Authors: S A Gebrezgabher, M P M Meuwissen & A G J M Oude Lansink, Wageningen University;
B A M Prins, Agricultural Economics Research Institute, LEI, The Netherlands.

Economic analysis of anaerobic digestion- A case of Green power biogas plant in the Netherlands

Abstract

One of the key concerns of biogas plants is the disposal of comparatively large amounts of digestates in an economically and environmentally sustainable manner. This paper analyses the economic performance of anaerobic digestion of a given biogas plant. A scenario analysis is carried out based on a linear programming model to identify feedstocks that optimize electricity production and to determine the optimal application of digestate. The economic analysis is also based on NPV and IRR concepts, to assess the cost-effectiveness of the biogas system. In addition to a default scenario, management and policy scenarios were investigated. Our findings show that treating RO as green fertilizer as opposed to manure (default scenario) is not only lucrative for the plant but also lessens the environmental burden of long distance transportation of concentrates. This paper also concludes that given the uncertainty of regulations concerning RO and the currently low values of digestate and heat, high investment and operating costs limit the feasibility of anaerobic digestion of wastes of farm origin and other co-substrates unless subsidies are provided.

Key words: Anaerobic digestion, biogas plant, methane yield, reverse osmosis (RO), linear programming (LP) model

1. Introduction

Manure residues from livestock industries have for long been identified as a major source of environmental pollution. Traditionally, these wastes have been disposed of, directly or after composting, as soil amendments in the agricultural industry. Since this practice has resulted in the degradation of air, soil, and water resources, new regulations for protecting the environment have been promulgated to control land application of animal manure (Van Horn et al., 1994). The nitrate-directive, 91/676/EEC regulates the input of nitrate on farmland, aiming to protect the ground and surface water environment from nitrate pollution. In principle, not more than 170 kg animal manure N may be applied per ha per year insofar as this is not in conflict with application standard for total P (Schroder and Neeteson 2008). The implementation of these environmental measures entails high costs of manure disposal for livestock farmers. As such, livestock industries and regulatory agencies are seeking alternatives for managing manure residues in an economically feasible and environmentally friendly manner. Several studies have shown that anaerobic digestion (AD) of organic wastes has the potential to manage these problems in a cost effective and environmentally sustainable manner.

Interest has recently been growing in the AD of organic waste of farm origin such as manure, crop residues and organic residues from food and agro-industries to generate renewable energy (Braun et al., 2002 and Weiland and Hassan, 2001). Processing manure to biogas through AD recovers energy that contributes no net carbon to the atmosphere (Martin, 2003) and reduces the risk from pathogens from land spreading, as thermophilic or mesophilic AD with a sanitization step destroys all or virtually all pathogens (Birkmose, 2000).

Besides biogas, AD produces digestate, which consists of a mixture of liquid and solid fractions. Applying digestate to the land is the most attractive option in terms of environmental issues (Gomez et al. 2005). A reliable and generally accepted means of disposing of the comparatively large amounts of digestate produced is of crucial importance for the economic and environmental viability of a biogas plant (Borjesson and Berglund, 2006). Murphy and Power (2008) investigated biogas production utilizing three different crop rotations to optimize energy production. Georgakakis et al. (2003) developed an economic evaluation model based on the concept of NPV to assess the cost-effectiveness of biogas production systems fed with pig manure. However, a complete economic analysis of AD incorporating outcomes from the production and application of digestate is still lacking.

The aim of this study is to analyse the economic performance of AD of a given biogas plant. A linear programming (LP) model is developed to identify feedstocks that optimize electricity production and determine optimal application of digestate. Green power biogas plant, a relatively large plant, located in the northern part of the Netherlands forms the basis for our analysis.

The paper is structured as follows. Section 2 introduces the case study. Section 3 will elaborate on the general framework, the data and assumptions made for developing the optimization model. Section 4 will analyze the model results and scenarios assessed. The final section contains the discussion and major conclusions.

2. Case study description

Green power biogas plant was established in 2007 by 50 swine farmers with an installation capacity of 70,000 tons of input on an annual basis. The total investment cost of the plant was €6.75 million, which accounts for silos, CHP unit, decanter, dryer and land. The important starting point for the plant was its commitment to process a contracted amount of pig manure from its member farmers. A schematic of Green power AD process is given in Figure 1.

The input materials are mixed, grinded and pumped to 2 pre-fomenters of 600 m^3 each. The fermentation starts and the mixture stays a week in these silos. This pre-fermented product flows to the main fermentor of $1800m^3$ and stays there for 40 days at 40 degrees. The biogas is burned in a combined heat and power generation (CHP) unit to generate electric power and heat. The electricity produced is sold to the local grid at a market price of €0.06/kwh with additional receipt of an MEP subsidy (€0.097/kwh) for a duration of 10 years. The plant is limiting electricity production to a total of 2MW/year, the amount for which subsidy is provided.

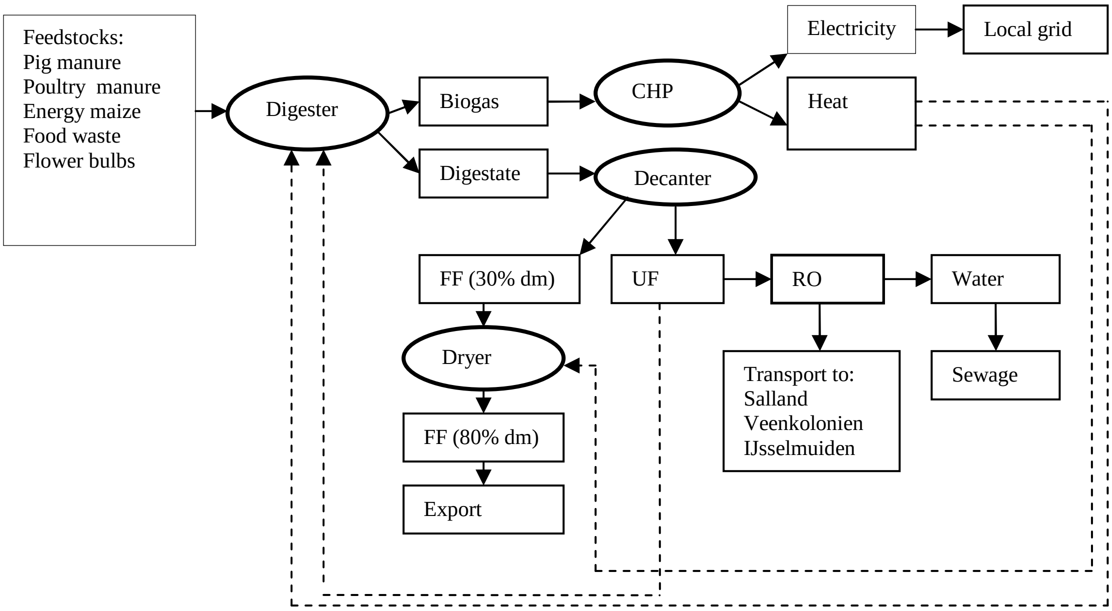

Figure 1 Schematic overview of Green power AD process

The heat is utilized within the plant for heating the digester and drying the digestate, which is separated into a solid and a liquid fraction. The solid fraction (FF 80% dry matter), rich in phosphate contains NPK of 9.3, 19.2 and 5.9 kg/ton respectively and is targeted for export to EU countries. The plant intends to sell FF concentrate at zero price but transportation cost will be fully paid by buyers. The ultra filtration (UF) is recycled to the digestion process, guaranteeing sufficient dilution of the substrate fed into the digester. The Reverse osmosis (RO), also referred to as a green fertilizer, contains NPK of 6.8, 0.6 and 11.5 kg/ton respectively. It is to be used as a supplement to animal manure on plots with low K qualities. Currently, the RO is treated as animal manure with an application rate limited to 170 kg (or 250 kg on grassland) N per ha per year. However, pilot projects are underway to test the fertilizing value and treatment of RO as a replacement to artificial fertilizer. The RO is to be transported to Salland, Veenkolonien and IJsselmuiden, regions relatively nearby the plant. The key decision parameters for the target regions are land availability, land usage, soil type, crops grown and distance from the plant.

3. Model description

3.1 Linear programming (LP)

After specifying a set of decision variables and constraints, linear programming is used in this study to maximize profit of the plant from sales of electricity and digestate application. A standard LP model with a profit-maximizing objective can be expressed as:

$$\textit{Maximize } Z = \sum_{j=1}^{m} c_j X_j$$

$$\textit{Subject to}:$$

$$\sum_{j=1}^{m} a_{ij} X_j \le b_i \quad i = 1 \ldots N$$

$$X_j \ge 0 \qquad j = 1 \ldots M$$

where X= vector of activities; c_j = gross margin per unit of activity j; a_{ij} = technical coefficients; and b_i = availability of resource i.

The activities which were identified as being relevant for the current study are classified as producing and selling of electricity and digestates, transporting of biomass to factory, hiring of people, transporting RO to target regions and storing digestates. The constraints relate to treatment capacity of the plant and digestate application. Moreover, the model will take cognizance of nutrient content of the concentrate as well as nutrient uptake of crops per each type of soil in each region and hence, the total amount of nutrients transported to a region should be less than or equal to the maximum nutrient uptake of that region.

3.2 Model parameterization and assumptions

Table 1, derived from the plant's records, depicts labor allocated to final products and the current proportion and cost of each feedstock. The model will only consider the feedstocks currently used by the plant but will vary the proportion of feedstocks to see how the methane yield varies.

Table 1 Input data and cost associated with each input (default scenario)

	Input (hr/year or Tons/year)	Biomass proportion (%)	Fee received (€/ton)	Input cost including transportation (€/ton)	Net cost (€/hr or €/ton)
Labor allocated to:					
Electricity	3,182				22.50
Digestate	936				22.50
Pig manure	49,275	73	-14	2.5	-11.5
Energy maize	7,425	11		38	38
Food waste	3,375	5		40	40
Poultry manure	6,075	9	-14	0	-14
Flower bulbs	1,350	2	0	0	0
Total biomass	**67,500**				

The potential production of biogas is directly related to the volatile solids content which is estimated from literature. For the purpose of this study, the methane productivity of pig manure, 0.356m^3 kg^{-1} VS (Table 2), was taken from a study done by Moller et al. (2004) while the methane yields, 0.39 m^3 kg^{-1} VS of energy maize and food waste of 0.5 m^3 kg^{-1} VS, are taken from a study done by Amon et al (2006). Another important parameter describing plant efficiency is organic degradation rate (Lindorfer et al. 2007) which is assumed to be 80% of VS-input for Green power due to the plant's short retention time.

Table 2 Methane yield of feedstocks specified as dry matter (DM) and VS (1)

Input	DM %	VS % of DM	Methane yield m^3 kg^{-1} VS
Pig manure	5-8	80	0.356[a]
Energy maize	35-39[b]	35	0.39[c]
Poultry manure	10-30	80	0.41[d]
Food waste	10	80	0.5[c]
Flower bulbs	10	80	0.5

1) Sources: a. Moller et al.(2004); b. Amon et al. (2004c) c. Amon et al. (2006) and d. Webb and Hawkes (1985)

With the given digestion process, the total feedstocks yield about 60,750 ton of digestate and water, which is expelled into the sewage at a cost of €1/m^3. The composition of digestate depends on feedstocks and can therefore vary. However, the plant provides tailor-made concentrates as per the needs of farmers. The composition of RO concentrate therefore stays the same. When RO is treated as green fertilizer, the application standard for artificial fertilizers will apply. Plant experts estimate that RO will be priced at €5/ton, otherwise the plant will pay €20/ton for its disposal.

Feedstock and digestate transport have a significant effect on the economy of the system. Some authors indicate a viable maximum distance of 15-25 km. The distance to target regions of Salland, Veenkolonien and IJsselmuiden is approximately 10-15, 60 and 35 km with a transportation cost of 3, 4 and 4 €/ton respectively.

3.3 Description of scenarios

Two groups of scenarios, management and policy scenarios, are investigated in addition to the default scenario. The default scenario is a model of the given situation; the proportion and price of feedstocks digested are as shown in Table 1. The plant receives an MEP subsidy, heat is used within the plant and RO is considered to be animal manure with a disposal cost of €20/ton and FF is exported to other EU countries.

The management scenarios analyze the impact of a change in the proportion and price per ton of feedstock, mainly energy maize, on methane yield and overall profitability. The quantity of pig manure digested will remain constant under all scenarios (as shown in Table 1) but we increase the percentage of energy maize digested to 15%, by reducing poultry manure to 5% (less poultry manure scenario) or food waste to 1% (less food waste scenario). Moreover, an analysis with lower energy maize price will be conducted (lower maize price scenario).

The policy scenarios are two-fold; focusing on both RO selling options and the MEP subsidy. In the RO scenario, we analyze the outcomes, in terms of RO allocation and profitability, if the RO is considered to be a “green fertilizer. We assume that both arable and grassland, are potential buyers when RO is treated as a green fertilizer but that only arable farms are potential buyers under the default scenario. Artificial fertilizers are used by both arable and grassland, but most dairy farmers with land will tend to apply their own manure, hence we excluded them from potential buyers under the default scenario. A scenario with no MEP subsidy will also be investigated to assess the plant’s performance in the absence of a subsidy.

4. Results

4.1 Technical results of scenarios

Table 3 presents technical results of default and alternative scenarios showing methane yield, production cost per unit of input, transportation of concentrates and shadow prices of inputs and capacity. Default scenario produces electricity yield of 222.30 kwh/ton of feedstock digested. Less poultry manure and less food waste scenarios result in a slightly higher methane yields of 224 and 227 kwh/ton respectively. Less food waste scenario resulted in a higher methane yield and lower production cost per unit of input as compared to the other scenarios. This is because, energy maize and poultry manure both have high dry matter content, and the cost of food waste is higher than the cost of poultry manure. Hence, less food waste scenario optimizes energy production as compared to default and less poultry manure scenarios.

The cost of feedstock is the next most important economic factor; a change in energy maize price results in a change in production cost of between -3.48 and -4.58 €/ton for default and lower maize price scenarios, respectively.

Under the default and management scenarios where RO is considered to be an animal manure, 1,913, 7,739 and 675 tons are transported to Salland, Veenkolonien and IJsselmuiden, respectively. Most of the RO is transported to Veenkolonien, as it comprises mostly of arable land. The regional data of Veenkolonien reveals that it has a shortage of nutrients. Approximately 80% of the fertilizable land already uses nutrients, while the remaining 20% can be regarded as potential application area, which makes the region more attractive for transporting RO.

RO as green fertilizer scenario results in transporting all the concentrate to Salland. Apart from the relatively lower transportation cost to the region, the deciding factor for transporting all the concentrates to Salland is that both arable and grassland are considered as potential buyers.

Table 3 Technical results of Green power for default and alternative scenarios

		Management scenarios			Policy scenario	
	Default	Less poultry manure	Less food waste	Lower maize price	RO as green fertilizer	No subsidy
Electricity yield (m^3/ton)	222.30	224.00	227.00	222.30	222.30	222.30
Electricity (mln kwh)	15.00	15.12	15.32	15.00	15.00	15.00
Digestate FF (ton/year)	8,000	8,000	8,000	8000	8,000	8,000
Digestate UF (ton/year)	14,000	14,000	14,000	14,000	14,000	14,000
Digestate RO (ton/year)	10,327	10,327	10,327	10,327	10,327	10,327
Water (m^3/year)	34,000	34,000	34,000	34,000	34,000	34,000
Unit cost of input (€/ton)	-3.48	-1.40	-3.56	-4.58	-3.48	-3.48
Transportation RO (tons):						
Salland	1,913	1,913	1,913	1,913	10,327	1,913
Veenkolonien	7,739	7,739	7,739	7,739	0	7,739
IJsselmuiden	675	675	675	675	0	675
Export FF (tons)	14,000	14,000	14,000	14,000	14,000	14,000
Expel water (m^3)	34,000	34,000	34,000	34,000	34,000	34,000
Shadow prices (€):						
Pig manure	36.54	36.54	36.54	36.54	36.54	21.07
Poultry manure	75.80	75.80	75.80	75.80	75.80	37.62
Energy maize	30.58	30.58	30.58	40.58	30.58	-11.79
Food waste	10.24	10.24	10.24	10.24	10.24	-20.80
Flower bulbs	50.24	50.24	50.24	50.24	50.24	19.20
Capacity	38.38	36.57	39.19	39.48	38.38	16.81

The shadow prices of all inputs remain the same under all the scenarios except the no subsidy scenario. Poultry manure has the highest shadow price of €75.80 and €37.62 with and without subsidy, respectively, followed by flower bulbs and pig manure. This is attributed to gate fees received by the plant. When there is no subsidy, energy maize and food waste have significantly lower or negative shadow prices, implying that increasing these feedstocks is not economical. Though energy maize and food waste both have high methane yields, their high costs result in a lower shadow prices. Therefore, increasing poultry manure in the total feedstocks would bring a better result under all the scenarios as compared to increasing other feedstocks. The shadow prices of energy maize and capacity are sensitive to price of energy maize. A one unit (ton) increase in capacity will result in an increase in gross margin of €38.38 under default scenario but the increase is larger, €39.48, with a lower energy maize price. The shadow prices are important decision parameters, as they allow model users to determine whether certain potential changes in the given situation might actually increase profitability.

4.2 Economic results of scenarios

Table 4 shows gross revenues, costs, profit before taxes, net present value (NPV) and internal rate of return (IRR) for all scenarios investigated. The economic results follow from the technical results. Default scenario resulted in earning a profit before tax of €1.2 million, showing a positive NPV of €4.2 million and an IRR of 21%. The IRR is the discount rate for which the total present value of future cash flows equals the cost of the investment. With subsidy, less poultry manure scenario resulted in the least profit before tax and NPV due to higher total feedstock costs. RO as green fertilizer scenario resulted in the highest profit before tax and an NPV of €1.4 million and €6.3 million respectively as a result of increased revenues from selling RO as a green fertilizer. In no subsidy situation, the plant operates under a loss and a substantial decline in NPV and IRR (showing a negative value) is observed, implying the subsidy plays a great role in the profitability of the plant.

Table 4 Economic results of Green power for default and alternative scenarios (€1000)

	Default	Management scenarios			Policy scenarios	
		Less Poultry manure	Less Food waste	Lower maize price	RO as green fertilizer	No subsidy
Revenues						
Sales of electricity	900	907	919	900	900	900
Sales of RO	-206	-206	-206	-206	52	-206
Sales of FF	0	0	0	0	0	0
MEP subsidy	1,455	1,467	1,486	1,455	1,455	0
Total revenues	2,148	2,167	2,199	2,148	2,407	694
Costs						
Pig manure	-566	-566	-566	-566	-566	-566
Poultry manure	-85	-47	-85	-85	-85	-85
Energy maize	282	384	384	208	282	282
Food waste	135	135	27	135	135	135
Flower bulbs	0	0	0	0	0	0
Total biomass cost	-234	-94	-240	-309	-234	-234
Total labor cost	166	166	166	166	166	166
RO transportation	39	39	39	39	31	39
Water disposal	35	35	35	35	35	35
O & M(1) cost	220	220	220	220	220	220
Interest & banking	255	255	255	255	255	255
Depreciation	337	337	337	337	337	337
Overhead(2)	175	175	175	175	175	175
Total cost(3)	993	1134	988	919	985	993
Profit before tax	1,155	1,034	1,211	1,229	1,406	-300
NPV(4)	4,195	3,233	4,592	4,770	6,267	-5,499
IRR	21%	19%	22%	22%	25%	0%

1) Operating and maintenance costs are inclusive of maintenance for digester, CHP unit and decanter
2) Overhead cost includes indirect costs such as salary of management, insurance cost and accountancy
3) Total labor cost, RO transportation cost, O & M and overhead costs are subjected to an average annual increase of 2%
4) Assuming discount rate of 10%, discounted over 20 years

5. Discussion and conclusions

This paper aimed to analyze the economic performance of AD of a given biogas plant. A scenario analysis was carried out based on a linear programming (LP) model to identify feedstocks that optimize electricity production and determine optimal application of digestate. The economic analysis was also based on NPV and IRR concepts to assess cost-effectiveness of the biogas system.

The default scenario produces electricity yield of 222.30 kwh ton^{-1} of feedstock digested. A higher yield is realized under the less food waste scenario. Our findings show that the number of tons of RO transported to regions and the distance transported are significantly different under the default and the RO as green fertilizer scenarios. The concentrate will stay closer to the plant when it is treated as green fertilizer, thus resulting in lower transportation costs and less environmental impact. Therefore, treating RO as green fertilizer is not only lucrative for the plant but also lessens the environmental burden of long distance transportation of concentrates. Moreover, it results in saving energy consumption for the production of chemical fertilizers.

A synthesized economic evaluation of all scenarios except the no subsidy scenario shows a positive NPV. The highest NPV and IRR values are observed under RO as green fertilizer scenario due to increased revenues from selling RO. The no subsidy scenario results in a negative NPV, implying that subsidy plays a great role in the profitability of the plant.

The economic analysis done in this study was based on a number of assumptions. The estimated methane yield of feedstocks was generated from literature as the plant is in its starting up phase, and a reliable estimate of technical performance could not be obtained. To insure that technical performance is not overestimated, values for yield were corrected by 80% due to the plant's short retention time. The investment costs accounted for in the study include land value, which, in the given situation, is treated as agricultural land as opposed to an industrial segment. The average price for an industrial segment is more than six times the average price for agricultural land (Segeren and Luijt, 2002).

The implementation of this environmentally friendly technique depends widely on a political framework that creates and provides an economically attractive incentive for running AD plants. Dutch renewables policy has been criticized for having been too unstable to provide sufficient incentives for investments in renewable energy technologies (van Rooijen and van Wees, 2006). The uncertainty in receiving subsidies makes a highly cost-efficient system important. Our recommendations for biogas plants to be profitable without a subsidy is to look for alternative revenues, for instance, from digestate and heat or savings in feedstock costs by making a contract with arable farms to supply them with RO concentrate in return for less expensive energy crops. At the moment, however, we can conclude that, given the uncertainty of regulations concerning RO and the currently low values of digestate and heat, high investment and operating costs limit the feasibility of AD of pig manure and other co-substrates unless subsidies are provided.

Acknowledgement

The study was funded by the agricultural economics research institute (LEI). Many thanks to the chairman of Green power biogas plant, Mr. Jan Schokker for the interviews and for giving us a tour of the plant.

References

Al Seadi T., Holm-Nielsen J. B. and Madsen M., 2006. Report on quality criteria for application of AD sludge as bio- fertilizer in agriculture. *Agrobiogas:* Deliverable 5.

Amon T., Amon B., Krvvoruchko V., Machmuller A., Hopfner-sixt K., Bodiroza V., Hrbek R., Friedel J., Potsch E., Wagentristl H., Schreiner M., and Zollitsch W., 2007. Methane production through anaerobic digestion of various energy crops grown in sustainable crop rotations. *Bioresource technology* 98: 3204-3212.

Aucamp D.C. and Steinberg D.I., 1982. The Computation of Shadow Prices in Linear Programming. *Journal of the Operational Research Society* 33: 557- 565.

Birkmose T., 2000. The Danish Agricultural Advisory Centre, The National Department of Crop Production.

Borjesson P. and Berguld M., 2006. Environmental systems analysis of biogas systems- Part I: Fuel-cycle emissions. *Biomass and bioenergy* 30: 469-485.

Braun R., 2007. Anaerobic digestion: a multi-faceted process for energy, environmental management and rural development. Improvement of Crop Plants for Industrial End Uses: 335–416.

Braun R., Brachtl E. and Grasmug M., 2002. Potential of biowaste co-digestion, Proceedings of the Seventh FAO/SREN-WORKSHP on Anaerobic digestion for Sustainability in Waste (Water) Treatment and Re-use, 19–22 May 2002, Moscow, Russia, pp. 184–193.

CBS, 2006. StatLine data bank, Dierlijke mest.

European Commission, 1991. Council directive, 91/676/EEC of 12 December 1991 concerning the protection of water against pollution caused by nitrates from agricultural sources. Off. J. Eur. Commun. L375(12), 1–8.

Georgakakis D., Christopoulou N., Chatziathanassiou A. and Venetis T., 2003. Development and use of an economic evaluation model to assess establishment of local centralized rural biogas plants in Greece. *Applied biochemistry and biotechnology* 109:275-284.

Gomez X., Cuetos M.J., Garcıa A.I. and Moran A., 2005. Evaluation of digestate stability from anaerobic process by thermogravimetric analysis. *Thermochimica Acta* 426: 179–184.

Henkens P. and Van Keulen H., 2001. Mineral policy in the Netherlands and nitrate policy within the European Community. *NJAS wageningen journal of life sciences*, North America, 49: 117-134.

IEA bioenergy, task 24, Good practice in Quality Management of AD Residues.

Karpenstein-Machan M., 2005. Energiepflanzenbau fur Biogasanlagen-betreiber. DLG-Verlags-GmbH, Frankfurt am Main, Germany.

Lindorfer H., Lopez P., Resch C., Braun R. and Kirchmayr R., 2007. The impact of increasing energy crop addition on process performance and residual methane potential in anaerobic digestion. *Water science and technology* 56: 55-63.

Lopez C.P., Kirchmayr R., Neureiter M. and Braun R., 2007. Effect of physical and chemical pre-treatments on methane yield from maize silage and grains. Institute for Environmental Biotechnology, department for Agrobiotechnology, BOKU-University of Natural Resources and Applied Life Sciences, Vienna, Austria.

Martin J. H., 2003. Report submitted to US Environmental Protection Agency. EPA Contract No. 68-W7-0068.

Moller H.B., Sommer S.G and Ahring B.K., 2004. Methane productivity of manure, straw and solid fractions of manure. *Biomass and Bioenergy* 26: 485–495.

Murphy J.D. and Power N., 2008. Technical and economic analysis of biogas production in Ireland utilizing three different crop rotations. *Applied energy* 10: 3-15.

Murphy J.D., Mckeorgh E. and Kiely G., 2007. Technical/economic/environmental analysis of biogas utilization. *Applied Energy* 77: 407–427.

Murto M., Bjornsson L. and Mattiasson B., 2004. Impact of food industrial waste on anaerobic co-digestion of sewage sludge and pig manure. *Journal of environmental management* 70: 101-107.

Pesta G., 2006. Anaerobic digestion of organic residues and wastes. Technische Universita¨t Mu¨nchen. Energy and Environmental Technologies of the Food Industry, Germany.

Schroder J.J. and Neeteson J.J., 2008. Nutrient management regulations in The Netherlands. *Geoderma* 144: 418–425.

Segeren A. and Luijt J., 2003. Segmenting the market for agricultural land in the Netherlands. *Tijdschrift voor Economische en Sociale Geografie* 93: 570-575.

Singh K.J. and Singh S., 2004. Comparative study of economics of different models of family size of biogas plants for state of Punjab, India. *Energy conversion and management* 45: 1329-1341.

Van Horn H.H., Wilkie A.C., Powers W.J. and Nordstedt R.A., 1994. Components of dairy waste management systems. *J. Dairy Sci.* 77: 2008–2030.

Van Rooijen S.N.M and Van Wees M.T, 2006. Green electricity policies in the Netherlands: an analysis of policy decisions. *Energy Policy* 34: 60–71.

Webb A. R. and Hawkest F.R., 1985. The Anaerobic Digestion of Poultry manure: Variation of Gas Yield With Influent Concentration and Ammonium-Nitrogen Levels. *Agricultural Wastes 14*:135-156

Weiland P. and Hassan E., 2001. Production of biogas from forage beets. Proceedings of the Ninth World Congress, Anaerobic Conversion for Sustainability, 2–6 September 2001, Antwerpen, Belgium, pp. 631–633.

Appendix: Model formulation

$$Max\ Z = ES + ROS - TLBC - OMC - \sum_{I=1}^{n} BM_i \times Cbm_i - ROTC - ROSC - FFTC - FFSC \tag{1}$$

$$Subject\ to:$$

$$MP = \sum_{i=1}^{n} BM_i \times VS_i \times Y_i \tag{2}$$

$$EP = MP \times Tcoeff_e \tag{3}$$

$$D = Tcoeff_d \times TBM \tag{4}$$

$$RO = Tcoeff_r \times D \tag{5}$$

$$FF = Tcoeff_f \times D \tag{6}$$

$$\sum_{i=1}^{n} BM_i \le TBM \tag{7}$$

$$BM_i = TBM \times P_i \tag{8}$$

$$\sum_{r=1}^{k} TRO_r \le RO \tag{9}$$

$$STRO = RO - \sum_{r=1}^{k} TRO_r \tag{10}$$

$$STRO \le MSC \tag{11}$$

$$N_r = Tcoeff_n \times TRO_r \tag{12}$$

$$P_r = Tcoeff_p \times TRO_r \tag{13}$$

$$K_r = Tcoeff_k \times TRO_r \tag{14}$$

$$N_r \le \sum_{c=1}^{m} L_{cr} \times Nreq_{cr} \times ROb_r \times ROacc_r \tag{15}$$

$$TLBC = LE + \sum_{d=1}^{j} LD_d \tag{16}$$

$$ROTC = \sum_{r=1}^{k} TRO_r \times tc_r \tag{17}$$

$$ROSC = STRO \times sc \tag{18}$$

Where: Z = gross margin (€)

ES = electricity sales (€)

ROS = RO sales (€)

TLBC = total labor cost (€)

OMC = operating and maintenance cost (€)

BM_i and = tons of biomass i digested (i = 1 to 5)

Cbm_i = cost of biomass i digested (i = 1 to 5)

ROTC = total transportation cost of RO (€)

ROSC = total storage cost of RO (€)

FFTC = total transportation cost of FF (€)

FFSC = total storage cost of FF (€)

MP = methane production (m^3)

VS_i = volatile solid content of biomass i (%)

Y_i = methane yield of biomass i (m^3/kg VS_i)

EP = electricity generation (kwh)

$Tcoeff_e$ = technical coefficient of generating electricity from $1m^3$ of CH_4

D = total quantity of digestate (ton)

TBM = total quantity of biomass digested (ton)

$Tcoeff_d$ = technical coefficient of digestate

$Tcoeff_r$ = technical coefficient of RO

$Tcoeff_f$ = technical coefficient of FF

P_i = proportion of biomass i in the total biomass

TRO_r = RO transported to region r (ton) (r = 1 to 3)

STRO = quantity of RO in storage (ton)

MSC = maximum storage capacity (ton)

Nr = total quantity of N transported from RO to region r (kg) (r = 1 to 3)

P_r = total quantity of P transported from RO to region r (kg) (r = 1 to 3)

K_r= total quantity of K transported from RO to region r (kg) (r = 1 to 3)

L_{cr} = Land available for crop c in region r (ha)

$Nreq_{cr}$ = Nitrogen requirement of crop c in region r (kg/year)

ROb_r = potential RO buyer in region r (%)

$ROacc_r$ = acceptance level of RO in region r (%)

LE = labor cost allocated to electricity (€)

LD_d = labor cost allocated to digestate d (€) (d = 1 to 2)

Tc_r = transportation cost per ton of RO to region r (€/ton)

Sc = storage cost per ton of RO (€/ton)