Biogas production from crop residues on a farm-scale level: Scale, choice of substrate and utilisation rate most important parameters for financial feasibility

Svensson, Mattias; Christensson, Kjell; Björnsson, Lovisa

2005

Biogas production from crop residues on a farm-scale level: Scale, choice of substrate and utilisation rate most important parameters for financial feasibility

L. M. Svensson, K. Christensson and L. Björnsson
Dept. of Biotechology, Lund University, P.O. Box 124, SE-221 00 Lund, Sweden

Abstract Anaerobic digestion would enable the energy potential of agricultural crop residues such as ley crops, sugar beet tops and straw to be harnessed in Sweden. These residues are so spread out that full utilisation of the potential by centralised slurry-based technology is difficult, its appearing that simple but effective high-solids reactor systems have a better chance of being economically viable on a farm-scale level (30-300 kW). In the present study, the financial prospects of single-stage fed-batch high-solids digestion on three different scales, 51, 67 and 201 kW, were calculated, on the basis of experimental results and observations on a laboratory- and pilot-scale. The biogas was disposed as heat, combined heat and power or as vehicle fuel. The results indicate the importance of choosing substrates with a high methane yield and a high nitrogen content, and the necessity of fully utilising both the capacity of the equipment installed and the energy carriers produced.
Keywords High-solids anaerobic digestion, farm-scale, crop residues, sugar beet tops, economy, biogas upgrading, combined heat and power, organic farming

Introduction

Crop residues from farming represent a large unexploited energy potential that could be harnessed by the production of methane(CH_4)-rich biogas through anaerobic digestion (AD) (Nordberg et al. 1998). Simultaneously, the retainment and availability of the nitrogen of the residues would be increased due to reduced emissions to the air and water and enhanced nitrogen mineralization (Torstensson 2003, Gunnarsson et al. 2005). Augmenting the nitrogen efficiency of green manuring would increase the revenue of organic farmers, through freeing of land for revenue-bringing crops and an increase in the yield and protein content of crops (Edström et al. 2005, Hansson and Christensson 2005). Organic crop farmers with limited access to animal manure are strongly dependent upon green manuring to supply the soil with the nitrogen needed (Cormack et al. 2003). The current practice of mulching, where the ley is cut and left in the field 2-4 times before it is terminated, does not exploit the full nitrogen-fixating capacity of the ley; more than 80 % of the nitrogen captured in the mulched material was either leached and resorbed by the growing ley, or lost to the air and water (Malgeryd and Torstensson 2005). In addition, after the termination of the ley in the autumn, the levels of mineralised nitrogen drastically increase, while simultaneously the nitrogen uptake of the autumn sown crop is very low. Consequently the risks of leaching are very high. If also the final ley harvest was removed and anaerobically treated, the levels of mineralised nitrogen would become lower, diminishing the degree of nitrogen leaching (Torstensson 2003).

Although the maintenance and process control of slurry digestion is relatively simple, the costs involved in the handling and heating of the slurry favours the use of large centralised plants (Ghosh 1984, Tenbrummeler et al. 1991, Nielsen et al. 2002). For crop residues, the longer transport distance to these centralised plants might tip the economic balance, since the crop residues, compared to liquid wastes such as liquid manure and food industry wastes, also carry costs for harvest and storage and for size reduction and dilution. In addition, process problems inherent in the high water content of the process, such as crust formation, are particularly pronounced in the case of dry or highly fibrous crop residues, such as wheat straw (WS) and ley crops (LC) (Braun 2002, Edström et al. 2005).

The crust formation can be avoided by developing and introducing high-solids reactor designs. The volumetric efficiency increases, and handling and heating costs are reduced since no extra water needs to be added (Legrand and Jewell 1986, Dalemo et al. 1993). This enables processes to be scaled down, which is advantageous in various respects: Increased utilisation of the biogas potential available, important in a rather sparsely populated country such as Sweden (Nordberg et al. 1998); facilitated introduction and development of new technology by starting on a smaller scale, with the genuine success story of Danish windpower as an example (Hansen et al. 2003, Kamp et al. 2004); facilitated certification and acceptance of the digestate as a plant nutrient conserving biofertiliser (Evans et al. 2004).

How cost-efficient could high-solids farm-scale reactors be in a country such as Sweden? In the Agrigas project at Lund University, a variety of different reactor systems were tested on a pilot-scale, providing a certain answer to this question (Anonymous 2003). In an earlier study (Svensson et al. 2005b), two high-solids AD technologies were compared to utilising conventional slurry digestion on a 51 kW scale. Substrates were an ensiled mixture of WS and sugar beet tops (SBT), 7:93, wet weight. The SBT tonnage treated corresponded to full utilisation of the SBT of a 150 ha model farm in Southern Sweden. All of the LC produced, and most of the WS, were supposed to be disposed of as green manuring. One of the high-solids technologies, a fed-batch single-stage digestion operation (1-SD), proved to be the most competitive. Nevertheless, the reference case unit costs of the energy carriers produced were higher than, or similar to, the prices of commercially available alternatives. In the present study, the financial prospects of scaling the 1-SD reactor design from 51 up to 67 kW, by substituting WS for LC, or up to 201 kW, by tripling the reactor volume and adding LC as a third substrate in a ratio corresponding to anaerobically treating all of the LC and SBT available on the model farm, while maintaining the SBT/WS ratio of the 51 kW scenario, were calculated. Experimental data both from laboratory and from pilot-scale studies, together with operational observations of pilot-scale trials, represent the basis for the full-scale calculations conducted in the present study. The CH_4 in the biogas is disposed of in any of three different ways: as ordinary heat (H), as combined heat and electric power (CHP), or as upgraded vehicle fuel (VF). Full utilisation of the products is assumed.

Methodology

The operational costs are all-inclusive, encompassing harvest and storage, the digestion process and the spreading of the digestate. Accounted investment costs on the other hand are in the 51 and 67 kW scenarios restricted to the reactor, the auxiliary equipment, and the biogas disposal technology. The assumption is that the model farm recently converted from conventional cattle rearing (dairy or beef) to organic crop farming, making it possible to exclude the investment costs of facilities already in place, such as bunker silos and liquid manure tanks. In the 201 kW scenario, investment costs of these two types of facilities are included to cover the extended storage needs. Real interest rate is 4 %; depreciation periods are 10 and 20 years, machines and reactors with auxiliaries respectively; real estate tax rate 0.28 % of investment costs; maintenance 5 % of machine investments; reactor availability 350 $d \cdot yr^{-1}$; labour costs 22.2 $€ \cdot d^{-1}$; digestate spreading costs are 1.11 and 3.33 $€ \cdot t_{ww}^{-1}$ (tonnes of wet weight), liquid and solids respectively; Value of total ammoniacal nitrogen (TAN) 1.78 $€ \cdot kg^{-1}$; exchange rate 9 $SEK \cdot €^{-1}$; electricity price (sell or buy) 8.33 $€ct \cdot kWh^{-1}$. Table 1 presents further details, such as substrate costs and specifics of the three different biogas disposal alternatives.

The CHP investment costs are scaled to fit the CH_4 production, assuming an average availability of 95 %. In contrast, the VF investment costs are fixed, irrespective of the CH_4 production. The maximum treatment capacity is 12 m^3 $biogas \cdot h^{-1}$, corresponding to 71 kW (60 % CH_4) in the 51 and 67 kW scenario. Since this small-scale recirculating water scrubber is still under development, the costs are approximate (Biorega, May 2004). The company speculates about the possibility to triple the capacity (36 m^3 $biogas \cdot h^{-1}$, 212 kW) while only doubling the investment costs. This, together with an assumed decrease in the electricity need of the upgrading process, is used to calculate the VF upgrading costs of the 201 kW scenario.

The electricity price is reasonable for Swedish conditions if the electricity is used directly by the producer. Selling the electricity to the grid brings a revenue roughly two thirds of this (Lantz 2004). In the following, only internal use is considered in the sale of electricity, both for purposes of simplicity and to allow for maximum profit. The organic TAN value is twice as high (Brolin et al. 1996, Hallén 2003) as the value of commercial mineral-based fertilisers (Swedish Farmers Supply and Crop Marketing Association, Feb 2005). The net benefit of implementing removal and anaerobical treatment of LC and SBT compared to traditional green manuring is calculated by subtraction, in the form of the calculated net contribution of recycled TAN ($TAN_{recycled,net}$, see table 3). This corresponds to 38 % of the TN in the added LC and SBT. LC is assumed to have no harvesting losses, while SBT has 25 % harvesting losses (Salo 1978). For a detailed description of the calculations and assumptions, see Svensson et al. (2005).

Table 1 General assumptions for the reference case calculations.

	51 kW	67 kW	201 kW
Harvest and storage costs, WS/SBT [$€\cdot t_{TS}^{-1}$]	44.4	44.4	44.4
Harvest and storage costs, LC [[$€\cdot t_{TS}^{-1}$]	-	55.5	55.5
H η_{heat}	0.90	0.90	0.90
H/1-SD investment costs (% machines) [k€]	68.1 (29 %)	68.1 (29 %)	158.1 (28 %)
CHP/1-SD investm. costs (% machines) [k€]	98.3 (47 %)	106.8 (51 %)	248.4 (52 %)
VF/1-SD investment costs (% machines) [k€]	193.1 (26 %)	193.1 (26 %)	408.1 (26 %)
CHP investment costs [$k€\cdot kW_{electr.}^{-1}$][2,3]	1.67	1.67	1.22
CHP installation costs [k€][3]	3.33	3.33	5.55
CHP administrative costs [$k€\cdot yr^{-1}$][3]	0.18	0.18	0.18
CHP maintenance and operation costs [$€ct/kWh_{el}$][1] [35]	1.67	1.67	1.33
CHP availability	0.95	0.95	0.95
CHP η_{el}[2]	0.30	0.30	0.30
CHP η_{heat}[2]	0.65	0.65	0.65
VF total investment costs (% machines) [k€]	125 (25 %)	125 (25 %)	250 (25 %)
VF energy needs [$kWh_{electr.}\cdot kWh_{CH4}^{-1}$]	0.106	0.106	0.100
VF η_{CH4}	0.985	0.985	0.985
VF availability, upgrading equipment [%]	95	95	95
VF availability, effective [%]	64	86	87

[1]The 5 % maintenance costs is not added for the CHP gas engine costs; [2]KraftWerK, Aug 2004; [3](Lantz 2004). t_{TS}: tonnes of total solids

Table 2 Substrate characteristics of the 150 ha model farm.

	SBT	WS	LC[3]
150 ha model farm [t_{ww}]	1200	300	600
TS [%]	12.0	92.0[2]	32.0
VS [%]	10.2	88.3[2]	28.2
TN [%]	0.39	0.10	1.18
Yield [$m^3\cdot(kg\ VS_{added})^{-1}$] / SRT [d]	0.33 / 20[1]	0.14 / 27[2]	0.33 / 30
VS degradation [%]	75	35	60
Yield [$m^3\cdot(kg\ VS_{added})^{-1}$][4]	0.34	0.15	0.33

[1](Svensson et al. 2004); [2]Svensson et al 2005 (Svensson et al. 2005a); [3](Lehtomäki and Björnsson 2005) [4]Assumed methane yields used in the calculations of the present study; t_{ww}: tonnes of wet weight

Table 2 presents the substrate characteristics of the model farm. The first set of methane yields are experimental, from pilot- or laboratory-scale studies of similar design. The second set represents the values used in the calculations of the present study. The increases in the methane yields are vindicated by increases in solid retention time (SRT) or co-digestion effects.

Table 3 presents the calculated treatment capacity and the process performance of the three different scenarios. By substituting WS for LC, the power output of the 51 kW scenario is increased to 67 kW without needing to scale up the reactor. The organic loading rate (OLR) of the 67 kW scenario is slightly higher; this is assumed to be plausible through the higher degree of VS degradation in LC compared to WS, evident by inspection of the amounts of digestate produced. The process heating need (presented as a percentage of the methane produced) is provided through biogas incineration in a furnace (H and VF) or an engine (CHP). This is the reason why the effective availability of the VF disposal alternative becomes lower than the inherent availability of the upgrading equipment in the 67 and 201 kW scenarios (see Table 1).

Table 3 Process performance of the three different scenarios.

	51 kW	67 kW	201 kW
SBT_{added} [kg $VS\cdot d^{-1}$]	283.4	249.7	469.6
WS_{added} [kg $VS\cdot d^{-1}$]	185.0	-	306.5
LC_{added} [kg $VS\cdot d^{-1}$]	-	237.7	862.4
$Substrate_{added}$ [kg $VS\cdot d^{-1}$]	468.5	487.4	1638.6
$Substrate_{added}$ [kg $TS\cdot d^{-1}$]	553.9	593.6	1949.3
Digestate [kg $TS\cdot d^{-1}$]	261.9	246.3	920.9
Yield [$m^3\cdot(kg\ VS_{added})^{-1}$]	0.266	0.337	0.301
CH_4 [$kWh\cdot^{-1}d$]	1223	1611	4831
$TN_{added\ material}$ [$kg\cdot yr^{-1}$]	3664	7200	19974
$TAN_{recycled,\ \mathbf{net}}$ [$kg\cdot yr^{-1}$]	1384	2719	7544
Process heating need [%]	10.6	8.7	7.4
V_{active} [m^3] / Modules [n]	127.7 / 2	127.7 / 2	383.0 / 6
Fill time / Av. SRT [d]	18 / 27	18 / 27	5 / 27.5
OLR_{active} [$(kg\ VS_{added})\cdot m^{-3}\cdot d^{-1}$]	3.67	3.82	4.28

In Fig. 1 the module based 1-SD reactor design is depicted in part, as a cross section of one reactor module. Besides certain turnkey modules involving pumping, control and gas incineration, the design is not commercially available. It is thus assumed that the buyers do all of the work or contracting themselves. Except for the interior insulation of the reactor floor, the insulation is external. Interior plastic sheeting provides gas tightness and corrosion protection. Heating is provided by the recycled leachate from the heated and insulated reservoir. The reactor is emptied through the doors along the short side, after it has been lifted up at the opposite end. The posterior WS filter serves not only as a particulate filter, but also as a microbial biofilm carrier, speeding up the digestion process by supplying a high initial concentration of slow-growing acetogens and methanogens. Colonisation occurs during a three-week startup period without feeding. The filter has a lifetime of at least a year (Svensson et al. 2004). Each module fills up in a certain time, and is then left with leachate recirculation. After emptying, a new cycle begins. In all three scenarios the digestate is passively drained in the end of each cycle. The drainage continues throughout the storage of the digestate, eventually achieving an assumed TS of 25 %. This practise is deemed not practically possible in the 201 kW scenario, thus including active dewatering up to 35 %.

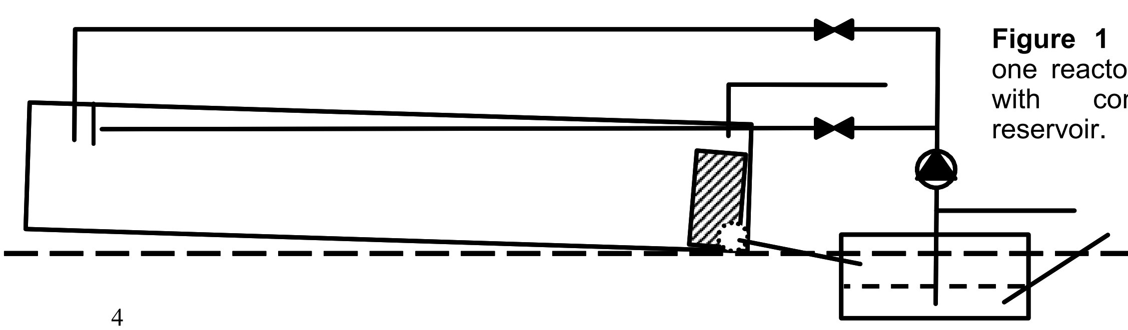

Figure 1 Cross-section of one reactor module together with common leachate reservoir.

The assumptions made and data reported up to this point all refer to the reference case calculations. In the results section, some of these parameters are changed with a certain percentage in order to perform a sensitivity analysis. In the discussion section the plausibility of these changes are discussed.

Results

Figure 2 presents the yearly reference case subcosts (label values, k€·yr^{-1}) for each of the nine possible combinations of reactor scaling and biogas disposal alternative. The bars depict the percentage each category contributes to the total costs. Regarding costs, the first two categories are investment costs, with the administrative costs for the electricity being included in the machine costs of the CHP alternative, real estate taxes being included in both the investment categories, except for the CHP gas engine costs, to which the tax is not applicable. Deductible incomes from electricity and recycled nitrogen are not shown. Categorising electricity as an income makes it possible to compare the resulting net unit costs of the heat supplied by the H and the CHP alternatives. These reference unit costs, normalised according to the energy content of the heat (H and CHP) supplied or the vehicle fuel produced (VF), are presented in Figure 3 (€ct·kWh^{-1}).

The results of a sensitivity analysis in which the investment costs, the operational costs and the price of electricity were changed by ± 20 %, the TAN value by ± 50 %, the $TAN_{recycled, net}$ value by ± 58 % and the gas utilisation degree by - 20 % are presented in Table 4 and in Figure 3. The effect of changing each of the categories is presented as a percentage. In Fig 3 the accumulated effect of changing these categories is presented (gas utilisation degree not included) - for each of the nine possible combinations - as a best and worst case, with the reference case unit costs for comparison.

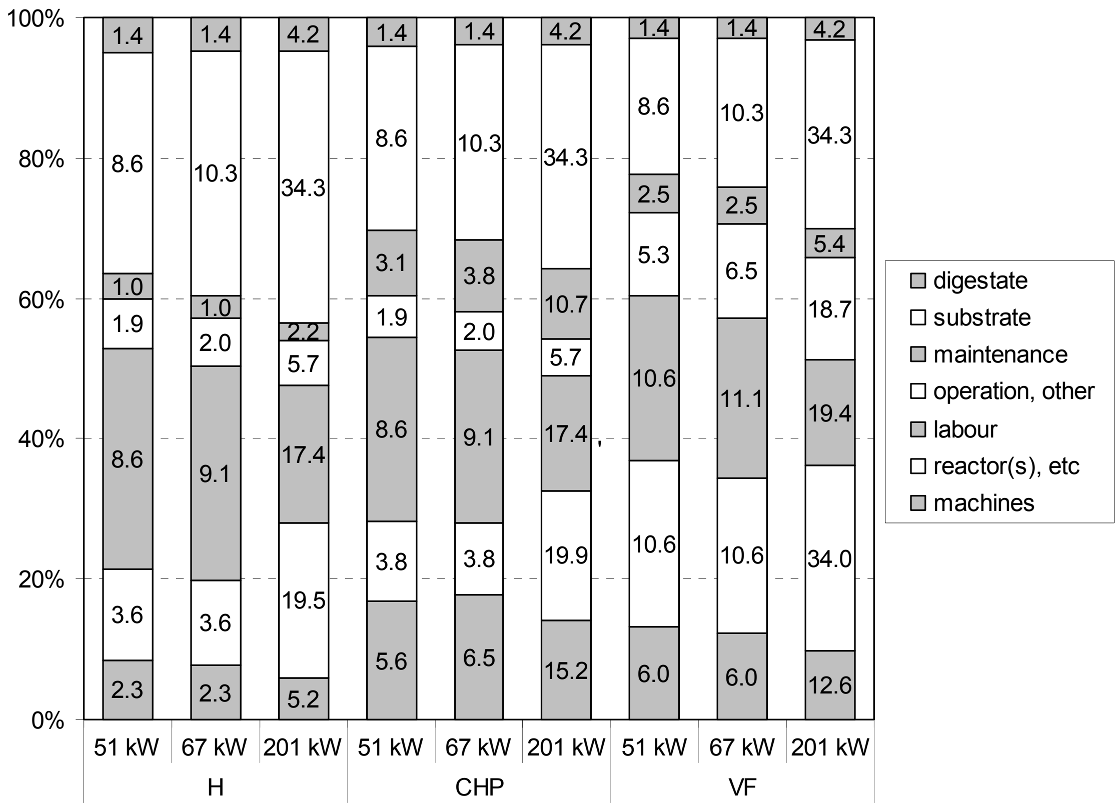

Figure 2 Subcosts (label values, k€·yr^{-1}) of the nine different combinations of scale and disposal tehcnology, the bars depicting the percentage each subcost contributes to the total costs.

Table 4 Percentage changes in the normalised unit net costs (€ct·kWh^{-1}), reference case.

	[± %]								
	51 kW			67 kW			201 kW		
	H	CHP	VF	H	CHP	VF	H	CHP	VF
Investment costs, ± 20 %	6	10	9	5	12	9	7	14	9
Operational costs, ± 20 %	17	21	12	18	25	14	16	24	13
Electricity price, ± 20 %	-	11	-	-	16	-	-	11	-
TAN value, ± 50 %	6	7	3	10	13	5	9	13	6
$TAN_{recycled, net}$, ± 58 %	7	9	4	11	16	6	10	15	7
Gas utilisation degree, -20 %	25	36	25	25	41	25	25	41	25

± 20 %: Investment costs: total investment costs changed; Operational costs: all operational costs changed, except for maintenance; Price of electricity: 6.67/10.00 €ct·kWh^{-1}. ± 50 %: TAN value, 0.89/2.67 €·kg^{-1}. ± 58 %: $TAN_{recycled, net}$, 16/60 % of TN. Gas utilisation degree: assuming a 20 % decrease in the utilisation of the available biogas.

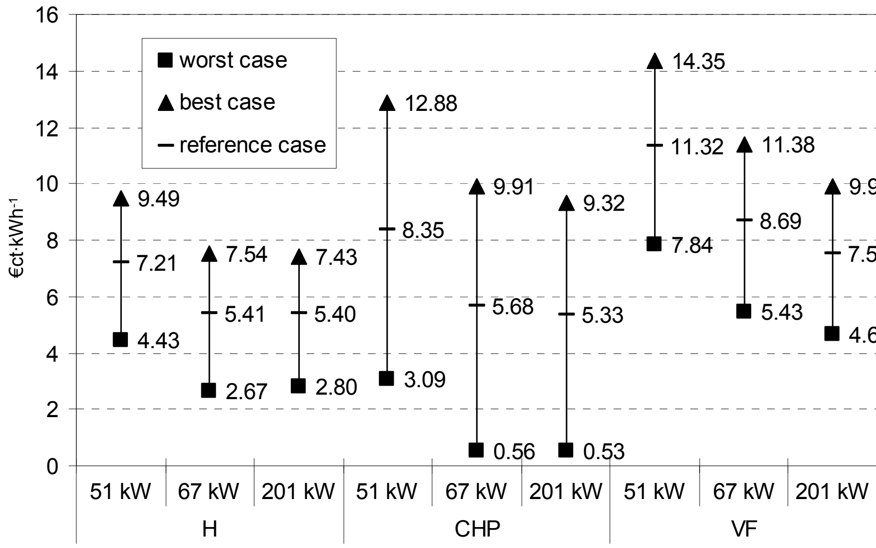

Figure 3 Unit costs variation (€ct·kWh^{-1}), accumulated effects of the sensitivity analysis presented as a worst and a best case, with reference case unit costs as a comparison.

Discussion

The present study shows that substituting WS for LC improves the economy, by increasing the methane yield and the amount of nitrogen recycled. The reference case unit costs of the 67 kW scenario is greatly improved compared to the 51 kW scenario because of the higher methane yield and nitrogen content of LC compared to WS. This is also evident when comparing the 67 and 201 kW scenario combinations of H and CHP. The economy is comparable, despite the benefits of scale-up in the 201 kW scenario. Besides the total costs being increased by approximately 10 % because of the extra investments made to meet increased storage needs, the WS addition worsens the economic situation further by bringing down the average methane yield of the 201 kW scenario. The WS addition gives structure to the digested bed structure, aiming to get a good contact between the solids and recycled leachate. If this addition truly is necessary is hard to know, since only inconclusive pilot-scale data exist: a pilot-scale operation of the same design with ensiled SBT as the only substrate had a good methane yield (see Table 1); single- and two-stage batch operations had worse performance, and channeling was observed (Anonymous 2003); channeling was also observed in a later two-stage batch trial with LC as the only substrate, but here a satisfactorily methane yield was obtained (see Table 1).

Increasing the effective availability (from 64 to 86-87 %, see Table 1) and the scale of the VF upgrading unit diminish reference case unit costs to such a degree that they are approximately level with the cost of commercially available CNG (Compressed Natural Gas)/biogas based vehicle fuel in Sweden (8.0 – 8.9 €ct·kWh^{-1}, exclusive of VAT. (www.lundsenergi.se, www.fordonsgas.nu, 1st of June 2005)). Compared to diesel in the case of occupational use by farmers, the comparison becomes worse, the price for that being 4.9 €ct·kWh^{-1} (occupational use, exempt of VAT (100 %) and CO2 tax (77 %) (Swedish National Tax Board, Dec 2004)). For trucks and passenger vehicles, the comparison is more favourable, the price being 9.4 €ct·kWh^{-1}, (www.spi.se, Jan 2005), since the aforementioned tax exemptions only apply to work machines, such as harvesters. Further increases in the VF equipment availability give neglible cost reductions. The unit upgrading cost of the two VF upgrading installations at 95 % availability are 3.4 and 2.4 €ct·kWh^{-1}, 71 and 212 kW respectively.

The sensitivity analysis presented in Table 4 show that full utilisation of the energy carriers supplied is the most important parameter to sustain an economically viable operation. The operational costs dominate the total costs, see Figure 2; this is reflected in the response in changing the operational and the investment costs. The relative importance of labour costs are cut markedly by scale-up, while the relative importance of substrate costs increase with scale-up. There is considerable uncertainty about the pricing and recycle rate of the organic TAN supplied. If the higher estimates hold, the economic impact this has is far from insignificant. In addition, if the increases in crop yields and crop protein contents are borne in mind, higher revenues can be expected. Field trials showed that a 100 ha farm with a five-year crop rotation would increase its profits by 9.2 k€·yr^{-1} by implementing anaerobic treatment of the LC and SBT, instead of ploughing them in as green manuring (Hansson and Christensson 2005).

Combinations including CHP displayed the highest level of sensitivity and, of the three gas disposal alternatives, is the only one supplying two types of energy carriers, the electricity generation diminishing the CHP heat production compared to H. The sensitising effect of deducting the income of electricity from the total costs enhances the effect of the lesser amount of heat supplied when the price of electricity and the CH_4 production are varied. As the best case indicates, the CHP unit costs has the potential of becoming lower than the H unit costs. From a practical stand-point, the CHP alternative is thus probably the most attractive disposal alternative, not only because it delivers electricity at a predictable and possibly in the future lower price than commercial sources, but also because the lesser amount of heat supplied facilitates its utilisation. The electricity can be fully utilised by selling the surplus to the grid.

How competitive are these prices of heat in Sweden? Inasmuch as the farmers can make use all of the heat and electricity they are supplied with, it is of interest to compare the prices with those of external energy carriers in which VAT and other regulatory taxes are included. In a normal oil-fuelled boiler (of 90 % efficiency) heat can be supplied at an operational cost of 10.1 and 4.6 €ct·kWh^{-1} for household and occupational use, respectively (for occupational use, exempt of VAT (100 %), energy tax (100%) and CO2 tax (79 %)(www.spi.se, Jan 2005; Swedish National Tax Board, Dec 2004)). A grain-fuelled furnace can supply heat at a total cost of 4.9 €ct·kWh^{-1} (LRF 2004). Thus, if only H is considered, one needs to lower the costs of the reference case rather markedly in order to be able to compete with other alternatives. Spending biogas to meet the process heating needs is in the reference case uneconomical for all three disposal alternatives.

Which future cost reductions are reasonable to expect? Substrate costs are probably fully optimised already. Labour costs depend on how the farmer value their own work; cost analysis show that conventional farming wouldn't be economical if the farmers didn't put the value of their own work very low (Sundberg et al. 1997). Reductions in investment costs can be estimated by employing the concept of learning curves, also known as teaming curves: the teaming rate expresses the constant percentage improvement in a technology for each doubling of the technology's cumulative installed capacity (McDonald and Schrattenholzer 2002). The concept is only applicable to emerging technologies, in this case the container reactors and the VF disposal equipment. A conservative teaming rate would be 5 %. If the SBT of southern Sweden would be fully utilised together with LC according to the 67 kW scenario, 486 installations of 201 kW could be supported. Starting at 10 installations, the costs could thereby be reduced by 25 %. Employing the technology in other countries with SBT would further decrease the costs; The 2560th installation would cost 34 % less. If a teaming rate of 10 % could be expected, the costs would be decreased with 44 and 57 %, respectively.

References

Anonymous. 2003. AGRIGAS Situation report 2002: Technology development to retain the biogas potential in high-solids residual crop products. Report, in Swedish Department of Biotechnology, Lund University, Lund.

Braun, R. 2002. Potential of Co-digestion: Limits and merits. Report IEA Bioenergy Task 37.

Brolin, L., A. Lindberg, H. Linders, and C. Cederberg. 1996. Flows of organic waste: Basis report for Action plan waste. Report, in Swedish, 4611, Swedish Environmental Protection Agency (Naturvårdsverket), Stockholm, Sweden.

Cormack, W. F., M. Shepherd, and D. W. Wilson. 2003. Legume species and management for stockless organic farming. Biological Agriculture & Horticulture 21:383-398.

Dalemo, M., M. Edström, L. Thyselius, and L. Brolin. 1993. Biogas from ley crops: Technology and economy of large-scale biogas production. Report, in Swedish, 162, Swedish Institute of Agricultural Engineering (JTI), Ultuna - Uppsala.

Edström, M., Å. Nordberg, and A. Ringmar. 2005. Evaluation of an agricultural biogas plant at Hagavik. Report, in Swedish with English summary, 31, Swedish Institute of Agricultural and Environmental Engineering (Institutet för jordbruks- och miljöteknik, JTI), Uppsala.

Evans, T., N. Lowe, and P. Matthews. 2004. Sustainable biosolids - welcomed practice through community partnership and the consequential economic benefits. Water Science and Technology 49:241-249.

Ghosh, S. 1984. Solid-phase digestion of low-moisture feeds. Biotechnology and Bioengineering Symposium 14:365-382.

Gunnarsson, A., U. Gertsson, and I. Bohn. 2005. Anaerobically digested crop material for improved nitrogen efficiency in a crop rotation with Beetroot (Beta vulgaris var. conditiva Alef.). Acta Horticulturae (in press).

Hallén, D. 2003. Farm production economy when connecting to a centralised biogas plant. Report, in Swedish, Federation of Swedish Farmers (Lantbrukarnas Riksförbund, LRF), Stockholm.

Hansen, J. D., C. Jensen, and E. S. Madsen. 2003. The establishment of the Danish windmill industry - Was it worthwhile? Review of World Economics 139:324-347.

Hansson, A., and K. Christensson. 2005. Biogas energises organic farming. Report, in Swedish, Swedish Board of Agriculture (Jordbruksverket), Jönköping, Sweden.

Kamp, L. M., R. Smits, and C. D. Andriesse. 2004. Notions on learning applied to wind turbine development in the Netherlands and Denmark. Energy Policy 32:1625-1637.

Lantz, M. 2004. Farm based biogas production for combined heat and power production: Economy and technology. Master's thesis, in Swedish with English summary. Lund University, Lund.

Legrand, R., and J. W. Jewell. 1986. Continuous anaerobic digestion of high solids biomass: Modeling and experiments. Pages 1077-1095 in D. L. Klass, editor. Proceedings of Energy from Biomass and Wastes X. Institute of Gas Technology, Chicago, Washington, D.C.

Lehtomäki, A., and L. Björnsson. 2005. Two-stage anaerobic digestion of energy crops: methane production, nitrogen mineralisation and heavy metal mobilisation (submitted June 2005). Renewable Energy.

LRF. 2004. Heat your farm with grain! Information brochure, in Swedish, 42531, Federation of Swedish Farmers (Lantbrukarnas Riksförbund, LRF), Stockholm.

Malgeryd, J., and G. Torstensson. 2005. Nitrogen Efficiency and Environmental Impact from different Strategies for Management of Green Manure Leys. Report, in Swedish with English summary, 335, Swedish Institute of Agricultural and Environmental Engineering (Institutet för jordbruks- och miljöteknik, JTI), Uppsala.

McDonald, A., and L. Schrattenholzer. 2002. Learning curves and technology assessment. International Journal of Technology Management 23:718-745.

Nielsen, L. H., K. Hjort-gregersen, P. Thygesen, and J. Christensen. 2002. Socio-economic analysis of centralised Biogas Plants: with technical and corporate economic analysis. in Danish, with extensive English summary (p 10), 136, The Danish Institute of Food Economics, Copenhagen.

Nordberg, Å., A. Lindberg, C. Gruvberger, T. Lilja, and M. Edström. 1998. Biogas potential and future biogas plants in Sweden. Report, in Swedish with English summary, 17, Swedish Institute of Agricultural Engineering, (Jordbrukstekniska institutet (JTI)) in co-operation with VBB Viak, a SWECO company, Uppsala.

Salo, M. L. 1978. Ensiling, preservation losses and effluent binding of sugar beet tops. Journal of the Scientific Agricultural Society of Finland 50:297-304.

Sundberg, M., W. Johansson, and H. Hjortsberg. 1997. Biogas in future agriculture and sustainable societies: Effects on soil, environment and economy. Report, in Swedish, 12, Swedish Institute of Agricultural Engineering (Jordbrukstekniska institutet (JTI)), Uppsala.

Svensson, L. M., L. Björnsson, and B. Mattiasson. 2004. Enhancing performance in anaerobic high-solids stratified bed digesters by straw bed implementation (submitted April 2004). Bioresource Technology.

Svensson, L. M., L. Björnsson, and B. Mattiasson. 2005a. Verifying the utility of straw bed priming in high-solids single stage stratified bed digesters (manuscript).

Svensson, L. M., K. Christensson, and L. Björnsson. 2005b. Biogas production from crop residues on a farm-scale level: Is it economically feasible under conditions in Sweden? (submitted May 2005). Bioprocess and Biosystems Engineering.

Tenbrummeler, E., H. Horbach, and I. W. Koster. 1991. Dry Anaerobic Batch Digestion of the Organic Fraction of Municipal Solid-Waste. Journal of Chemical Technology and Biotechnology 50:191-209.

Torstensson, G. 2003. Organic farming: Leaching risks and nitrogen turnover. Organic farming systems with and without livestock on clay soil in Southwestern Sweden. Results from 1997-2002. Report, in Swedish, 73, Division of Water Quality Management, Swedish University of Agricultural Sciences, Uppsala.