IMPROVING ANAEROBIC DIGESTION EFFICIENCY OF HOG MANURE IN PASSIVE HEATING SOLAR GREENHOUSES ON THE CANADIAN PRAIRIES

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Keywords: anaerobic digestion, energy balance, biogas, greenhouse, heat exchange, manure, hog, cold climate

ABSTRACT

In cold climates, it is generally accepted that much of the methane produced by anaerobic digestion of animal wastes is used to keep the digester within the mesophillic range of operation (30-38° C), sometimes yielding little or no net annual production for electricity or facility heating. Optimizing digester tank insulation, enclosing the digester in a passive heating solar greenhouse, allowing influent to reach ambient greenhouse temperature and providing heat exchange between outflow and incoming digester wastes, the energy balance can be substantially improved. This paper uses data from a passive solar greenhouse, data from lagoon-fed and direct barn -fed hog manure to model a small pilot scale digester (2000 litre) at 50° latitude in Western Canada. Results indicate a greenhouse improved gas economy more than just insulation because a greenhouse allowed heat exchange and preheating of manure to ambient temperatures.

INTRODUCTION

Farm scale anaerobic digestion of animal manures is gaining substantial interest due to renewed attention to green energy and greenhouse gas mitigation. In cases of cold climate conditions, however, economics of high capital costs and high operating costs do not warrant the value of the gas produced by anaerobic digestion processes. This is especially true in locations like the Canadian Prairies where cold winter months demand a substantial portion of the gas produced be used just to keep the system within the mesophyllic range (35° C). This prompted the search for alternative, low intensity methods to maintain digester temperatures and preheat incoming waste streams. Recent studies in Turkey have shown active heat transfer from solar collectors can reduce biogas used for heat requirements to 7% from 26% of total gas produced (Kocar, Eryasar 2007). In Egypt, modelling a thermophyllic digester performance was greatly improved with an active solar roof, and heat recovery from effluent eliminated the need for supplementary heat (El-Mashad et al. 2004). In Greece, Axaopoulos et al. (2001) also used an active solar collection system to improve biogas output. While each of these studies were located in warm-climate countries, enhanced insulation and use of passive solar heating may bring about similar results in cold climates. In North America, rising natural gas prices and more stringent regulations on manure spreading for odour control suggest anaerobic digesters deserve another look. Ongoing research in the Canadian prairies has shown passive heating solar greenhouses with a heat sink (gravel filled insulated north wall) can raise ambient temperatures by 20° C, even in the coldest months (Bashada et al. 2006). The study also tested insulated glazing types, finding argon filled plastic glazing to be superior to bubble wrap and double poly glazing. This paper proposes the installation of a small-scale anaerobic digesters inside passive solar greenhouses and models the energy balance in such a situation. A greenhouse offers protection against the coldest weather, allowing lower energy inputs for tank temperature maintenance and increasing incoming manure temperatures through preheating within the greenhouse. Both aspects are investigated in this paper as well as cost payback from methane saved.

Several authors have preformed extensive models of heat transfer for anaerobic digesters (Gebremedhin et al. 2005), including attention to cold weather situations (Wu and Bibeau 2006). In this paper a simple set of calculations to model heat balance and transfer were used. Net energy produced by a reactor in the form of biogas is the energy remaining after operational demands:

$$Q_{net} = Q_{prod} - Q_{operation} \quad (1$$

where Q_{net} is the net energy gain, Q_{prod} is the total energy produced in the digester and $Q_{operation}$ is energy used in digester functioning. Q_{prod} is considered constant throughout the year and $Q_{operation}$ is variable depending on insulation thickness and incoming manure temperature. This energy balance considers only operational heating requirements and makes no allowance for waste heat in the conversion of methane to heat energy. In previous studies conversion of methane to heat has been reported at 70% efficiency (direct) and 90% when electricity is generated and waste heat then recovered and used for heating (25% and 65% efficiencies (Heduit et al. 1986). Very high efficiency furnaces (90%) are currently available.

As shelter from cold weather, a greenhouse has many advantages from a conventional structure due to low capital cost, simple construction and passive heat gain that may impact the energy balance of methane production requirements. The two operational heat requirements are: 1) maintaining the tank temperature within the mesophyllic range (35° C), and 2) bringing input wastes up to temperature before addition to the tank.

$$Q_{operation} = Q_{maint} + Q_{input} \qquad (2$$

It is generally accepted that input heating requires more energy than tank maintenance, but the input manure temperature can vary widely if its kept in a lagoon or are directly sourced from a warm barn.

Tank Temperature Maintenance Heat

Anaerobic tank temperature maintenance is calculated for 35° C and varying insulation thicknesses. Maintenance heat loss is calculated using the equation:

$$Q_{maint} = U\,A\,\Delta T\,\Delta t \qquad (3$$

Where Q_{maint} is total energy required, U is the overall heat transfer coefficient (W/m^2K), A is the surface area of the reactor, at t is time (s). Overall heat transfer is calculated as:

$$U = 1/((1/h_1)+(1/(dxw/k))+(1/h_2)) \qquad (4$$

Where U is overall heat transfer, h_1 and h_2 are thermal conductivities of manure and air, dxw is insulation thickness and k is the heat transfer coefficient of the insulation. When insulation thickness is greater than 0.01 m both h_1 and h_2 become insignificant and for the purposes of this paper they are ignored. Figures for thermal conductivity were obtained from recent studies (Abdou et al. 2005).

Manure Input Heat

In a standard anaerobic system, heat required to bring manure up to tank temperature is straightforward:

$Q_{\text{input}} = m\, c\, \Delta T$ (5

Where Q is energy required (J), *m is* mass of manure (g), c is the specific heat of manure (J/g/degree) and T is temperature change (C).

Pre-heating of influent in anaerobic systems is preferred to adding cold wastes because it slows down the system and causes shock to the microbial balance. A greenhouse allows preheating manure in three ways: direct solar heating, ambient greenhouse heating and heat recovery from effluent.

$Q_{\text{input}} - (Q_{\text{solar}} + Q_{\text{ambient}} + Q_{\text{recovery}})$ (6

1) A small diameter intake pipe with coiling to take advantage of solar radiation within the greenhouse. This treatment is followed by final temperature adjustment (if needed) by a hot-water heat exchange powered with digester biogas. Assumptions here are that half the pipe circumference will be available for solar heating, and that mean daily solar radiation intensity changes with the season (monthly intervals used). The equation used was:

   $Q_{\text{solar}} = \pi r l\, R t$ (7

   where Q_{solar} is the heat gained by exposure to sunlight, π is pi, r is the pipe radius, l is the pipe length, R is the average daily global radiation during daylight hours on the 21^{st} of each month and t is the hours of sunlight for that day.

2) Ambient heat available for manure preheating was calculated using monthly greenhouse mean temperatures (Fig. 1) assuming daily manure input was stored in the greenhouse (uninsulated steel tank) during the warmest part of the day for each month mean temperatures were above lagoon temperature (10 C). Equation 5 was used to find heat needed to bring manure up to the ambient greenhouse temperature and equations 3 and 4 used to determine time required.

3) We calculated the heat recovered by using effluent manure to equilibrate with influent manure in a divided holding tank. Depending on the influent manure temperature and the time of year, one system may offer better heat gain over another. It is expressed as:

   $Q_{recovery} = (T_{effluent} - T_{influent\backslash})/2$ (8 where $Q_{recovery}$ is the heat taken from digester effluent, $T_{effluent}$ is the temp of effluent $T_{influent}$ is influent manure temp (C). This assumes the equilibration tank is insulated from greenhouse with no heat loss to ambient environment.

METHODS

Model Anaerobic Digester Details

This model was developed for a 2 m^3 pilot- scale anaerobic digester currently under construction, but the operating parameters are common to most farm operations. Raw manure (3-5% VS) can be stored in a lagoon (annual mean temp 10° C) or fed directly into the digester from the barn (farrow 20° C; finish 15° C). A 15 to 20 day hydraulic retention time (HRT) in the digester reduces pathogens and odours while converting approximately 30% of the organic content to methane. Biogas production can vary greatly depending on VS input and ranges from 0.4-2 m^3/m^3 tank volume /day (Heduit et al. 1986). This study uses a conservative figure of 0.6 m^3/m^3, of which 70% is assumed to be methane.

The energy balance around the digester was modelled using the equations listed above and local parameter values. Using existing monthly temperature values for southern Manitoba (Environment Canada, monthly means) and recorded data for a passive heating solar greenhouse vs outside temperatures (Bashada et al. 2006) a curve was constructed (Fig 1). The three greenhouse glazing types used by Bashada et al. (argon, bubble wrap, double poly) produced similar greenhouse heat profiles, so poly was selected for use in this model because of its low cost. An integration of the outside temp curve and the digester temperature (35° C) gave 389 degree-months. Greenhouse temperature curve integration assumed venting would take place at temperatures over 35° C and gave 167 degree months. Heat loss by the model 2 m^3 tank was calculated in MJ/month/degree of difference between the tank and ambient temperatures. Results were then comparable in absolute MJ of heating required to make up the heat loss. This amount was assumed to come from methane produced by the digester (307 m^3 or 10,828 MJ/yr). Changes in insulation thickness could then be compared to the biogas used by a digester located outside and one located inside a solar greenhouse.

Heat requirement for manure input was calculated at fractional daily replacement of tank over a 15 day HRT. Manure sources were either lagoon (yearly mean temp 10° C) or direct from finishing barn (mean temp 15° C except in summer, see Fig 1).

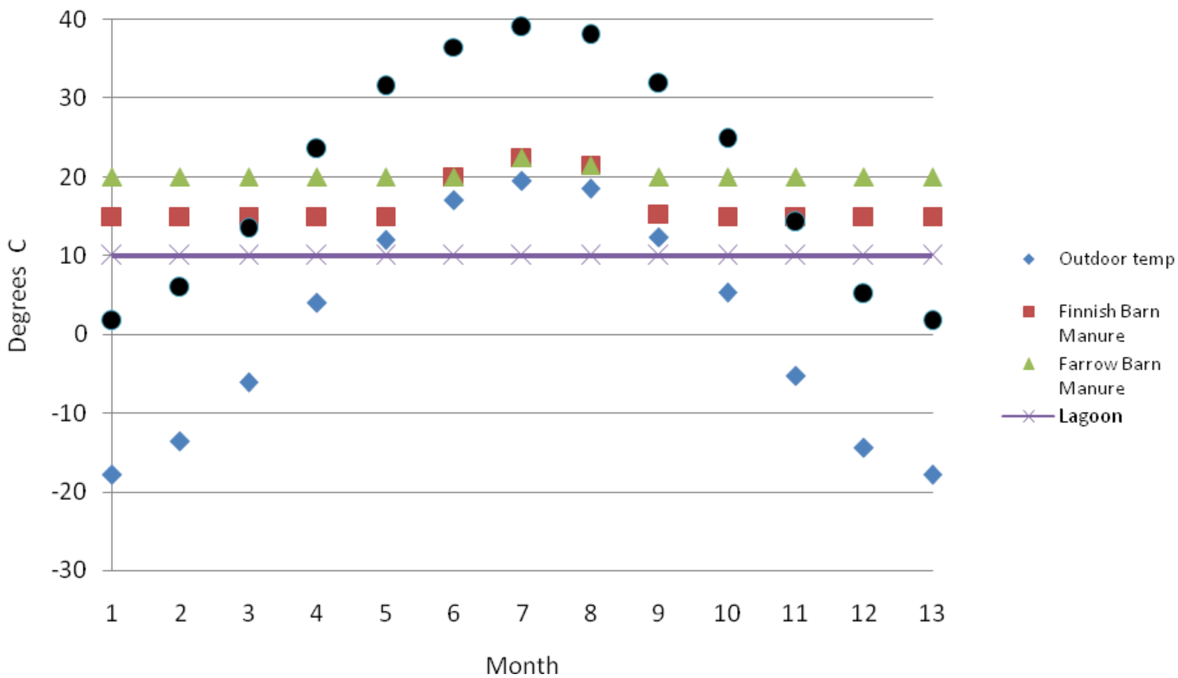

Figure 1 Manure input temperatures for lagoon, farrow and finish operations. Outdoor and greenhouse monthly temperatures are for averages in Winnipeg Manitoba, Canada. The numbered months on the x axis goes from January to January for curve symmetry.

Equation 6 was used to calculate preheating requirements by each of the preheating methods listed above. The solar heating option assumed an inflow pipe would have residence time in the greenhouse with full exposure to sunlight (6 cm di. 47 meters in length and 4.4 m^2 of surface exposed to solar radiation). Ambient heating assumed the storage tank would be filled during the day and kept there until it reached daily mean greenhouse ambient temperature. This calculation is considered conservative as no allowance was made for mid-day temperature spikes. The option of effluent heat recovery with cold (10° or 15° C) influent in a passive heat exchange tank was assumed to equilibrate completely but the required residence time for this was not calculated.

Costing

Increase in digester tank insulation added to the capital cost but also saved methane that would have been used in heating. These variables were plotted (insulation cost + cost of methane used) vs. insulation thickness to find optimum insulation thickness. Tank insulation was priced by a local contractor (poly urethane foam-in-place \$1.20/ ft^2/ in. or \$508/m^2/m) and heat transfer derived using known density (35.2 kg/m^3) and literature values for heat transfer coefficients (0.0291 W/mK (Abdou, Budaiwi 2005). The value of pure methane was set at the local price of \$0.30/m^3. As insulation costs were not recouped in the first year of operation, capital cost recovery (no-interest) was estimated using current gas rates.

RESULTS

The model worked successfully in revealing potential savings in anaerobic digester construction and location. Gas consumption was reduced significantly by locating a digester in a passive heating solar greenhouse compared with one outdoors at the same insulation thickness (Table 1). Insulation of 0.04 m (4 cm) saw net yields of heating requirements increase from 4473 MJ/yr to 8103 MJ/yr from a 10,828 MJ gross production. At 0.05 m of insulation, tank temperature maintenance is equal to manure input heating for an outdoor digester but less than half when located in a solar greenhouse. When manure is preheated with heat recovery input heat is halved. This fact underscores the need to consider the energy budget of an entire system, as significant savings are possible by minimizing heat loss by the incoming manure (e.g., direct from barn digester feed).

Table 1 Annual heat requirements of a 2 m^3 litre anaerobic digester on the Canadian prairies. Annual methane production is equivalent to 10,828 MJ.

	Maintenance Heat		Manure Input Heat			
	Outside	Greenhouse	Lagoon 10° C	With recovery	Finish 15° C	With recovery
Heating requirements (degree months)	389	167	300	150	220	110
MJ (with 0.15 m insulation)	1714	735	5028	2514	3699	1850
MJ (0.08 m insulation)	3201	1373				
MJ (0.04 m insulation)	6355	2725				

Preheating of manure by solar radiation within the greenhouse did not significantly impact the overall heat budget. Eight hour exposure to radiation in December (300 Wh/m^2) would increase the daily manure input temperature (0.02 C in Dec and 0.09 in June). Ambient radiant heating however, would have significant contribution to the overall energy requirements. Mean monthly greenhouse temperatures were above 10° C for all months except mid November to mid February, giving at least 9 months of heat gain from residence time in the greenhouse (Fig. 2). The ambient temperature provided all of the heat required to bring manure to digester temperature for 4 of the summer months. In all cases the relatively small amount of manure was heated within 1 hr or less (Fig. 3). Ambient heating helped improve the gas savings by $22 for the year (Table 2), which is a 25% savings of the entire annual production with minimal cost outlay. The model was considered accurate for a small digester in a greenhouse but was not attempted for larger digesters due to lack of year round greenhouse thermal storage data.

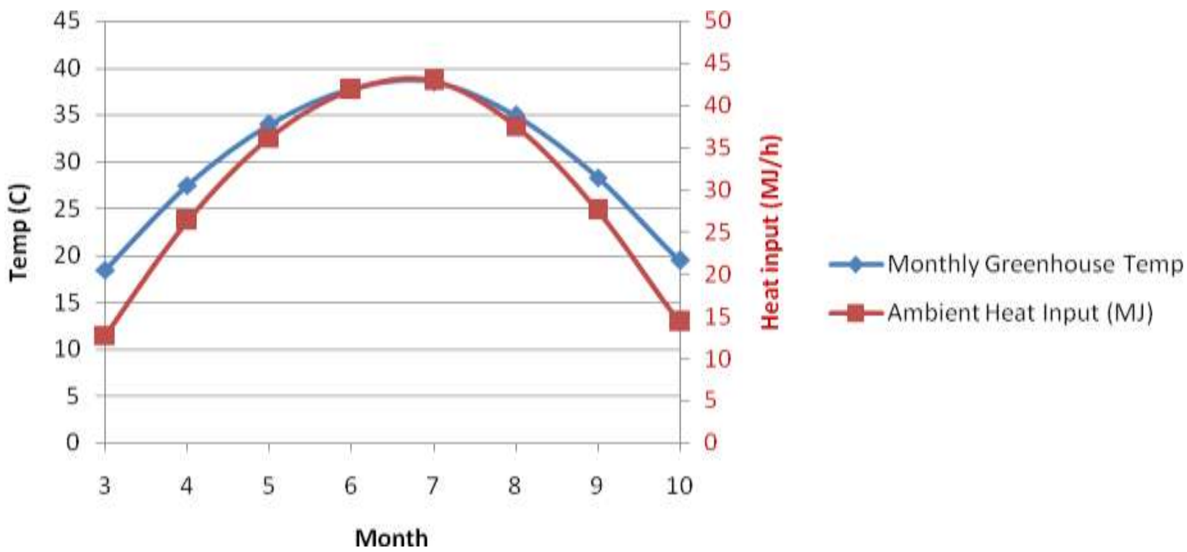

Figure 2 Greenhouse temperature and heat absorbed by daily manure input (133 litres) assuming incoming manure of 10 C and residence time to bring it up to ambient temperature. Only full months of mean greenhouse temp above 10 C are included (March to October).

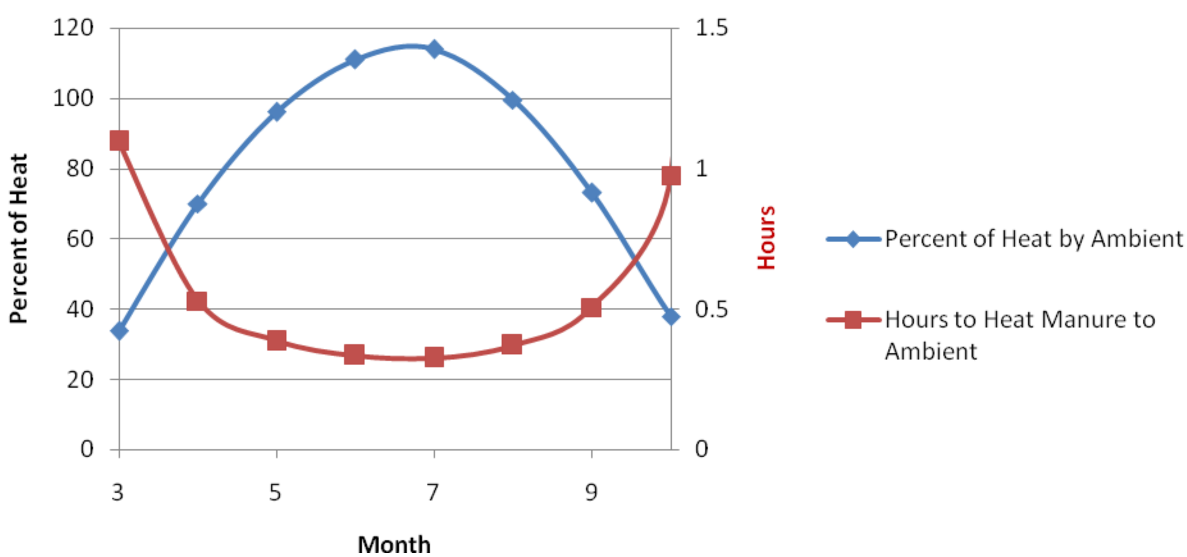

Figure 3 Use of ambient greenhouse heat to pre heat influent manure (133 litres from 10° C). Note spring and fall seasons require additional heat to bring manure to mesophylic range (35° C).

The model was useful in determining optimum insulation levels at the given insulation and gas costs. A non-linear relationship between insulation costs and savings in energy was established, and optimum thicknesses of insulation were found for each scenario (Table 2), where "optimum" is defined as shortest number of years to pay back the cost of insulation. An outdoor tank location required 0.08 m (8 cm) of insulation for the best eventual payback of 15.5 years, whereas barn-direct manure with passive heat recovery and only 0.02 m insulation achieved payback in only 3 years (Fig 4). The optimization process indicates that more insulation is not necessarily better from a capital cost perspective. If insulation prices remain steady and gas prices increase, the optimization will shift to greater insulation. The value of the greenhouse or heat recovery equipment was not considered in this payback modelling.

Table 2 Cost of insulation and benefit from lower gas costs for 2 m^3 anaerobic digester located outside; in greenhouse with input manure at 10 C (Gnhse); 15 C manure (Finish), and 15 C with heat recovery (Finish HR). Total value of annual gas production is $92. Blank cells indicate no cost repayment at current gas price rate. Ambient greenhouse heating of influent produced lower gas cost of $22 per year but this was not included in the Capital Cost payback.

		Gas cost @ $0.30/$m^3$				Years to pay insulation Capital cost			
Insulation thickness (m)	Insul cost @ $508/ m/$m^2$	Outside	Gnhse	Finish	Finish HR	Outside lagoon	Gnhse lagoon	Gnhse Finish	Finish HR
0.01	45	249	131	143	124				
0.02	89	149	88	92	73			4.9	2.9
0.04	179	97	66	65	46		6.9	4.4	3.4
0.05	224	86	61	60	41	33	7.3	5.0	3.9
0.07	313	74	56	53	35	16.2	8.7	6.3	5.0
0.08	358	70	54	51	33	15.5	10	7.0	5.5
0.09	403	67	53	50	31	15.5	10	7.7	6.1
0.1	448	65	52	49	30	15.8	11	8.4	6.7
0.15	671	57	49	45	26	19	16	12.1	9.6
0.2	895	54	47	43	24	23	20	15.7	12.5
0.25	1119	51	46	42	23	27	25	19.4	15.4
0.3	1343	50	46	41	22	32	29	23.1	18.4

A sensitivity analysis for heat requirements for maintenance and input heat was performed using different sized digesters revealing the small digester used in the model skews the importance of maintenance heat (and thus insulation) when compared with very large digesters (Figs. 5 & 6).

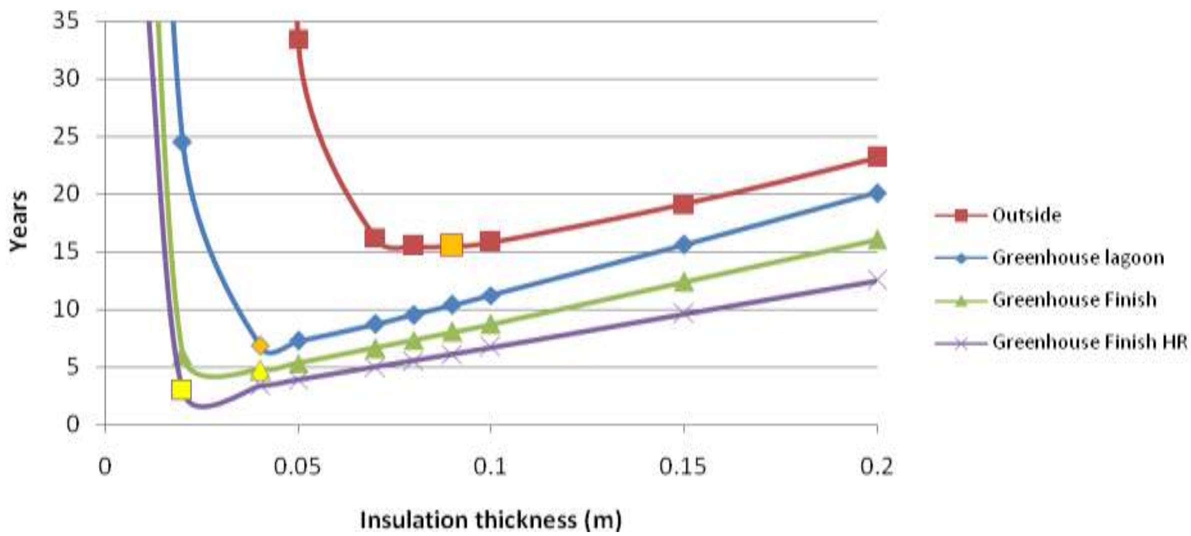

Figure 4 Years to recover capital cost of insulation to digester tank using methane purchase offset (at \$0.30/m3). Digester located outside receives manure from lagoon as well as one greenhouse curve. Other curves show a greenhouse digester with warmer manure intake (finish barn 15 C) and with heat recovery from heat exchange. Optimum insulation is identified in yellow marker on each curve.

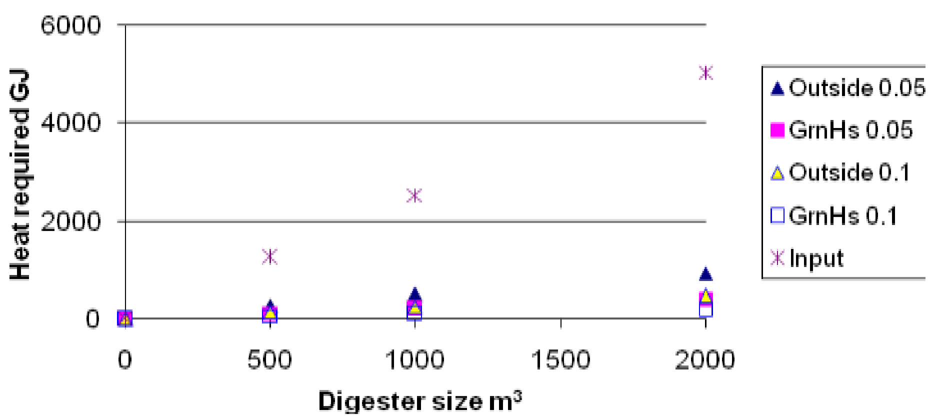

Figure 5 Annual maintenance and manure input heat requirements for different sizes of digesters, beginning with the model 2 m^3 digester. Input requiremnts assume no heat recovery or ambient greenhouse heating.

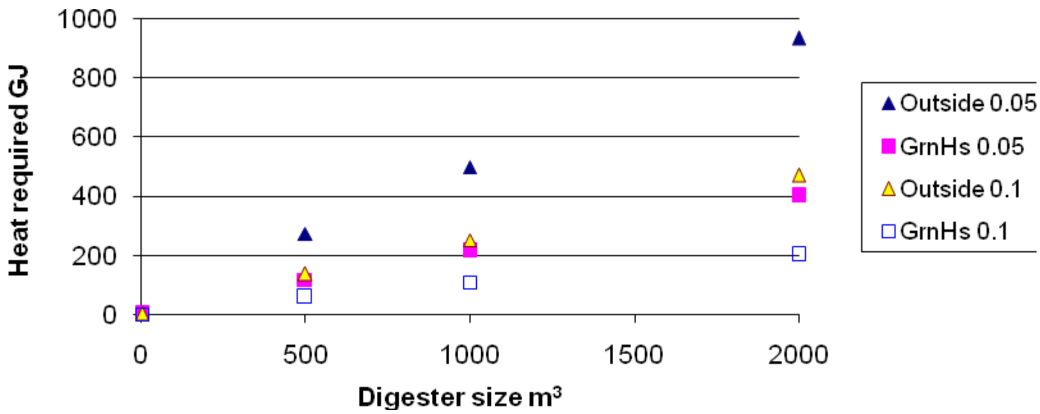

Figure 6 Annual maintenance heat for a range digester sizes highlightling the benefits of increased insulation and the use of a greenhouse.

CONCLUSIONS

This study may be useful for designing new facilities because it indicates the importance of conducting an energy balance with methane generating digesters. Heat loss to the environment was found to be of less relative importance than the heat required to bring manure to digester temperature. If facilities in cold countries can be designed with manure heat in mind, anaerobic digesters can produce much more gas for other purposes than operation maintenance. The use of a greenhouse is shown to be very beneficial for small digesters particularly for preheating of manure to ambient greenhouse temperatures. This was found to have benefit for 9 months of the year in Winnipeg, Canada, known for its very cold winters. A problem still to be solved is the fact that gas consumption on farms occurs mostly in the winter and gas is most easily produced in the summer. While greenhouses improve the winter heating needs of a digester, a surplus in the summer in not feasible to hold over until the following winter.

The heat balance model will continue to be useful as energy costs increase making optimum insulation levels and capital costs of greenhouse construction smaller in relation to the value of the gas saved by better energy balance.

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