setting their HRTs to zero i.e. the feedstocks were not considered to pass through the components.
The remainder of the components are only considered by the tool in order to calculate their energy requirements; they were therefore set to zero.

3.8.3. Addition of components

The addition of components had to be performed in a systematic way so that the effects of adding a component could be easily seen. The same three components – input buffer, digester, and output buffer – were always present in the analysis, and the other components – digester 2, shredder and heating (different levels) – were systematically added, whilst recording the corresponding changes in performance and cost. Mixers were not added as they were no suitable factor was found by which they could be deemed to improve methane yield (see section 3.4.3), and they would only serve to increase cost with no benefit. These combinations are shown in a matrix (see *Table 12).* This shows all the possible combinations of additions of components added to the original system.

As the ambient temperature is 15-25ºC, it was decided that digestion should take place at the mean temperature of 20ºC. Where heating was used, 3 separate heating temperatures were chosen; 25, 30 and 35ºC. It is appreciated that modelling over a year using weather data for ambient temperature would provide more accurate results, but is outwith the scope of this study.

Table 12 - Matrix showing combinations of components

	Component			
System name	Digester 1	Digester 2	Heating Temp. (°C)	Shredder
1	x	x		
2.1	x		25	
2.2	x		30	
2.3	x		35	
3	x			x
4.1	x	x	25	
4.2	x	x	30	
4.3	x	x	35	
5	x	x		x
6.1	x		25	x
6.2	x		30	x
6.3	x		35	x
7.1	x	x	25	x
7.2	x	x	30	x
7.3	x	x	35	x

As a check that the tool is valid for the analysis of a small-scale system, the details for the system as it stands were input; this gave a daily biogas output of 1.3-1.8m^3/day; within the estimates (based on 4-5 hours cooking time/day and 200-450l/h for cooking) for actual production of 1-2.5 m^3/day.

3.8.4. Costing of components

As discussed in section 3.5.1 above, the additional cost of a second digester would simply be the same as the original digester, as they are identical. In this case study, this would be £550. However, the costs of heating and shredders were not quantified; in section 3.5 it was decided that due to the large range of solutions available, they should be evaluated on a case by case basis.

Shredder

For this plant, processing 150kg of swine manure/urine per day, it was deemed most appropriate to equate this feedstock to sludge, which is similar in moisture content and biogas production potential. Ideally, a range of studies analysing this feedstock would have been analysed, and the most appropriate shredder chosen and costed.

However, whilst there is a range of information on pre-treatment of feedstock, and the effect upon biogas yield (amongst other factors), cost information is extremely limited. Müller (2001) states that "The evaluation of capital and operational costs is difficult, because of the lack of full-scale experience", but gives a rough estimate of between $70-150 USD/ton for capital and operation and maintenance costs. This was the only data available on the subject of cost, and as it considered only larger scale, was deemed insufficient for the purposes of cost analysis.

Heating

For heating methods, a document compiled by MinErgy Pvt. Ltd. (2014) was consulted; this group has vast experience working with the type of BD used for the case study – indeed, the BD used in Cameroon is based on the design used in Nepal, of which there are over 280,000 built and in operation (BSP Nepal, 2012).

The recommendation from this document was a solar-powered heater, using water which is then pumped through the BD to heat the substrate to the required temperature. A schematic of the recommended system is shown in F*igure 6*.

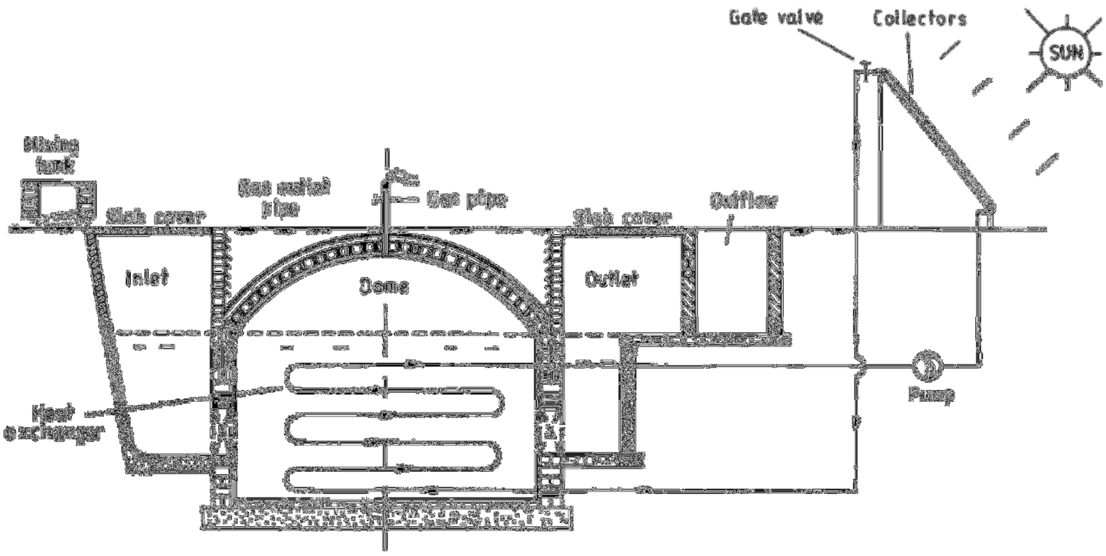

Figure 6 - Schematic of solar-heated BD (MinErgy Pvt. Ltd., 2014)

Again, however, costs were unavailable. It was therefore decided that the model be altered slightly; rather than making comparisons between yield improvement and cost increase, a boundary was set so that a maximum acceptable cost increase could be determined.

The payback period for the plant as it stands is currently 4 years (approximately). It was decided to analyse a range of acceptable payback periods; increases of 25, 50, 75 and 100% (i.e. 4 years to 5, 6, 7 and 8 years respectively) were set. In evaluating the maximum acceptable investment, the following was used:

$$Maximum\ investment = 5 \times yearly\ income - 1000$$

Where

$$Yearly\ income = £20\ per\ month \times 12 \times yield\ increase\ ratio$$

If an addition to the plant caused biogas yield to improve and the associated cost increase meant that the payback period was acceptable, then the additional component(s) could be considered a success and be recommended.

4. Results

4.1. Variation in Performance

The performance and financial details for the original system are shown in *Table 13*. When components were added to the system, improvements in biogas production were recorded as shown in *Table 14*. This compares the 7 possible systems (15 configurations in all when different heating regimes are considered) with the original system. It shows that with the addition of a singular component, it would appear that adding heating would improve yield the most. A shredder is the second most advantageous addition and a second digester the least.

Table 13 - Performance and financial details for original system

Income/year (£)	Biogas yield (m^3/day)	Capital cost (£)	Payback period (years)
240	1-2.5	1000	4.16

Again, when two components are added, it is always the combination including heating that improves yield the most. Therefore, if heating is comparable in price to either a shredder or a second digester, its addition should be prioritised.

When using all three components, it is clear that the best results are achieved when heating at higher temperatures. The performance variability factors in *Table 7* (derived in section 3.6) are factors by which to scale up biogas yield and as such these results are to be expected. It is when analysed in combination with the maximum allowable investment that they become more interesting.

Table 14 - Yield improvements for all systems

System	Yield improvement (%)
1 - Second digester	11.7
2.1 - Heating at 25°C	22
2.2 - Heating at 30°C	44
2.3 - Heating at 35°C	66
3 - Shredder	38
4.1 - Second digester, heating at 25°C	54
4.2 - Second digester, heating at 30°C	61
4.3 - Second digester, heating at 35°C	85
5 - Second digester, shredder	54
6.1 - Shredder, heating at 25°C	68
6.2 - Shredder, heating at 30°C	99
6.3 - Shredder, heating at 35°C	129
7.1 - Second digester, shredder, heating at 25°C	88
7.2 - Second digester, shredder, heating at 30°C	122
7.3 - Second digester, shredder, heating at 35°C	156

4.2. Maximum Allowable Investment

Evaluating maximum allowable investment using the formula derived in section 3.8.4, *Table 15* was gained for a 5 year payback period; *Table 16* compares this with 6, 7 and 8 year payback periods. Note that the maximum investment covers initial investment and maintenance costs, as well £100 for a pipeline to supply and sell biogas to a neighbour – assumed to be sold at the same value the household is presently gaining through firewood savings.

Table 15 - Maximum investment possible with 5 year payback period

Maximum Acceptable Investment for a 5 Year Payback Period		
System	Income/year (£)	Maximum investment (£)
1 - Second digester	268.08	340.4
2.1 - Heating at 25°C	292.8	464
2.2 - Heating at 30°C	345.6	728
2.3 - Heating at 35°C	398.4	992
3 - Shredder	331.2	656
4.1 - Second digester, heating at 25°C	369.6	848
4.2 - Second digester, heating at 30°C	386.4	932
4.3 - Second digester, heating at 35°C	444	1220
5 - Second digester, shredder	369.6	848
6.1 - Shredder, heating at 25°C	403.2	1016
6.2 - Shredder, heating at 30°C	477.6	1388
6.3 - Shredder, heating at 35°C	549.6	1748
7.1 - Second digester, shredder, heating at 25°C	451.2	1256
7.2 - Second digester, shredder, heating at 30°C	532.8	1664
7.3 - Second digester, shredder, heating at 35°C	614.4	2072

Table 16 - Maximum investment possible with 5, 6, 7 and 8 year payback periods

Maximum Acceptable Investment (£) with Payback Period				
System	5 year payback period	6 year payback period	7 year payback period	8 year payback period
1	340.4	608.48	876.56	1144.64
2.1	464	756.8	1049.6	1342.4
2.2	728	1073.6	1419.2	1764.8
2.3	992	1390.4	1788.8	2187.2
3	656	987.2	1318.4	1649.6
4.1	848	1217.6	1587.2	1956.8
4.2	932	1318.4	1704.8	2091.2
4.3	1220	1664	2108	2552
5	848	1217.6	1587.2	1956.8
6.1	1016	1419.2	1822.4	2225.6
6.2	1388	1865.6	2343.2	2820.8
6.3	1748	2297.6	2847.2	3396.8
7.1	1256	1707.2	2158.4	2609.6
7.2	1664	2196.8	2729.6	3262.4
7.3	2072	2686.4	3300.8	3915.2

4.3. Summary of Results

Tables 14, 15 and *16* show the following:

System 1 – Second digester

Adding a second digester to the system increased biogas production by 11.7%. Maximum possible investment was £340.40, £608.48, £876.56 and £1144.64 for 5, 6, 7 and 8 year payback periods respectively.

System 2 – Heating

Heating the original system to 25 ºC increased yield by 22%. Maximum possible investment was £464, £756.80, £1049.60 and £1342.40 for 5, 6, 7 and 8 year payback periods respectively.

Heating to 30 ºC increased yield by 44% - allowable investment increased to £728, £1073.60, £1419.20 and £1764.80 for 5, 6, 7 and 8 year payback periods respectively, whilst heating to 35ºC yielded 66% more biogas than the original system with an allowable investment of £992, £1390.40, £1788.80 and £2187.20 for 5, 6, 7 and 8 year payback periods respectively.

System 3 – Shredder

Adding a shredder to the original system led to a 38% improvement in yield, with allowable investment thresholds of £656, £987.20, £1318.40 and £1649.60 for 5, 6, 7 and 8 year payback periods respectively.

System 4 – Second digester and heating

Adding a second digester and heating to 25ºC improved yield by 54%. Maximum possible investment was £848, £1217.60, £1587.20 and £1956.80 for payback periods of 5, 6, 7 and 8 years respectively.

Adding a second digester and heating to 30ºC improved yield by 61%. Maximum possible investment was £932, £1318.40, £1704.80 and £ 2091.20 for payback periods of 5, 6, 7 and 8 years respectively.

Adding a second digester and heating to 35ºC improved yield by 85%. Maximum possible investment was £1220, £1664, £2108 and £2552 for payback periods of 5, 6, 7 and 8 years respectively.

System 5 - Second digester and shredder

Adding a second digester and a shredder to the original system led to a 54% increase in yield, with maximum possible investment values of £848, £1217.60, £1587.20 and £1956.80 for payback periods of 5, 6, 7, and 8 years respectively.

System 6 – Shredder and heating

Adding a shredder and heating to 25ºC improved yield by 68%. Maximum possible investment was £1016, £1419.20, £1822.40 and £2225.60 for payback periods of 5, 6, 7 and 8 years respectively.
Adding a shredder and heating to 30ºC improved yield by 99%. Maximum possible investment was £1388, £1865.60, £2343.20 and £2820.80 for payback periods of 5, 6, 7 and 8 years respectively.
Adding a shredder and heating to 35ºC improved yield by 129%. Maximum possible investment was £1748, £2297.60, £2847.20 and £3396.80 for payback periods of 5, 6, 7 and 8 years respectively.

System 7 – Second digester, shredder and heating

Adding a second digester, shredder and heating to 25ºC improved yield by 88%. Maximum possible investment was £1256, £1707.20, £2158.40 and £2609.60 for payback periods of 5, 6, 7 and 8 years respectively.
Adding a second digester, shredder and heating to 30ºC improved yield by 122%. Maximum possible investment was £1664, £2196.80, £2729.60 and £3262.40 for payback periods of 5, 6, 7 and 8 years respectively.
Adding a second digester, shredder and heating to 35ºC improved yield by 156%. Maximum possible investment was £2072, £2686.40, £3300.80 and £3915.20 for payback periods of 5, 6, 7 and 8 years respectively.

4.4. Discussion of Results

Comparing systems with a single additions; i.e. systems 1, 2 and 3 it can be seen that heating to 30ºC or above provided the largest yield improvement, followed by the addition of a shredder (which had a comparable yield improvement to heating to 30ºC), with the addition of a second digester giving the least yield improvement.
Whilst costs are unknown, a shredder would likely cost less than £656 which is the maximum possible investment with a 5 year payback period.

The cost of a second digester would be £550, plus £100 for a pipeline connection to a neighbour – over the acceptable limit of £340.40, so this investment does not seem worthwhile with a 5 year payback period. However, is has been shown to be a viable option if an acceptable payback period for a BD is set at 6 years – this may be an option for households which require larger quantities of gas (and may have larger incomes due to size).
Considering heating, whilst it is clear that heating to a higher temperature yields more biogas, it is not obvious which heating regime would be the most viable, and thus further work is required in costing such systems.

Comparing systems with two additions; i.e. systems 4, 5 and 6 it can be seen that the systems using heating have the highest biogas yields; the most advantageous system is system 6, which utilises heating in addition to a shredder (yield improvements 68-129%). The second best system here uses a second digester and heating (yield improvements 54-85%), followed by a second digester and shredder (yield improvement of 54%).
As it is likely that a shredder would cost less than a second digester (£550), if heating is to be used in conjunction with another component, a shredder should be given priority over using a second digester.

System 7, which utilises heating, a second digester and a shredder, shows a yield improvement from 88-156%. This top-end figure is the highest yield improvement found. Interestingly, systems 7 and 6 overlap in yield improvement, and a careful analysis of cost vs. yield would have to be undertaken system 7 were to be considered; it may be that system 6 is more financially viable.

These results show that appreciable gains in biogas yield can be made with little modification to a small-scale household BD. Further work is required to fully cost heating and shredding systems in order to verify their viability for investment in the short-term for small-scale household plants.

Large scale plants tend to have a longer lifespan, and hence payback periods than small-scale BDs - in the region of 20 years. It is partially due to this that generally, only large-scale plants operate with a second digester, heating and shredders. In addition to this, a large scale plant will have a far higher output of biogas and so maximum possible investment in these components would increase accordingly.

If this 20 year lifespan were applied to a small-scale BD, then the maximum investment would be £4360 for a second digester, £4856, £5912 and £6968 for heating at 25, 30 and 35 ºC respectively and £5624 for a shredder. Using all three systems in combination, heating to 35 ºC, would allow an investment of £11288.
Whilst costs are currently unknown for heating and shredding systems, it can be appreciated that they would be likely affordable with a 20 year payback period.

However, in a developing country, 20 years is a relatively long time. In Cameroon, where the average life expectancy is 55 (World Bank, 2015), such an investment would not be deemed worthwhile. Payback period of a plant, and cost, is a huge driver behind the technology of small-scale BDs; we have just shown that with a 6 year payback period, a second digester is a viable option – yet the majority of these plants only incorporate one. Designers possibly deemed such an investment unattractive to potential end users, thus discounting it.

4.5. Recommendations

Reviewing the above results, the following recommendations can be made:

- If a payback period of 6 years is set, then a second digester is a viable option
- Whilst costs of heating systems are unknown, they have the highest impact on biogas yield. It is therefore recommended that the greatest investment be put into heating systems
- Heating at 25, 30 and 35ºC increased yield by 22, 44 and 66%; clearly showing that heat has a considerable impact on biogas yield and that higher temperatures give far higher biogas yields. It is likely that a system which would provide 25ºC heat would be the same as a system which would provide 35ºC heat. It is therefore recommended that if such a system is installed, it be run at the optimal temperature for the specific substrate (as opposed to a lower temperature to save on bills).
- Heating should be used if ambient temperature is less than 15°C
- If an improvement using two components and including heating is to be considered, the addition of a shredder should take priority over a second digester
- Finances are clearly quite tight for such a small-scale BD, which only gains profit through solid fuel savings. It is therefore recommended that a market for the digestate be found to increase profit and reduce payback period.

5. Conclusions and Future Work

It was recognised that BDs have the potential to reduce greenhouse gas emissions through burning methane, rather than allowing it to escape into the atmosphere. In addition, they reduce the need for firewood to be burned, releasing carbon dioxide and contributing to deforestation.

Whilst large-scale plants are gaining in popularity in more developed countries, they are less accessible in developing countries due to cost limitations; the aim of this study was therefore to explore ways in which small-scale plants could become more profitable, with minimal additional investment. To do this, a literature review was conducted to determine the best computational method to use to model a small-scale BD.

Once a suitable tool was found, it was analysed for components modelled, to discover which were pertinent to biogas yield. Another literature review was undertaken to determine how these particular components affected performance (biogas yield) and financial viability.

It was found that adding an additional digester improved biogas yield by 17.7% (a mean value taken from 5 studies). It was recognised that for further accuracy, specific substrates would have to be examined so that substrate-specific values could be programmed into the tool. Additionally, where information lacked, lab work could be undertaken – these measures were, however, outwith the scope of this study.

An additional digester would increase the cost by £38.20 x the original digester volume – this again was an average value from studies examined.

To examine heating, values for a range of studies examining the effects of heating were plotted on a graph, and an r^2 average value for the biogas yield increase over time was obtained. As the tool calculated yield based on a temperature of 35ºC, this formula was used to decrease yield at temperatures below 35ºC, and increase yield at temperatures above 35ºC (between 20ºC to 45ºC, as these are the limiting temperatures of bacteria operating within a mesophilic BD). The cost increase for heating was taken as the reduction in available gas (if a gas heater is used) plus the initial capital required.

Studies for mixers were inconclusive and thus no yield or financial factors were derived; shredders were found to provide a mean yield improvement of 27.6%, and cost was to be evaluated on a case by case basis.

The performance variability factors were then used to alter biogas yield if their relevant component was present in the system, and the financial variability factors were built into a new "Financial Viability" section.

Once the tool had been altered, it had to be validated. For this, data for an existing plant in Lelbach, Germany was used. This plant was modelled, and it was decided that outputs from the tool would have to be within 50% of actual data for the tool to be deemed valid. The tool showed reasonable levels of accuracy in estimating biogas and electricity output – overestimating by 33% and 11% respectively - but not in heat output – overestimating by 105%. This discrepancy was likely down to differences in the CHP engines used, and was considered acceptable as heat output was not a focus of this study.

Once the tool had been validated, it had to be altered so that it was suitable to model a case study of a small-scale household BD in Belo, Cameroon. This was done by "stripping back" the tool so that only the three components used in the small-scale case study were present; input buffer, digester and output buffer. This was done by reducing the HRT time of the pasteuriser and second digester, as well as the electrical requirements of all other components to zero.

Once this was completed, the components pertinent to biogas production (additional digester, shredder and heating at 25, 30 and 35ºC) were modelled in every combination possible – 15 in all – to analyse their impact upon biogas yield and financial viability.

It was found that heating provided the highest increase in yield, followed by a shredder and with the addition of a second digester. For combinations of two components, heating in combination with a shredder appeared to be the best option, and for all three components, highest yield was gained by heating at higher temperatures.

It was therefore recommended that solutions for low-cost heating be found, and secondarily, shredders. The cost of a second digester was already known so it was recommended that with an acceptable payback period of 6 years or more, a second digester be used. It was also noted that a driver for cost was acceptable payback period, which in developing countries can be very tight; this led to the recommendation that ways to ease this be explored, such as additional revenue from the plant.

During the course of this research, it became apparent that the following areas could provide useful and insightful research avenues:

- The literature review uncovered very few software-based tools available which could be used to model BDs. There is scope to develop this tool further, or create a new tool based on findings in this report - if made freely available this could encourage potential future investors and could provide a boost to the BD industry
- It was acknowledged that the performance variability factors could have been more accurate. This could have been done by deriving substrate, system and temperature specific factors for each component, from a very wide ranging literature review, or from laboratory work. Built into the tool, this would improve the accuracy enormously
- Climate data could be built into the tool, to model a BD over a year as the ambient temperature fluctuates and biogas production is affected if the BD is unheated. If heated, the heating requirement could be calculated over the year with greater accuracy

- The tool did not take into account dynamic effects e.g. the heat available to the digesters is dependent on the gas available which is dependent on the heat of the digesters. Such effects could be included for greater accuracy

- A literature review revealed a scarcity of information on the subject of low-cost heating and insulation systems – research into which could provide invaluable to end-users of BDs in cooler climates.

- Additionally, whilst the impacts of mechanical pre-treatment has been reasonably well-documented, it would appear that such systems are only available to large-scale plant; any research done on a small scale is conducted using lab equipment. Research and development in this field could prove a useful exercise, as it has already been shown that mechanical pre-treatment can have a substantial effect on biogas yield

- The major driver behind the acceptability of investment costs appears to be payback period. This is due to plant lifetime, and also the fact that people in developing countries find long payback periods unfeasible. Ways to improve the acceptability of payback period increases should be explored – potentially through improvements in plant robustness, co-operative/community BDs, and additional ways to make income from the plant, such as selling the digestate as fertiliser

6. Appendix I – Small-Scale Case Study Plant Details

Table 17 - Cost breakdown for small-scale BD case study

Budget Bill of Quantities and Cost for Biodigester Capacity for 10m³

S.N item			10 cu m	
	Unit	Unit cost(cfa)	Quantity	Total cost(cfa)
Building Materials				
1 Block (5"*4*10")	Piece	171	750	128250
2 Sand (coarse)	M3	13500	1.5	20250
3 ,, (fine)	"	12000	1.6	19200
4 Gravel 5/15	"	29600	2	59200
5 Cement	Bag	5500	35	192500
6 6m.m iron Rod	12 m	1500	3	4500
7 Acrylic emulsion paint	Lit	4500	4	4500
8 Binding wire	Kg	1200	0.5	600
Sub Total 1				**429,000**
Building Labour				
9 skilled labour	No	5000	17	85000
10 unskilled labour	No	3000	40	120000
SUPERVISON				70000
Sub Total 2				**275,000**
Pipe and Appliances				
11 inlet pipe 4" P.V.C	Mt.	900	4	3600
12 Dome gas pipe	Pcs	1500	1	10000
1.5"(G.I.)	Mt.	7500	02	15000
13 G.I. pipe 1/2 "	Pcs	200	3	600
14 socket ½"	Pcs	200	6	1200
15elbow ½"	Pcs	250	3	750
16 T. socket ½"	Pcs	400	1	400
17 Union ½	Pcs	4800	4	19200
18 Gas valve ½"	Pcs	1000	1	1000
19 Reducing elbow 1.5"	Mt.	800	2	1600
to 0.5"	Pcs	15000	2	12000
20 STOVE	Pcs	250	4	1000
21 Rubber hose pipe	Pcs	300	7	2100
22 Rubber hose clip 0.5"	Pcs	600	3	1800
23 Nipple 0.5"				
24 Teflon tape	NO			10000
25 PLUMBING				
Sub Total 3.				**80250**
Total 1+2+3		8		**784,250**

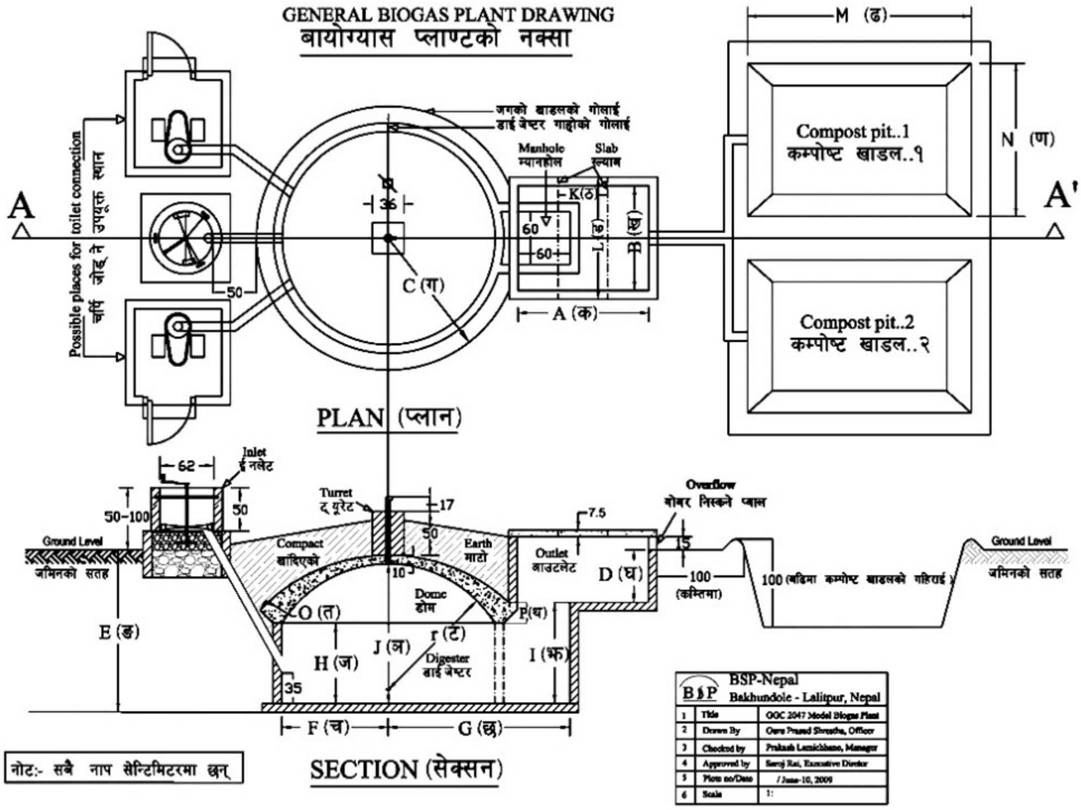

Figure 7 - General biogas plant drawing, design for small scale BD case study (BSP Nepal, 2015

Table 18 - Dimensions for Figure 7 (BSP Nepal, 2015)

Measurement of Different Part for Different Size Biogas Plants

Different Parts of Plant			Plant Size M3			
			2	4	6	8
A	(क)	Length Outlet (inside) (For 2m3 Diameter)	148	140	150	170
B	(ख)	Width Outlet (inside) (For 2m3 Diameter)	148	120	120	130
C	(ग)	Digester Layout Radius	105	130	150	165
D	(घ)	Floor Outlet - Bottom of Overflow	40	50	60	65
E	(ङ)	Deft of Digester	150	150	155	170
F	(च)	Radius Round Wall	80	102	122	135
G	(छ)	Centre Digester - Manhole Wall	-	185	208	221
H	(ज)	Floor Manhole - Bottom Dome	65	86	92	105
I	(झ)	Floor Manhole - Floor Outlet	-	112	116	127
J	(ञ)	Floor Digester - Tope Dome	150	151	160	175
r	(ट)	Dome Template Radius	81	113	144	167
K	(ठ)	Width Outlet Slab (For 2m3 Diameter)	58	55	58	65
L	(ड)	Length Outlet Slab (For 2m3 Diameter)	174	145	145	155
M	(ढ)	Length Compost Pit	100	200	200	200
N	(ण)	Width Compost Pit	100	100	150	200
O	(त)	Thickness Bottom of Dome	20	23	26	26
P	(थ)	Pressure Height	35	26	24	22

7. References

Abdel-Hadi, M.A., Abd El-Azeem, S.A.M., 2008. *Effect of heating, mixing and digester type on biogas production from buffalo dung*. Misr Journal of Agricultural Engineering, Vol. 25(4), pp. 1454–1477.

Alkhamis, T.M., El-khazali, R., Kablan, M.M., Alhusein M.A., 2000. *Heating of a biogas reactor using a solar energy system with temperature control unit.* Solar Energy, Vol. 69(3), pp. 239–247.

Angelidaki, I., Ellegaard, L., Ahring, B.K., 2000. *A comprehensive model of anaerobic bioconversion of complex substrates to biogas*. Biotechnology and Bioengineering, Vol. 63(3), pp. 363–372.

Arora, K., 2015. Calibrating Slurry Tank Manure Applicators. https://www.extension.iastate.edu/Pages/communications/EPC/Fall03/slurrytank.html Accessed 21/08/2015

Arikan, O.A., Mulbry, W., Lansing, S., 2015. *Effect of temperature on methane production from field-scale anaerobic digesters treating dairy manure.* Waste Management, Vol. 43, pp. 108–113.

Baier, U., Schmidheiny, P., 1997. *Enhanced anaerobic degradation of mechanically disintegrated sludge.* Water Science and Technology, Vol. 36(11), pp. 137–114.

Barjenbruch, M., Kopplow, O., 2003. *Enzymatic, mechanical and thermal pre-treatment of surplus sludge*. Advances in Environmental Research, Vol. 7(3), pp. 715–720.

Cenex, 2009. *Biomethane Toolkit - A guide to the production and use of biomethane as a road transport fuel* (Online). Available at https://www.americanbiogascouncil.org/pdf/Cenex-biomethane-toolkit-2009.pdf, accessed 24/08/2015.

Colorado State University, 2015. *Anaerobic Digestion Feasibility Tool* (Online). Available at https://erams.com/ad_feasibility_ad_tool/, accessed 24/08/2015

Chiambah, E., 2014. *Biogas Demonstration Site to Educate the Belo Community in the Highlands of the North West Region of Cameroon.* Proposal for Belo Rural Development Association (BERUDA), P.O. Box 22, Njinikom, Boyo Division
North West Region, Bamenda, Cameroon

Bouallagui, H., Haouari, O., Touhami, Y., Cheikh, R.B., Marouani, L., Hamdi, M., 2004. *Effect of temperature on the performance of an anaerobic tubular reactor treating fruit and vegetable waste.* Process Biochemistry, Vol. 39(12), pp. 2143–2148.

Bond, T. and Templeton, M.R., 2011. *History and future of domestic biogas plants in the developing world.* Energy for Sustainable Development, Vol. 15(4), pp. 347–354.

BSP (Biogas Support Programme) Nepal, 2012. *Interim Phase Year Book.* http://www.bspnepal.org.np/docs/publication/year_book_2012.pdf, Accessed 10/07/2015

BSP (Biogas Support Programme) Nepal, 2015 (Online). Available at http://www.bspnepal.org.np/?option=cms&cid=16, accessed 22/08/2015

BPEX, 2010. *Added Value from Pig Manure and Slurries* (Online). Available at http://pork.ahdb.org.uk/media/2261/added_value_from_pig_manures_and_slurries.pdf, accessed 17/07/2015

Chen, T.H., Chynoweth, P., BIljetina, R., 1990. *Anaerobic digestion of municipal solid waste in a nonmixed solids concentrating digester.* Applied Biochemistry and Biotechnology, Vol. 24–25(1), pp.533–544.

Dachs, G., Rehm, W., 2006. *Der Eigenstromverbrauch von Biogasanlagen und Potenziale zu dessen Reduzierung.* Germany: Hg. v. Solarenergieförderverein Bayern e.V. München (Online). Available at https://www.sev-bayern.de/content/bio-eigen.pdf, accessed 05/08/2015

Callaghan, F.J., Wase, D.A.J., Thayanithy, K., Forster, C.F, 1998. *Co-digestion of waste organic solids: batch studies.* Bioresource Technology, Volume 67(2), pp. 117-122.

Carrère, H., Dumas, C., Battimelli, A., Batstone, D.J., Delgenès, J.P., Steyer, J.P., Ferrer, I. 2010. *Pre-treatment methods to improve sludge anaerobic degradability: A review.* Journal of Hazardous Materials, Volume 183(1–3), pp. 1-15

Chae, K. J., Jang, A., Yim, S. K., Kim, I.S., 2008. *The effects of digestion temperature and temperature shock on the biogas yields from the mesophilic anaerobic digestion of swine manure.* Bioresource Technology Vol. 99(1), pp 1–6.

European Commission, 2014. *Quarterly Report on European Electricity Markets.* Market Observatory for Energy, DG Energy, Volume 7 (3; third quarter of 2014).

Engelhart, M., Krger, M., Kopp, J., Dichtl, N., 2000. *Effects of disintegration on anaerobic degradation of sewage excess sludge in downflow stationary fixed film digesters*. Water Science and Technology, Vol. 41(3), pp. 171–179.

Ezzati, M. and Kammen, D.M., 2001. *Quantifying the Effects of Exposure to Indoor Air Pollution from Biomass Combustion on Acute Respiratory Infections in Developing Countries.* Environmental Health Perspectives, Vol. 109(5), pp. 481-488.

Flessa, H., Ruser, R., Dörsch, P., Kamp, T., Jimenez, M.A., Munch, J.C. Beese, F., 2002. *Integrated evaluation of greenhouse gas emissions (CO2, CH4, N2O) from two farming systems in southern Germany.* Agriculture, Ecosystems and Environment, Vol. 91(1-3), pp. 175–189.

Forest Fuels, 2015. *Fuel price comparisons* (Online). Available at http://www.forestfuels.co.uk/about-wood-fuel/fuel-price-comparisons, accessed 21/07/2015

Forest Power, 2015. *Density of wet wood and loose density of wood chips* (Online). Available at http://www.forestpower.net/data/liitteet/11620=1017_density_of_wet_wood.pdf, accessed 21/07/2015

Forestry Commission Scotland, 2011. *Woodchip Drying.* Technical Development Report reference FCPR045 (Online). Available at http://www.biomassenergycentre.org.uk/pls/portal/docs/PAGE/RESOURCES/REF_LIB_RES/PUBLICATIONS/TECHNICAL_DEVELOPMENT/FCPR045%20WOODCHIP%20DRYING.PDF, accessed 15/07/2015

Gautam, R., Baral, S., Herat, S., 2007. *Biogas as a sustainable energy source in Nepal: Present status and future challenges.* Renewable and Sustainable Energy Reviews, Vol 13(1), pp. 248–252.

Geraghty, M., Roscoe, A.J., Cloonan, M., Currie, J., (2004). *Biomass - Using Anaerobic Digestion.* (Online). Available at http://www.esru.strath.ac.uk/EandE/Web_sites/03-04/biomass//index.html, accessed 15/05/2015.

Gibbons, J.M., Ramsden, S.J., Blake, A., 2006. *Modelling uncertainty in greenhouse gas emissions from UK agriculture at the farm level.* Agriculture, Ecosystems and Environment, Vol 112(4), pp. 347–355.

Hahn, H., Rutz, D., Ferber, E., Kirchmayer, F., 2010. *Examples for financing of biogas projects in Germany, Austria, The Netherlands, Denmark and Italy.* Report for IEE Project 'BiogasIN' (Online). Available at http://www.biogasin.org/files/pdf/Financing_of_biogas_projects_in_top_5_EU_countries.pdf, Accessed 05/08/2015

Hahn, H., 2011. *Guideline for financing agricultural biogas projects - Training material for biogas investors.* Report for IEE Project 'BiogasIN' (Online). Available at http://www.biogasin.org/files/pdf/WP3/D.3.5_IWES_EN.pdf, accessed 05/08/2015

Hashimoto, A.G., 1982. *Effect of mixing duration and vacuum on methane production rate from beef cattle waste.* Biotechnology and Bioengineering, Vol. 24(1), pp. 9-23.

He, P.J., 2010. *Anaerobic digestion: An intriguing long history in China.* Waste Management, Vol. 30(4), pp. 549–550
Ho, C.C., Tan, Y.K., 1985. *Anaerobic treatment of palm oil mill effluent by tank digesters*. Journal of Chemical Technology and Biotechnology, Vol. 35(2), pp. 155–164.

IEA, 2002. *World Energy Outlook* (Online). Available at http://www.worldenergyoutlook.org/media/weowebsite/2008-1994/weo2002_part1.pdf, accessed 01/06/2015

IEA, 2014. *Bioenergy Task 37 - Country Reports Summary* (Online). Available at http://www.ieabioenergy.com/wp-content/uploads/2015/01/IEA-Bioenergy-Task-37-Country-Report-Summary-2014_Final.pdf, accessed 10/07/2015

IEA, 2015. *Energy and Climate Change: World Energy Outlook Special Report* (Online). Available at https://www.iea.org/publications/freepublications/publication/WEO2015SpecialReportonEnergyandClimateChange.pdf, accessed 01/08/2015

INFORSE – Europe, 2006. *Guideline for Estimation of Renewable Energy Potentials, Barriers and Effects* (Online). Available at http://www.inforse.org/europe/pdfs/RE-asses-06.pdf, accessed 23/07/2015

IPCC, 2001. *Climate Change: The Scientific Basis* (Online). Available at http://www.grida.no/climate/ipcc_tar/wg1/pdf/wg1_tar-front.pdf, accessed 15/08/2015

ISAT (Information and Advisory Services on Appropriate Technology), 1999. *Biogas Digest Volume I; Biogas Basics* (Online). Available at http://www.sswm.info/sites/default/files/reference_attachments/ISAT%20GTZ%201999%20Biogas%20digest%20Volume%20I%20Biogas%20Basics.pdf, accessed 18/08/2015

ISAT (Information and Advisory Service on Appropriate Technology), 2015. *Biogas Digest Volume III; Biogas - Costs and Benefits and Biogas – Programme Implementation.* (Online). Available at http://www.sswm.info/sites/default/files/reference_attachments/GTZ%20ISAT%201999%20Biogas%20Digest%20Vol%203.pdf, accessed 10/08/2015.

ISO 6976 (1995) Natural gas - *Calculation of calorific values, density, relative density and Wobbe index from composition*

James, S.C., Wiles, C.C., Swartzbauch, J.T., Smith, R.B., 1980. *Mixing in large-scale municipal solid waste sewage sludge*. Biotechnology and Bioengineering, Vol. 22 (SI) pp. 259–272.

Kaltschmitt, M., Hartmann, H., Hofbauer, H., 2009. *Energie aus biomasse.* 2nd ed. Berlin, Heidelberg: Springer.

Karellas, S., Boukis, I., Kontopoulos, G. 2010. *Development of an investment decision tool for biogas production from agricultural waste.* Renewable and Sustainable Energy Reviews, Vol. 14(4), pp. 1273–1282.

Karim, K., Hoffmann, R., Klasson, K.T., Al-Dahhan, M.H., September 2005. *Anaerobic digestion of animal waste: Effect of mode of mixing.* Water Research, Vol. 39(15), pp. 3597–3606.

Karim, K., Hoffmann, R., Klasson, K.T., Al-Dahhan, M.H., November 2005. Anaerobic digestion of animal waste: Waste strength versus impact of mixing. Bioresource Technology, Vol. 96(16), pp. 1771-1781.

KTBL, 2015. *Online European Feedstock Atlas Basic Version* (Online). Available at http://daten.ktbl.de/euagrobiogasbasis/navigation.do?selectedAction=Startseite, accessed 16/17/2015.

Lang. M., and Lang, A., 2015. The 2014 German Renewable Energy Sources Act revision – from feed in tariffs to direct marketing to competitive bidding. Journal of Energy & Natural Resources Law, Vol. 33(2), pp. 131-146.

LEAD, 2006. *Livestock's Long Shadow. Environmental Issues and Options* (Online). Available at ftp://ftp.fao.org/docrep/fao/010/a0701e/a0701e.pdf, accessed 03/07/2015

Liu, D., Liu, D., Zeng, R.J., Angelidaki, I., 2006. *Hydrogen and methane production from household solid waste in the two-stage fermentation process.* Water Research, Vol. 40(11), pp. 2230-2236.

Lohri, C.R., Rodic, L., Zurbrügg, C., 2013. *Feasibility assessment tool for urban anaerobic digestion in developing countries.* Journal of Environmental Management, Vol. 126(15), pp. 122–131.

Luo, G., Xie, L., Zhou, Q., Angelidaki, I., 2011. *Enhancement of bioenergy production from organic wastes by two-stage anaerobic hydrogen and methane production process.* Bioresource Technology, Vol. 102(18), pp. 8700-8706.

Maschinenring Waldeck-Frankenberg eV., 2015. *Eckdaten SBW Biogas Lelbach* (Online). Available at http://www.mr-wa-fkb.de/erneuerbare_energien/biogas-erzeugung/.eckdaten_lelbach.html, accessed 24/08/2015

Maspolim, Y., Zhou, Y., Guo, C., Xiao, K., Ng, W.J., 2014. *Comparison of single-stage and two-phase anaerobic sludge digestion systems – Performance and microbial community dynamics.* Chemosphere, Vol. 140, pp. 54–62.

Methanogen ltd., 2010; Report prepared for The Peak District National Park Authority and East Midlands Development Agency. *A Toolbox Guide for Assessing the Feasibility of an Anaerobic Digestion Project Developed for the Benefit of a Community or for a Single Farm* (Online). Available at http://www.r-e-a.net/upload/toolkit_-_david_collins_community_biogas.pdf, accessed 24/08/2015

MinErgy Pvt. Ltd., Nepal. 2014. *Optimization of Biogas Plants using Digester Heating Technologies.* Submitted to Biogas Sub Component National Rural and Renewable Energy Programme (NRREP), Alternative Energy Promotion Center (AEPC) Khumaltar, Lalitpur, Nepal (Online). Available at http://www.aepc.gov.np/docs/resource/subreport/20140708034742_Final%20Report_Digester%20Heating.pdf, accessed 12/08/2015

Montgomery, L.F.R., Bochmann, G., 2014. *Pre-treatment of feedstock for enhanced biogas production.* IEA Bioenergy, ISBN 978-1-910154-05-2.

Müller. J.A., 2001. *Prospects and problems of sludge pre-treatment processes.* Water Science and Technology, Issue 44(10), pp. 121–128.

Nasr, N., Elbeshbishy, E., Hafez, H., Nakhla, G., El Naggar., M.H., 2012. *Comparative assessment of single-stage and two-stage anaerobic digestion for the treatment of thin stillage.* Bioresource Technology, Vol. 111, pp. 122-126.

Nijaguna, B.T., 2007. *Biogas Technology.* New Age International Pvt Ltd Publishers, ISBN: 8122413803.

Olesen, J.E., Schelde, K., Weiske, A., Weisbjerg, M.R., Asman, W.A.H., Djurhuus, J., 2006. *Modelling greenhouse gas emissions from European conventional and organic dairy farms.* Agriculture, Ecosystems and Environment, Vol. 112(2-3), pp. 207–220

Ong, H., Greenfield, P., Pullammanappallil, P., 2002. *Effect of mixing on biomethanation of cattle-manure slurry*. Environmental Technology, Vol. 23(10,) pp. 1081–1090.

Pakarinen, O.M., Tähti, H.P., Rintala, J.A., 2009. *One-stage H2 and CH4 and two-stage H2 + CH4 production from grass silage and from solid and liquid fractions of NaOH pre-treated grass silage.* Biomass and Bioenergy, Vol. 33(10), pp. 1419-1427.

Palmowski, L., Muller, J., 1999. *Influence of the size reduction of organic waste on their anaerobic digestion.* In: Mata-Alvarez, J., Tilche, A., Cecchi, F. (Eds.), Proceedings of the second international symposium on anaerobic digestion of solid wastes, Barcelona, pp. 137-144.

Parkin, G.F., Owen, W.F., 1986. *Fundamentals of anaerobic digestion of wastewater sludges*. J Environ Eng Vol. 112(5), pp. 867–920.

Regulation (EC) No 1069/2009, 2009. *Laying down health rules as regards animal by-products and derived products not intended for human consumption and repealing Regulation (EC) No 1774/2002 (Animal by-products Regulation).*

Road Haulage Association, 2006. *Cost Tables* (Online). Available at https://www.rha.uk.net/docs/internet/operatingcosts/RHA%20Cost%20Tables.pdf, accessed 10/07/2015.

Rogers, G., Mayhew, Y. 1992. *Engineering Thermodynamics: Work and Heat Transfer.* Longman Scientific; 4th edition. ISBN: 0582045665

Safley Jr., L.M., Westerman, P.W., 1994. *Low-temperature digestion of dairy and swine manure.* Bioresource Technology, Vol. 47(2), pp. 165-171.

Sasse L., 1998. *Biogas Plants.* A Publication of the Deutsches Zentrum für Entwicklungstechnologien - GATE in: Deutsche Gesellschaft für Technische Zusammenarbeit (GTZ) GmbH, Eschborn, Germany (Online). Available at http://www.susana.org/_resources/documents/default/2-1799-biogasplants.pdf, accessed 22/07/2015

Scheinberg, A., Wilson, D.C., Rodić, L., 2010. *Solid Waste Management in the World's Cities. UN-habitat's Third Global Report on the State of Water and Sanitation in the World's Cities.* Earthscan for UN Habitat, London (Online). Available at http://mirror.unhabitat.org/pmss/listItemDetails.aspx?publicationID=2918, accessed 24/08/2015

Schievano, A., Tenca, A., Scaglia, B., Merlino, G., Rizzi, A., Daffonchio, D., Oberti, R., Adani, F., 2012. *two-stage vs Single-Stage Thermophilic Anaerobic Digestion: Comparison of Energy Production and Biodegradation Efficiencies.* Environmental Science and Technology, Vol. 46(15), pp. 8502–8510.

Schils, R.L.M., Verhagen, A., Aarts, H.F.M., Šebek, L.B.J., 2005. *A farm level approach to define successful mitigation strategies for GHG emissions from ruminant livestock systems*. Nutrient Cycling in Agroecosystems, Vol. 71, pp. 163–175.

Sharma, S.K., Mishra, I.M., Sharma, M.P., Saini, J.S., 1988. *Effect of particle size on biogas generation from biomass residues*. Biomass, Vol. 17(4), pp. 251-263.

Sharma, S.K., Saini, J.S., Mishra, M., Sharma, M.E., 1989. *Biogasification of woody biomass: Ipomoea fistulosa plant stem.* Biological Wastes, Vol. 28(1), pp 25-32.

Sharma, C.K., 1996. *Overview of Nepal's Energy Sources and Environment.* Atmospheric Environment, Vol. 30(15), pp. 2717-2720.

Song, Y.C., Kwon, S.J., Woo, J.H., 2004. *Mesophilic and thermophilic temperature co-phase anaerobic digestion compared with single-stage mesophilic- and thermophilic digestion of sewage sludge.* Water Research, Vol. 38(7), pp. 1653–1662.

Stenstrom, M.K., Ng, A.S., Bhunia, P.K., Abramson, S.D., 1983. *Anaerobic digestion on municipal solid waste*. J Environ Eng 1983, Vol. 109(5), pp. 1148–1158.

TDBP (Tanzania Domestic Biogas Programme), 2015 (Online). Available at http://www.biogas-tanzania.org/tdbp/about/category/archievements, accessed 26/07/2015

Tian, H., Duan, N., Lin, C., Li, X., and Zhong, M, 2014. *Anaerobic co-digestion of kitchen waste and pig manure with different mixing ratios.* Journal of Bioscience and Bioengineering, Vol. 120(1), pp. 51-57.

Tilley, E., Ulrich, L., Luethi, C., Reymond, P., Zurbruegg, C. 2014. *Direct Use of Biogas* (Online). Available at http://www.sswm.info/content/direct-use-biogas, accessed 19/08/2015

Troschinetz, A.M., Mihelcic, J.R., 2008. *Sustainable recycling of municipal solid waste in developing countries*. Waste Management, Issue 29(2), pp. 915–923.

UNESCO, 2012. *Education For All Global Monitoring Report; Youth and Skills – Putting Education to Work* (Online). Available at http://unesco.nl/sites/default/files/dossier/2012_gmr.pdf?download=1, accessed 16/07/2015

Wang, Z., Chen, S., Frear, C., Kruger, C., Granatstein, D. 2009. *Advanced small-scale anaerobic digester design tailored for household user living in cold climate.* Washington State University, Pullman WA (WSU) and Biological and Environmental Systems and Technologies, LLC, Pullman, WA (BEST).

Warwick, H. and Doig, A., 2004. *Smoke – the Killer in the Kitchen: Indoor Air Pollution in Developing Countries* (Online). Available at http://practicalaction.org/docs/smoke/itdg%20smoke%20report.pdf, accessed 10/07/2015

Wett, B., Phothilangka, P., Eladawy, A., 2010. *Systematic comparison of mechanical and thermal sludge disintegration technologies*. Waste Management, Vol. 30(6), pp. 1057–1062.

Weiland, P., *Biogas production: current state and perspectives*., 2010. Applied Microbiol Biotechnology, Vol. 85(4), pp. 849–860.

WHO, 2015. *Indoor Air Pollution* (Online). Available at http://www.who.int/indoorair/en/, accessed 23/07/2015

Wiese, J., and Kujawski, O, 2008. *Operational Results of an Agricultural Biogas Plant Equipped with Modern Instrumentation and Automation.* Water Science and Technology, Vol. 57(6), pp. 803–808.

Wilson, D.C., Rodić, L., Scheinberg, A., Velis, C.A., Alabaster. G. 2012. *Comparative analysis of solid waste management in 20 cities.* Waste Management and Research, Vol. 30(3), pp. 237–254.

World Bank, 2015. *Life expectancy at birth, total* (Online). Available at http://data.worldbank.org/indicator/SP.DYN.LE00.IN, accessed 22/08/2015.

Xe.com, 2015. *Exchange rates*. Available at www.xe.com, accessed29/07/2015