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Article

Decision Support for the Construction of Farm-Scale Biogas Digesters in Developing Countries with Cold Seasons

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Abstract: Biogas production is a clean renewable energy source that can improve lives in developing countries. However, winter temperatures in some areas are too low to enable enough biogas production in small unheated digesters to meet the energy requirements of households. Low-cost, high yield reactors adapted to the local climate are needed in those situations. A decision-support model was developed to assist in the design of biogas reactors capable of meeting households' year-round energy needs. Monthly biogas production relative to household energy needs was calculated for the scenario of suburban Hanoi, Vietnam. Calculations included pig number, slurry (manure water mixture) dilution, retention time and biogas/solar heating. Although using biogas to heat the digester increased biogas production, it did not lead to an energy surplus, particularly with the 1:9 slurry dilution rate commonly used on pig farms. However, at a 1:3 slurry dilution, the use of solar heating to provide 90% and biogas 10% of the heat required to heat the digester to 35 °C improved the biogas production by 50% compared to psychrophilic production. The energy needs of an average five-person family throughout the year required 17 fattening pigs. This model can establish the best solution for producing sufficient energy throughout the year.

Keywords: anaerobic digestion; developing countries; psychrophilic; heating; methane production; mathematical modeling; mesophilic

Abbreviations:

A	Area of the slurry in contact with the biogas in (m²)
Bu_x	Theoretical methane production potential ($L_{CH4}.Kg^{-1}VS$)
Cp	Thermal capacity ($J.kg^{-1}.K^{-1}$)
D	Diameter (m)
FAO	Food and Agriculture Organization of the United Nations
h	Heat transfer coefficient
hc	Convective heat transfer coefficient ($W.m^{-2}.K^{-1}$)
H_d	Depth of the digester (m)
H_{loops}	Height of the loops in the hose (m)
hr	Radiative heat transfer coefficient ($W.m^{-2}.K^{-1}$)
HRT	Hydraulic retention time (days)
k	Dimensionless kinetic parameter
L	Length (m)
l	Distance from the bottom of the digester to the groundwater level (m)
LHV_{CH_4}	Lower heating value of methane ($MJ.m^{-3}{}_{CH4}$)
$\dot{m}$	Mass rate (kg. day^{-1})
$\dot{m}_{exc}$	Mass rate of manure excreted per animal and per day ($kg.animal^{-1}.day^{-1}$)
$\dot{m}_{slu}$	Mass rate of slurry ($kg.animal^{-1}.day^{-1}$)
$\dot{m}_w$	Mass rate of water mixture used in the slurry ($kg.animal^{-1}.day^{-1}$)
nhw_{circ}	Number of times the water circulates inside the digester
n_{loops}	Number of loops of the heating pipes
N_{ani}	Number of animals
P	Perimeter of the digester at the bottom (m)
$\dot{Q}_x$	Energy required or produced by *x* ($J.day^{-1}$)
$\dot{Q}l_x$	Heat losses from x ($J.day^{-1}$)
S_0	concentration of organic material in the feed ($KgVS.m^{-3}feed$)
SNV-VN	Netherlands Development Organization: Biogas program for the animal husbandry sector in Vietnam
SRT	Solids Retention Time (days)
T	Temperature (K)
Ta	Air temperature (K)
$\overline{Td}$	Average temperature inside the digester (K)
t_h	Heating period (s)
U	Wind speed ($m.s^{-1}$)
U	Thermal transmittance ($W.m^{-2}.K^{-1}$)
v	Velocity inside the pipes ($m.s^{-1}$)
V	Volume (m^3)
$\dot{V}$	Volumetric flow ($m^3.day^{-1}$)
VFA	Volatile Fatty Acids
VS	Volatile Solids

$VS\ ed$	Easily digestible carbohydrates
$VS\ sd$	Slowly digestible carbohydrates
x_{CH_4}	Methane fraction in biogas

Greek Symbols

β	Constant value for non-insulated vertical side walls
β_0	Biochemical methane potential determined by a batch fermentation test ($L_{CH4}.Kg^{-1}VS$)
$\gamma_{\ t}$	Cumulative methane production during period *t* ($NL_{CH4}.Kg^{-1}VS$)
δ	Thickness of the pipe (m)
λ	Thermal conductivity ($W.m^{-1}.K^{-1}$)
μm	Microorganism growth rate (days)
ξ	Percentage of energy requirements of the heating water provided by the biogas
ρ	Density ($kg{\cdot}m^{-3}$)

Subscripts

$a \rightarrow b$	From a to b
atm	Atmosphere
$circ$	Circulation
d	Digester
do	Dome of the digester
e	Earth
edo	Earth layer above the digester dome
ext	External
fw	Fresh Water (water from the tap before heating)
g	Biogas
gr	Ground
hw	Hot water used to heat the digester
in	Input to the digester
int	Internal
out	Output of the digester
p	Pipe
slu	Slurry: excreta and washing water
$summer$	Summer period
top	Upper part of the digester
$winter$	Winter period

1. Introduction

Climate change, the exhaustion of fossil fuels and phosphorus reserves [1] and unequal access to energy, sanitation and development are among the challenges that humanity will have to overcome in the future. Human livelihoods are highly unequal, with some countries accounting for a majority of worldwide resource consumption, while others have just enough resources to survive. Wealth and economic development can be related to energy consumption and the type of energy used [2]. Environmental economists are still developing new methods to classify energy sources and to analyze the relationship between energy consumption and economic growth. However, general agreement exists that development involves increasing energy demands. According to the FAO [3], "the poor availability of efficient modern energy services in many regions is a fundamental barrier to economic and social development". Sari *et al.* [4] analyzed economic development and energy consumption in six developing countries and concluded that an increase in energy consumption is essential for development. This energy could be provided by improving energy efficiency and using renewable energy to avoid increasing environmental pressure and to achieve sustainable development [5]. In contrast to the high quality energy used in developed countries, poor households in developing countries in Asia use dry animal dung or firewood as energy sources [6]. These poor quality energy sources cause health problems because they are often burned in stoves in kitchens without chimneys.

Anaerobic digestion to produce biogas in developing countries can contribute to sustainable development, reducing energy costs and environmental problems by replacing traditional fuels and also conserve P and N, which are needed for food and feed production [7–9]. Renewable biogas energy production will reduce the impact of deforestation to obtain firewood and can help to reduce greenhouse gas emissions from energy production [10]. This technology can also improve manure management by sanitation and reuse in fertilization, recycling the N and P in the organic matter [11].

Approximately 40 million digesters are currently in use in developing countries [6]. These small digesters have simple designs to keep construction, operation and maintenance costs low. The digesters are not heated and are buried in the soil to maintain as constant a temperature as possible. However, recent studies have shown that digesters do not produce enough gas to meet households' energy requirements during winter in the subtropics and in the mountainous regions of the tropics [12,13], while during summer, they may produce too much biogas, which is then released into the environment [6].

Three types of digesters are standard in these countries: bag digesters, floating-drum digesters (where the inside pressure is constant) and fixed-dome digesters (where the volume is constant). None of those digesters perform sufficient mixing. The hydraulic retention time (HRT) and solids retention time (SRT) are often different for digesters without stirring where organic matter is accumulating in the digester. The retention time should generally be at least 10–15 days to allow for the population of methane-forming bacteria to double at the low digester operating temperature [14], but the HRT should be much longer when the temperature is below mesophilic temperature. The temperatures in buried digesters fluctuate widely, with the result that biogas production and design need to be improved to provide a reliable, renewable supply of energy throughout the year. This effect could be achieved by increasing the retention time, with an HRT of approximately 50 days recommended in Nepal [15]. The problem is that increasing the retention time requires an increase in the size of the digester. Because of the higher costs of building large digesters, the optimal retention time is not met in some areas, such as the Hanoi region of Vietnam, where a recent study showed that the retention time was less than 20 days for 57% of existing digesters and that 68% had a retention time shorter than 30 days [11]. This finding emphasizes the need for the assessment of digester size in relation to biomass supply and energy consumption because "reducing the loading rate and thereby increasing retention time would improve the biogas production per unit of organic matter at psychrophilic range" [16]. The increase in digester efficiency with size must be weighed against the resulting construction problems because large-dome digesters built from bricks could collapse due to weight. Unit production costs also increase with increasing dome digester size, and heat loss may increase. Therefore, retention time, size, heat loss, productivity and costs must be included in decision-support computations.

1.1. Construction and Management of Simple, Small Digesters

Anaerobic digestion in simple digesters depends on the temperature inside the digester, which is influenced by external conditions [17]. Simple, efficient methods to increase the temperature inside digesters could provide sustainable solutions to improve biogas production [12]. Two sources of energy to heat the digester have been proposed: solar energy and energy from biogas combustion [14].

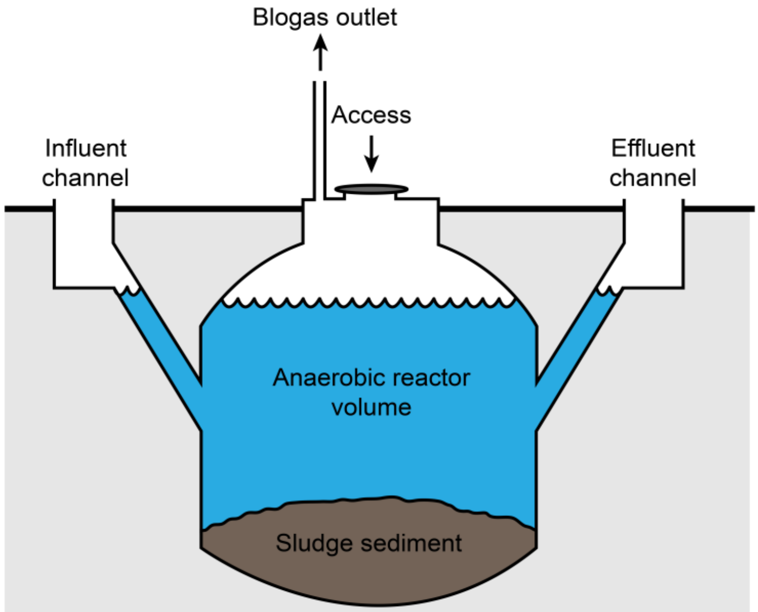
Covering the digester with a greenhouse can provide sufficient energy to heat the digester, as shown for an Indian floating-dome digester [17,18]. The greenhouse increased the temperature during the daytime but was only able to maintain an acceptable nighttime temperature when insulation was used in the construction. In South America, greenhouse heating of a bag digester increased the slurry temperature [19].

A fixed-dome digester heated by heat exchange with water has been designed in which heat is generated by solar captors and circulated inside the digester during sunshine hours [20]. The temperature of the slurry in this system can also be increased by mixing the slurry with additional hot water from the solar panels, which is feasible because the slurry for simple digesters is generally diluted with water to enhance through flow [21]. While this solution is interesting, it is important to bear in mind that increasing the temperature may be achieved at the expense of increasing the volume of the digester.

Installing insulation around the digester has been proven to efficiently reduce the heat requirement and to enable a high temperature to be maintained in the digester [20,21]. Coating the digester wall with charcoal has been proposed as a simple form of insulation [22]. This insulation increases biogas production by more than 10% on average during the winter, but rain and percolating water erode the charcoal insulation [22–24]. Thus, there is a need for development of cheap and more resilient insulation to improve this design (Figure 1).

The analysis of methods to increase the temperature inside the digester has shown that the required heating decreases as digester size increases because the retention time is sufficient to enable high production at low temperatures. However, a net energy gain may not be guaranteed if this heat is supplied by biogas. A sustainable solution may be the use of a combination of methods to increase the temperature inside the digester [21]. In this context, the use of biogas to heat the digester in combination with another heating method may be a viable solution. The present study aims to provide farmers with a simple tool to assess the feasibility of a combined heating system (solar + biogas heater) depending on the biomass entering the digester. This decision-support model is intended to aid in the construction of simple digesters for cold environments that produce a constant rate of biogas throughout the year and to define the sustainability of a heated digester in relation to available biomass.

Figure 1. Schematic diagram of the simple unheated biogas digester. The diluted manure water mixture is added manually to the influent channel and digested slurry is removed manually from the effluent channel (© University of Southern Denmark).



2. Materials and Methods

A simple model was developed linking biogas production to digester volume, retention time, feedstock addition rate and composition and air temperature. The retention time depends on the required rate of biogas production, which strongly depends on the ambient temperature. The model was constructed in simple terms to limit the data requirements because little information is available in rural areas of developing countries.

Calculations were carried out using Mathematica® software [Wolfram Research, Champaign, IL (worldwide headquarters); Oxfordshire, UK (European headquarters)] with a dome digester in the province of Hanoi in northern Vietnam used as a case study. The aim was to achieve constant biogas production throughout the year at the level achieved in the summer. The calculations made the following assumptions:

1. Animal slurry is a mixture of manure and water mixture. The composition is determined by the manure:water ratio.
2. The heat capacity of the slurry is equal to that of water.
3. The density of the slurry is equal to that of water.
4. The temperature of the input slurry is equal to the ambient air temperature [19].
5. Ground temperature is constant from the top to the bottom of the digester, and the mean monthly soil temperature is equal to the mean monthly air temperature.
6. The flow rate of the slurry does not influence heat losses from the digester [24].
7. Only the exact amount of water needed to heat the digester is heated.
8. The water used to heat the digester is all heated from the ambient water temperature to the required temperature of 50 °C.
9. Water is used as a heat exchange fluid and is circulated through tubes in the digester once daily.

2.1. Digester Design

Daily biogas production depends on the number of animals on the farm and the HRT. The volume of the digester was calculated using the volume of slurry produced daily per pig on the farm:

$$V_d = N_{ani} \times \frac{\dot{m}_{slu}}{\rho_{slu}} \times HRT \tag{1}$$

The daily mass rate of slurry produced per animal on the farm and fed to the digester was calculated using the manure:water ratio:

$$\dot{m}_{slu} = \dot{m}_{exc} + \dot{m}_w \tag{2}$$

The depth and diameter of the digester were calculated at different volumes using a diameter to depth ratio of 1.5 [23]. The system was solved to determine the diameter and depth of each digester from the feed rate and retention time. Therefore, discrete heat loss calculations were carried out using the specific characteristics of the digester for each number of animals.

2.2. Heat Transfer

The parameters used to calculate heat fluxes are reported in Table 1.

Table 1. Heat transfer coefficients used in the calculations [21,25].

Parameter	**Abbreviation**	**Heat transfer coefficient ($W.m^{-2}.K^{-1}$)**
Radiative heat transfer coefficient from the slurry to the digester dome	hr	4.65
Convective heat transfer coefficient from the slurry to the digester dome	hc	4.4
Radiative heat transfer coefficient from the digester to the atmosphere	hr_0	4.65
Convective heat transfer coefficient from the digester to the atmosphere as affected by wind speed u ($m\ s^{-1}$).	hc_0	5.7 + 3.8 u
Heat transfer coefficient inside the hose/plastic pipe	hp_{int}	400
Heat transfer coefficient outside the hose/plastic pipe	hp_{ext}	400

Heating may be required to achieve constant biogas production throughout the year. To assess the energy required to heat the plant, the heat losses from the digester must be evaluated. Here, the daily heat required to heat the digester to a mesophilic temperature (35 °C) was taken to be equal to the sum of the daily heat losses and the daily heat required to bring the slurry to the desired digestion temperature. The heat required was calculated according to the calculation proposed by Kishore [21] as:

$$\begin{aligned}\dot{Q}_d = {} & U_d \times A \times (Td - Ta) + \frac{\lambda_e}{l} \times A \times (Tgr - Td) + \beta \times \lambda_e \times (Tgr - Td) \times P \\ & - N_{ani} \times \dot{m}_{slu} \times Cp_{slu} \times (T_{in} - T_d)\end{aligned} \tag{3}$$

Heat losses depend on the slurry area in contact with the biogas and soil. Moreover, the heat losses of the digester are influenced by the soil and air temperatures. A recent model developed by Kätterer and Andrén [26] relates soil temperature to air temperature or soil surface temperature, whereby the temperature of the soil measured at 7 a.m. can be assumed to represent the mean daily soil temperature for depths below 25 cm, and below this depth, the ground temperature is assumed to be constant. Kätterer and Andrén [26] presented supporting data showing the soil temperature below a depth of 25 cm, and their results were confirmed by measurements of soil and air temperature at 805 m above sea level in Chiang Mai, Mae Sa Mai, Thailand [27]. However, because the present decision-support model was intended to have a low demand for input data, the soil temperature (Tgr) was assumed to be equal to the mean monthly air temperature, as in the model of Kishore [21].

Thermal transmittance of the digester ($W.m^{-2}.K^{-1}$):

$$U_d = \frac{1}{\frac{1}{hc_{slu\to g} + hr_{slu\to g} + 2{,}2hc_{slu\to g} \times \left(\frac{dp}{dT}\right)_{Td}}} + \frac{\lambda_{do}}{\delta_{do}} + \frac{\lambda_{edo}}{\delta_{edo}} + \frac{1}{\frac{1}{hr_{do\to atm} + hc_{do\to atm}}} \quad (4)$$

where p, the pressure inside the digester in mm Hg, is calculated from the Antoine equation:

$$p = e^{\left(18{,}403 - \frac{3885}{Td+230}\right)} \quad (5)$$

2.3. Heating the Digester

The digester was heated by circulating hot water through a plastic hose. The heating system was assumed to be designed according to Deublein and Steinhauser [25], with hot water circulating every three minutes over a period of two hours. Under these conditions, for the average farm, this results in a flow rate inside the pipes of approximately 2.5 L s^{-1}, which can be achieved by small solar-powered pumps if needed.

The rate of hot water that should circulate daily inside the pipes was calculated as:

$$\dot{V}_{hw} = \frac{\dot{Q}_d}{Cp_{hw} \times \rho_{hw} \times (Thw_{in} - Thw_{out})} \quad (6)$$

From Equation (10) we can deduce the daily mass of hot water that should be used:

$$\dot{m}_{hw} = \frac{\dot{V}_{hw} \times \rho_{hw}}{nhw_{circ}} \quad (7)$$

Finally, the daily heat required to heat the hot water used in one day was determined as:

$$\dot{Q}_{hw} = \dot{m}_{hw} \times Cp_{hw} \times (Thw_{in} - Tfw) + (nhw_{circ} - 1)(\dot{m}_{hw} \times Cp_{hw} \times (Thw_{in} - Thw_{out}) \quad (4)$$

To compensate for the heat losses during a day, the water has to be circulated in the pipes at a volumetric rate of $\dot{V}_{hw}$. The farmer has to manage the digester manually, and no electronic regulation tools are used. Thus, for practical reasons, the digester should be heated perhaps just once a day, for example, in the morning. The flow rate inside the pipes was determined for this heating period. The diameter of the pipe, Dp, was set at 20 mm, a common hose diameter. The velocity inside the pipes was calculated as:

$$v_{hw} = \frac{\dot{V}_{hw} \times 4}{\pi \times Dp^2 \times t_h \times 3600} \quad (9)$$

The pipe length and thermal transmittance were calculated by (**5**) and ((**7**), respectively:

$$Lp = \frac{\dot{Q}_d}{U_p \times \overline{Td} \times \pi \times Dp} \quad (5)$$

$$\overline{Td} = \frac{Thw_{in} + Thw_{out}}{2} - Td \quad (6)$$

$$U_p = \frac{1}{\frac{1}{hp_{int}} + \frac{1}{hp_{ext}} + \frac{\delta p}{\lambda p}} \text{ with } hp_{int} = hp_{ext} \quad (7)$$

The number of loops, n_{loops}, was determined as a function of the diameter of the digester:

$$n_{loops} = \frac{Lp}{\pi \times Dd} \quad (8)$$

The height of the loops, H_{loops}, cannot exceed the depth of the digester H_d, and the heating system has to be contained inside the digester. The digester was assumed to be two-thirds full of slurry. Therefore, the height of the heating system was set to less than two-thirds of the digester depth:

$$H_{loops} = n_{loops} \times (Dp + 2 \times \delta p) < \frac{2}{3} H_d \quad (9)$$

The parameters needed to calculate the dimensions of the heating system are presented in Table 2.

Table 2. Parameters used in the computations.

Parameter	Thermal conductivity λ (W.m^{-1}.K^{-1})	Thickness δ (m)	Diameter *D* (m)	Temperature *T* (°C)	Heat capacity Cp (J.kg^{-1}.K^{-1})	Density *ρ* (kg.m^{-3})
Digester dome (do)	0.5	0.15	-	-	-	-
Earth layer above the dome (edo)	1	0.3	-	-	-	-
Earth (e)	1	-	-	-	-	-
Hose:plastic pipe (p)	0.3	0.002	0.02		-	-
Input slurry (in)	-	-	-	Ta	4180	1000
Input hot water (hw_{in})	-	-	-	50	4180	1000
Output hot water (hw_{out})	-	-	-	40	4180	1000
Fresh water (w)	-	-	-	25	4180	1000

2.4. Methane Production

The calculations were carried out using a bacterial growth rate adapted to psychrophilic conditions. This growth equation (**10** is valid for the digester temperature range 15–30 °C [28]:

$$\mu m(Td) = 0.0019e^{0.1478 \times Td} \quad (10)$$

Methane production was assessed using a modified Hashimoto equation [16] to represent biogas production in developing countries, where the digester is not stirred. The lack of mixing leads to sedimentation and thus to different SRTs and HRTs. The sedimentation increases the retention time of the solids and inoculum:

$$\gamma_{winter}\,(HRT, \mu m, Td) = \beta_0 \times [1 - \frac{k}{\mu m(Td) \times \left(HRT + \frac{1}{\mu m(Td)]}\right) - 1 + k}] \quad (11)$$

In the summer time in the study region, the outside temperature is above 22 °C, which is similar to the temperature reported in the Indian study by Khoiyangbam *et al*. [13,23]. The biogas production in summer was assessed using the Hashimoto equation, which is valid for digestion temperatures between 20 °C and 60 °C:

$$\gamma_{\ summer}(HRT, \mu m, Td) = \beta_0 \times [1 - \frac{k}{\mu m(Td) \times HRT - 1 + k}] \quad (17)$$

$$\mu m(Td) = 0.13 \times Td - 0.129 \quad (18)$$

Equation (17) was also used to determine the methane production when the digester is heated to 35 °C. The kinetic constant, $\boldsymbol{k}$, is calculated as follows:

$$k = 0.6 + 0.0206 \times \mathrm{Exp}(0.051 \times \mathrm{S}_0) \quad (19)$$

2.5. Characterization of the Biomass Resource

The number of animals on the farm clearly determines biogas production. In this study, we decided to focus on fattening pigs, which are raised and sold within a few months. More than one pig is raised per year, e.g., a pig house may hold 10 fattening pigs at a time, representing 10 pig places. Therefore, when assessing the amount of biomass available on a pig farm, it is essential to know whether excreta production is calculated per pig place or per pig. The amount of excreta produced per day is obtained by multiplying the amount of excreta produced per animal by the number of animals present on the farm. To assess the energy production, the biogas composition has to be determined. The equations from Symons and Buswell [29] Equations (20) and (21) were used to assess the theoretical methane potential of the slurry and the methane fraction (x_{CH_4}) in the biogas produced:

$$C_nH_a0_bN_c + \ xH_20 \ \rightarrow \left(\frac{n}{2} + \frac{a}{8} - \frac{b}{4} - \frac{3c}{8}\right) CH_4 \quad (20)$$

$$C_nH_a0_bN_c + \ xH_20 \ \rightarrow \left(\frac{n}{2} - \frac{a}{8} + \frac{b}{4} + \frac{3c}{8}\right) CO_2 \quad (21)$$

where $C_nH_a0_bN_c$ is the Volatile Solids (VS) composition of the pig slurry:

$$x_{CH_4} = \frac{CH_4}{CH_4 + CO_2} = \frac{Bu_{CH_4}}{Bu_{CH_4} + Bu_{CO_2}} \quad (22)$$

$$Bu_{CH_4} = \ Bu_{VS\ ed\ CH_4} + Bu_{VS\ sd\ CH_4} \quad (23)$$

$$Bu_{CO_2} = \ Bu_{VS\ ed\,CO_2} + Bu_{VS\ sd\,CO_2} \quad (24)$$

Table 3 presents the fractions of the various components of VS from fattening pigs used to estimate the biogas composition. The table also includes the VS composition of cattle manure so that the model can be used to assess the concentration of CH_4 in biogas from digesters fed with cattle manure, for which the biochemical methane potential is β_0 = 148 L CH_4 kg^{-1} VS [30].

Table 3. Composition of the organic matter (VS) in pig and cattle manure [30].

VS component	Number of atoms				VS fraction	
	C	H	O	N	Pig manure	Cattle manure
VS (VFA)	2	4	2	0	0.072	0.036
VS (protein)	5	7	2	1	0.229	0.15
VS (lipid)	57	104	6	0	0.137	0.069
VS_{ED} (carbohydrate) *	6	10	5	0	0.347	0.434
VS_{SD} (carbohydrate) **	6	10	5	0	0.166	0.191
VS (lignin) ***	10	13	3	0	0.049	0.121
Total					1	1

* Slowly digestible carbohydrates (SD); ** Easily digestible carbohydrates (ED); *** Number of atoms for VS (lignin) obtained from [31].

2.6. Evaluation of Energy Outcomes

Using the equations above the biogas production can be estimated by using the data presented in Table 4. Further, surplus energy due to heating with biogas to provide a defined fraction of the energy needed to reach mesophilic temperature can also be estimated with the model that is uploaded on the website SUSANE.info. [32]

Table 4. Parameters used in the model.

Variable	Abbreviation	Value
Time of heating per day	th	2 h
Constant for non-insulated vertical side walls [21]	α	1.37
Distance from the bottom of the digester to the groundwater level [21]	l	5 m
Efficiency of the biogas boiler	η	55%
Thickness of the dome [21]	δdo	0.15 m
Thickness of the earth layer above the dome [21]	δedo	0.3 m
Thickness of the hose	δp	0.002 m
Diameter of the hose	dp	0.02 m
Ground temperature (monthly average)	gr	Ta (°C)
Wind speed – monthly average	u	2.5 $m.s^{-1}$
Lower heating value of methane gas	LHV_{CH_4}	36,000,000 $J.m^{-3}$
Number of times the water circulates inside the digester	nhw_{circ}	1

Daily methane production:

$$\dot{V}_{CH_{4_{35°C}}} = \frac{\gamma_{35°C}(HRT, \mu m, Td) \times V_d \times S_0}{HRT} \quad (25)$$

Daily biogas production:

$$\dot{\boldsymbol{V}}_{\boldsymbol{g}} = \frac{\dot{\boldsymbol{V}}_{\boldsymbol{CH_4}}}{\boldsymbol{x}_{\boldsymbol{CH_4}}} \quad (26)$$

Energy produced daily as biogas:

$$\dot{Q}_g = \dot{V}_{CH_4} \times LHV_{CH_4} \quad (27)$$

To assess the feasibility of heating the digester using biogas, the energy required to heat the hot water was compared with that produced as biogas:

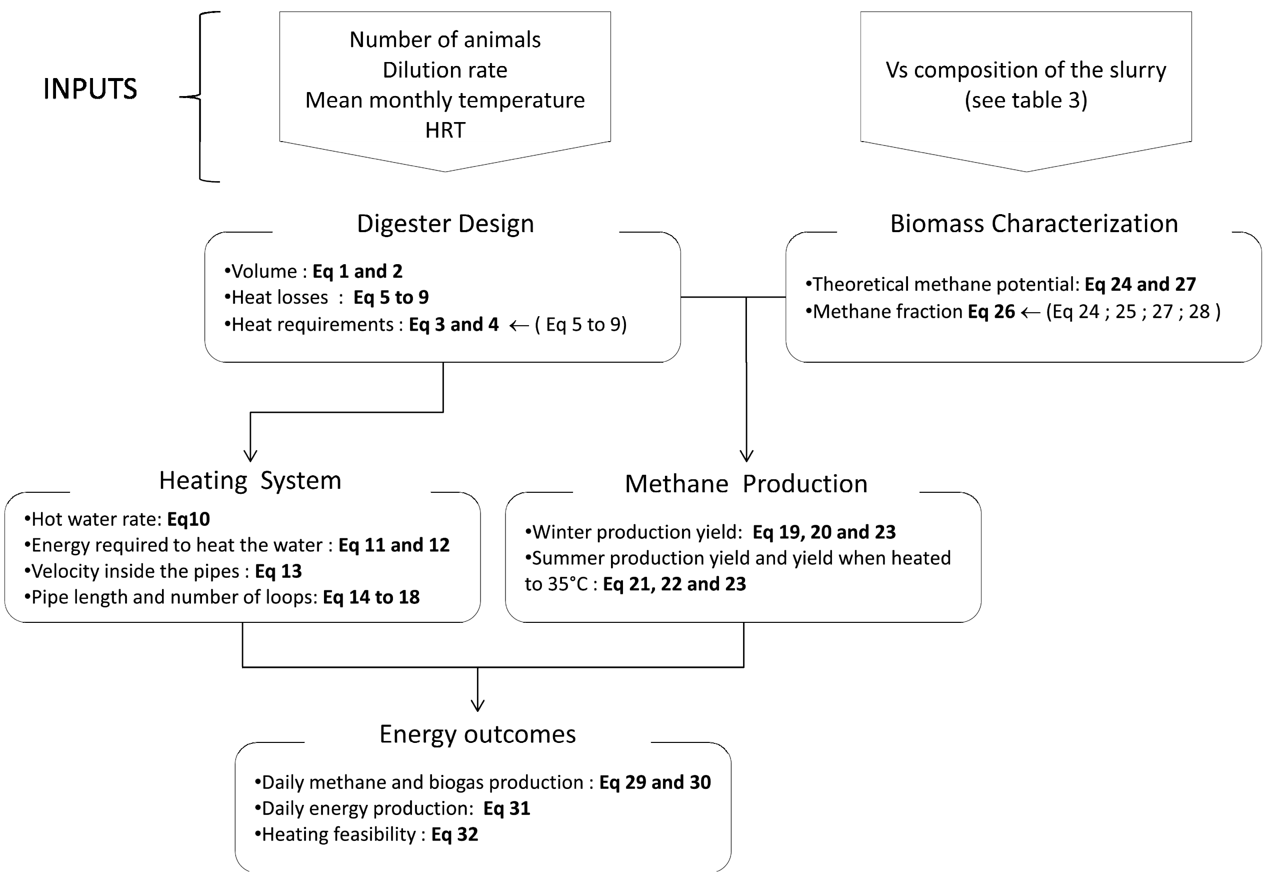
$$\dot{Q}_{g_{35°C}} + \xi \times \dot{Q}_{hw} > 0 \text{ and } \dot{Q}_{g_{35°C}} + \xi \times \dot{Q}_{hw} > \dot{Q}_{g_{winter}} \quad (28)$$

The inputs for the model calculations are listed in Table 4.

2.7. How Does the Model Work

A schematic algorithm to a better understanding of how the model is working is presented in Figure 2.

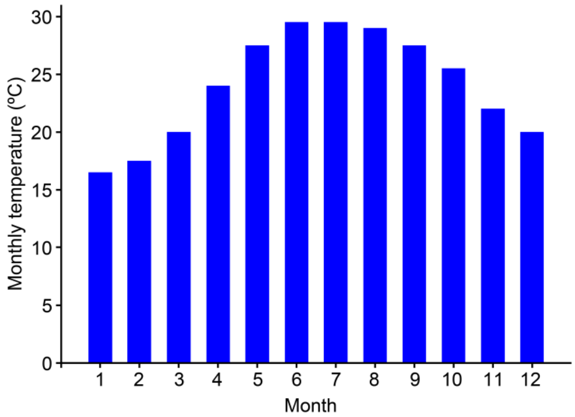
Figure 2. Scheme of the model.



3. Results and Discussion: Case study in Hanoi

Recent surveys of Vietnamese farms indicate that in regions with low winter temperatures, the temperature in the digester may decline to levels where the biogas production fails to meet the needs of the household [11]. In the northern regions of Vietnam, the low winter temperatures (Figure 3) lead to low biogas production due to psychrophilic anaerobic digestion conditions, so this situation represents an ideal example for testing our decision-support model. Simulations were carried out to show how the household can establish a level of biogas production that fulfills its needs throughout the year. This simulation included evaluating the effect of installing technology to heat the biogas digester. The intention of this exercise was to predict how the setup in which the digester is heated with a fraction of the biogas produced must be adjusted to achieve surplus biogas production as a function of digester size, the dilution of animal manure and biomass availability (number of pigs). The average number of fattening pigs (pig places) on farms in the suburb of Hanoi studied here is 16, and the average farm household numbers five people [11,33].

Figure 3. Mean monthly temperature (°C) in Hanoi [34].



3.1. Energy Requirements and Biogas Production

The amount of biogas needed has to be assessed to set the target for biogas production. Vu *et al.* [33] reported that 0.8–1.0 m^3 of biogas per day would be sufficient to supply the needs of a family of five-six people. This value is somewhat lower than the energy needs of a household in India, where the daily energy requirement for cooking is estimated to be 0.34–0.42 m^3 of biogas per person, *i.e.*, 1.7–2.1 m^3 for five people [35]. The Indian rates of energy consumption mirror those set by the FAO/CMS [15] for India/Nepal, which assume a daily biogas energy need of 1.5–2.0 m^3 for a household of six people. The differences in these assessments can be due to variations in the quality of the biogas, *i.e.*, the CH_4 concentration, which is affected by the composition of the feed entering the digester. The volume of biogas needed to produce enough energy decreases at increasing concentrations of CH_4 in the gas, and this concentration is higher for pig manure than for cattle slurry. In Vietnam, the manure is mainly provided by pigs, whereas in India, it is provided by cattle. Thus, this study assumed that the daily energy need was 1.4 m^3 day^{-1} for an average pig farm with 16 fattening pigs and a household of five members.

Mean monthly air temperature (Figure 3) was assumed to represent the mean monthly digester temperature [36]. For biogas production, two seasons were distinguished depending on digester temperature, with an average summer air temperature above 20 °C yielding mesophilic conditions, and an average winter temperature below 20 °C leading to psychrophilic conditions. Thus, mesophilic conditions dominate from April to November and psychrophilic conditions from December to March. When heated, the digester temperature was set to 35 °C, *i.e.*, the fermentation in the digester was assumed to be in the mesophilic range.

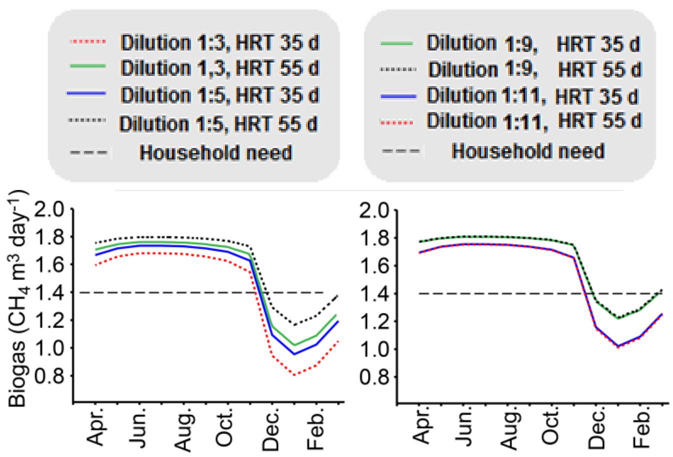
The biochemical methane potential of manure from fattening pigs is β_0 = 356 L CH_4 kg^{-1} VS [30]. The CH_4 concentration was calculated to be 0.62 L CH_4 L^{-1} biogas, and the heat production of the biogas, expressed as the lower heating value (LHV), was 36 $MJ.m^{-3}$.

On average, a Vietnamese fattening pig excretes 0.864 $kg.day^{-1}$ of solid manure [33]. An excessively high loading rate of VS inhibits biogas production, and at 35 °C, the optimum loading rate per m³ digester volume is 1–3 kg VS day^{-1} [16] and the maximum advisable rate is 5 kg VS m^{-3} day^{-1}. The amount of biomass added to the digester is important because the feed volume affects the retention time, and the size of the digester should be adjusted according to the feed rate and digester temperature. Farmers in Vietnam are advised to dilute the slurry with water to avoid clogging of the biogas digestion plant, and the dilution rate is generally between 1:8 and 1:11 [11,33]. The retention time of digesters is therefore often too low because digesters are constructed assuming a dilution rate of 1:3, as advised by the SNV-VN consultancy [33]. Our model calculations examined the effect of different manure:water ratios on the efficiency of heating. The manure:water ratios (m:w) used in the calculations and S_0 values were as follows; m:w of 1:1 gave S_0 120 kg VS m^{-3} feed, m:w 1:3 of gave 60 kg VS m^{-3} feed, m:w of 1:5 gave 40 kg VS m^{-3} feed, m:w of 1:9 gave 24 kg VS m^{-3} feed and m:w of 1:11 gave 20 kg VS m^{-3} feed.

3.2. Daily Biogas Production as Affected by Hydraulic Retention Time and Dilution

For the farm mentioned above, the daily biogas production rate was assessed for HRTs of 35 and 55 days and dilution rates from 1:3 to 1:11 at each retention time (Figure 4). Increasing the degree of dilution at the same HRT increased biogas production by the digester. The positive effect of dilution was most pronounced at short HRTs. For example, with a HRT of 35 days increasing the dilution rate from 1:5 to 1:9 increased biogas production by 5.4%, and increasing the dilution rate from 1:9 to 1:11 increased biogas production by 0.8% while for a HRT of 10 days the production was increased by 9.2% and 1.4% respectively. The high dilution rate on Vietnamese farms is not optimal, as the positive effect of dilution is counteracted by the shorter retention time of digesters not designed to cope with the daily addition of large amounts of diluted slurry [11,33]. Even if the digester volume was increased by 20%, biogas production would not increase by more than 1% as the dilution of the slurry increased from 1:9 to 1:11, but at a dilution rate of 1:3, the biogas production would increase by 25%. Thus, when the pig pen is cleaned on a daily basis, part of the washing water could be directed to the slurry store rather than to the digester to avoid over-dilution. In terms of current dilution and HRT levels, biogas production in winter was found to be insufficient to meet the demands of the household (Figure 4).

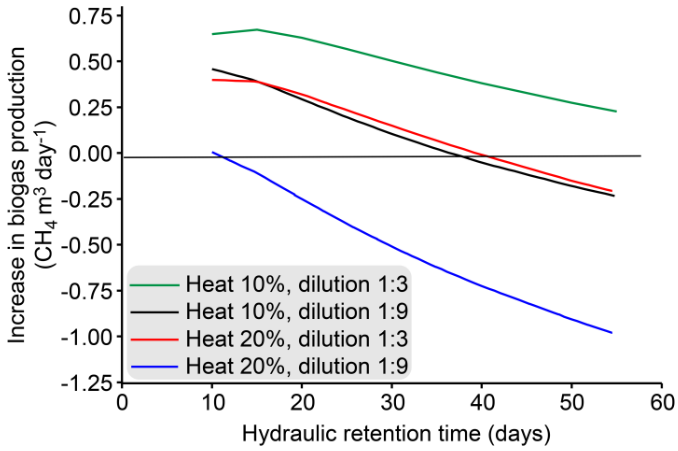
Figure 4. Daily rate of biogas production on a Vietnamese farm with 16 fattening pigs for different dilution rates and HRT, without heating the digester. The household need for biogas energy was assumed to be 1.4 m³ per day.



3.3. Heating the Digester

During winter, using the biogas to heat the digester to 35 °C reduced net biogas production. However, combining solar and biogas energy to heat the digester through the long winter period with intermittent solar energy production may contribute enough biogas to meet the needs of the household, despite the fact that there can sometimes be several days in a row without sunshine. Dilution of the slurry will increase the need for heat. In the present example, heating to 35 °C when 20% of the heat was supplied by the biogas did not result in a surplus of biogas delivered to the household at a dilution rate of 1:9 (Figure 5).

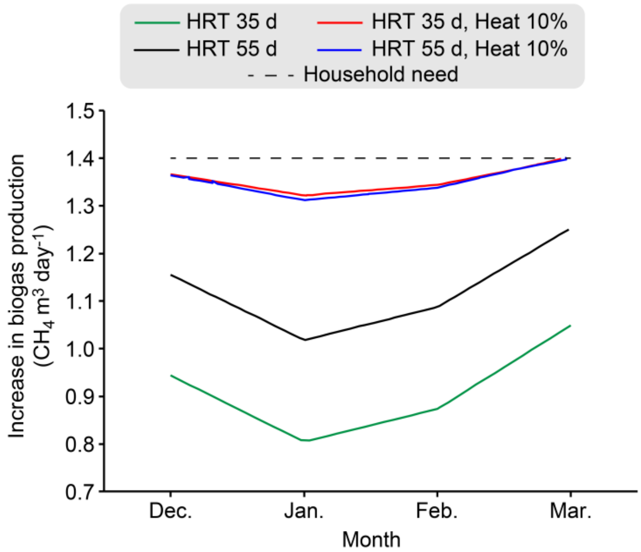
Figure 5. Average net increase in biogas delivered to the household if 20% or 10% of the biogas produced is used to heat the biogas digester to 35 °C (manure from 16 animals).



However, when only 10% of the heat was supplied by the biogas, a net increase in biogas production was achieved, but only if the HRT was less than 40 days. At a dilution rate of 1:3, the net production was positive under both low and high biogas consumption conditions, except when 20% of the heat was supplied by biogas and the retention time was longer than 40 days (Figure 4). The higher net production at shorter retention times is due to the lower amount of energy needed to heat a smaller digester than a larger digester, indicating the interaction between the effect of a longer HRT and heat consumption. For a biogas heating system providing 10% of the heating energy needed by the digester, production can be improved by 48%, 22% and 2% for manure:water ratios of 1:3,1:5 and 1:9, respectively. At a dilution rate of 1:11 the production of biogas does not increase. This finding shows how important it is to avoid adding too much water to the slurry, especially if the purpose of dilution is to heat the digester.

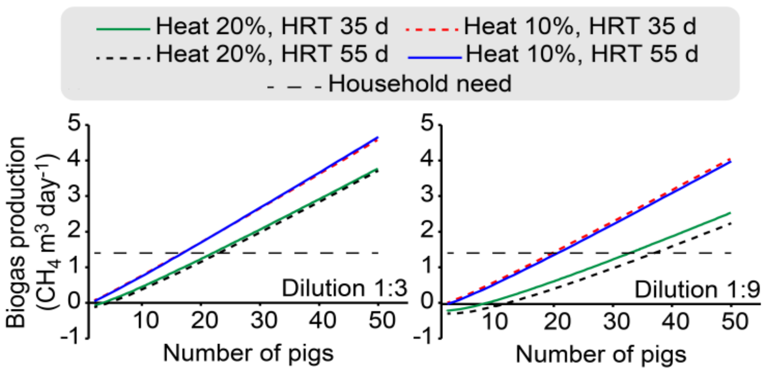
Digester heating is important during the winter. Using 10% of the biogas to increase the digester temperature to 35 °C at a dilution rate of 1:3 improves the biogas production at HRTs of 35 and 55 days (Figure 6). If the dilution rate is 1:9, then the biogas production will not be better than without heating.

Figure 6. Daily biogas production in winter from the manure of 16 animals, with 10% of the digester heat provided by biogas at a dilution ratio of 1:3.



The net outcome of heating is affected by the amount of manure (number of pigs) on the farm. Increasing pig production from 16 to 22 fatteners and heating with 20% biogas would allow for biogas production to fulfill household energy demand at an HRT of 34–35 days and a dilution ratio of 1:9 (Figure 7). If only 10% of the heating energy needed to be provided by biogas, 17 fatteners would be required to meet the energy needs of the household. Thus, it is necessary to know the demand for biogas heating as well as the manure production rates and expected solar energy capture.

Figure 7. Effect of the number of animals on biogas delivery to the household when the digester is heated to 35 °C with solar energy and biogas. Biogas contributes 10% and 20% of the digester heat needed during periods with little or no solar heating, and the biogas boiler has an efficiency of 55%.



Heating the digester using biogas should not be the first and only solution to the decrease in biogas production during winter. However, when the digester is heated using a solar power system, it is interesting to know how much biogas could be used to compensate for short-term periods without solar radiation, and this can be roughly evaluated using the model developed here. To evaluate the feasibility of heating a simple Deebandhu digester, the model has to be tested experimentally using a real heating system configuration.

In summer time, the air temperature is high and biogas production high. Heating the digester in winter time does not influence the summer production and do not lead to more biogas production in summer time. It contributes to have a "more" constant production all around the year and not to a higher production in summer time.

4. Conclusions

The specific dilution rate of the feedstock (manure) is important for biogas production from small digesters due to the effect of dilution on hydraulic retention time. The model presented here can be used to construct digesters with suitable dimensions tailored to the number of animals and the local climate. According to our calculations, the currently practiced manure:water dilution ratio of 1:9 is not advisable if the digester must be heated in the winter. In the subtropics, where winter temperatures can fall below 20 °C, using biogas to heat simple digesters buried in the soil means that less gas is available to households. Using a combination of solar provided heat and biogas to heat the digester (the latter during periods without solar heat) can provide enough surplus biogas to meet household requirements on a standard pig-producing farm in Vietnam. For example, heating the digester to 35 °C with the biogas contributing 10% of the heat means that a standard dome digester can almost produce the energy needed by the household during a "normal" winter by increasing the volume of gas delivered by approx. 50%. To meet family energy needs, 17 pigs will be needed instead of the standard number of 16 pigs. If biogas contributed 20% of the energy used to heat the digester, then the manure from 22 fatteners would be needed on a farm with a "standard" retention time of 35 days to meet the energy requirements of the household. Very few data are needed to carry out the calculations of this model, therefore, the calculations with the model will be very useful when advising farmers to invest in biogas digesters, and also if the farmers have to decide between constructing a joint larger communal digester that could be heated instead of one digester per farm.

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Conflicts of Interest

The authors declare no conflict of interest.

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