Biogas from energy crops—optimal pre-treatments and storage, co-digestion and energy balance in boreal conditions

M. Seppälä, T. Paavola, A. Lehtomäki, O. Pakarinen and J. Rintala

ABSTRACT

The objective of this research was to evaluate the biogas production from crops in boreal conditions, focusing on the optimal pre-treatment and storage methods, co-digestion and energy balance of farm-scale crop based biogas plants. Alkaline treatments offered some potential for improving the methane yield from grass and sugar beet tops. The results show that the CH4 yield of energy crops can be maintained by appropriate ensiling conditions for even after 11 months in ambient conditions. The CH4 yield was best preserved with wet grass mixture without additives. Co-digestion of manure and crops was shown to be feasible with feedstock volatile solids (VS) containing up to 40% of crops. The highest specific methane yields of 268, 229 and 213 l CH4 kg⁻¹ VSadded in co-digestion of cow manure with grass, sugar beet tops and straw, respectively, were obtained during feeding with 30% of crop in the feedstock, corresponding to 85–105% of the total methane potential in the substrates as determined by batch assays. The energy output:input ratio of farm-scale grass silage based biogas plant varied significantly (3.5–8.2) with different assumptions and system boundaries being lowest when using only inorganic fertilizers and highest when half of the heat demand of the system could be covered by metabolic heat.

Key words | co-digestion, energy balance, energy crops, methane production, pre-treatment, storage

INTRODUCTION

Anaerobic digestion is an appropriate technique for converting wet biomass such as energy crops into renewable energy. The most important parameter in choosing crops for methane (CH4) production is the net energy yield per hectare, which is defined mainly by biomass yield and convertibility to CH4, as well as cultivation inputs (Weiland 2003). The ideal energy crop can be characterised by the high yield (dry matter per hectare), low energy input to produce the crop, low production costs and low nutrient requirements (McKendry 2002). These features can be dependent on climate, soil, water consumption, pest resistance and fertilizer requirements which are area specific. It is noticeable that the energy efficiency of any biomass based energy system is dependent on the energy requirement of the biomass production as well as the energy requirements of the energy production process. In boreal conditions, many conventional forage crops, such as timothy grasses, are among the most efficient producers of biomass, they are easy to cultivate and often have good digestibility as well as (Lewandowski et al. 2003). Lately also maize had proved to be a potential energy crop for biogas production also in boreal conditions (Table 1).

This study was part of the EU 6th framework program project: CROPGEN—Renewable energy from crops and agrowastes. The University of Jyväskylä (JyU) was one of the ten partners in this project. The objective of the research...
at JyU was to evaluate and estimate the biogas production from crops in boreal conditions, focusing on the optimal pre-treatment and storage methods, co-digestion and energy balance of farm-scale crop based biogas plants. In this paper we summarise the main results of the research at JyU.

### OPTIMAL STORAGE AND PRE-TREATMENTS OF ENERGY CROPS FOR BIOGAS PRODUCTION IN BOREAL CONDITIONS

#### Storage of energy crops

Storage of energy crops intended for biogas production is crucial, as in boreal conditions fresh crops are not available throughout the year and biogas production has to be maintained also in wintertime when the demand and price of energy are highest. The purpose of storage is to minimise the energy losses and ensiling has been proposed as a suitable storage method for crops to be used in biogas production (Egg et al. 1993).

The purpose of this study was to evaluate the effect of storage in boreal field conditions for up to 11 months on the methane potential of grasses. The substrates used were 1) grass mixture (a mixture of timothy *Phleum pratense*, red clover *Trifolium pratense* and meadow fescue *Festuca pratensis*) and 2) ryegrass *Lolium sp.* harvested in 2005 (Laukaa, Finland). Crops were baled in plastic-covered round bales immediately after harvest (referred to as wet grass) or after 24 h pre-wilting in the field. Additive (Josilac, lactic acid bacteria) was added to part of the pre-wilted crops during baling. Bales were stored outdoors in ambient conditions.

The effect of storage on chemical characteristics and CH$_4$ yield of grass mixture and ryegrass stored wet, pre-wilted and with or without additive was studied in field conditions. pH remained around 5 even after 11 months of storage, with only few exceptions. The measured total solid (TS) and VS concentrations varied during the storage period, probably due to ambient conditions and variation between bales. The CH$_4$ potential of wet and pre-wilted grass mixture slightly increased during the storage, while that of ryegrass decreased (Figure 1, Pakarinen et al. 2008). Loss of mass (wet weight) in bales with grass mixture stored for 11 months was between 18 and 29%, but with rye grass no mass loss occurred. After 11 months of storage the most optimally preserved CH$_4$ yield was found with wet grass mixture (Figure 1).

The results show that the CH$_4$ yield of energy crops can be maintained by appropriate ensiling conditions for at least up to 11 months in ambient conditions. Several factors, such as crop species, pre-wilting, harvest time, additives and storage time can affect the ensiling process, and thus the final effect on CH$_4$ yield can be complex. Ensiling has been found as an appropriate method for storing grasses for biogas production also in earlier studies (Männert et al. 2002, 2005).

According to this study VS loss during storage seems to be a major factor in determining the preservation of CH$_4$ yield. According to these results storage can enhance the CH$_4$ potential (m$^3$ kg$^{-1}$ VS) of crops, which can further help in maintaining a high CH$_4$ yield (m$^3$ t$^{-1}$ original wet weight) despite quite high VS losses of VS in some cases. The present and previous studies (e.g. Lehtomäki et al. 2007, submitted) suggest that the CH$_4$ potential (m$^3$ kg$^{-1}$ VS) of energy crops

<table>
<thead>
<tr>
<th>Crop</th>
<th>Yield t TS ha$^{-1}$</th>
<th>Methane yield m$^3$ CH$_4$ ha$^{-1}$</th>
<th>Gross energy yield MWh ha$^{-1}$</th>
<th>Passenger car transport 1,000 km ha$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grasses*</td>
<td>8–12</td>
<td>2,900–4,500</td>
<td>29–45</td>
<td>36–56</td>
</tr>
<tr>
<td>Maize†</td>
<td>9–18</td>
<td>4,000–8,000</td>
<td>40–80</td>
<td>50–100</td>
</tr>
<tr>
<td>Tops of sugar beets‡</td>
<td>3–5</td>
<td>900–1,500</td>
<td>9–15</td>
<td>11–18</td>
</tr>
<tr>
<td>Straws‡</td>
<td>2</td>
<td>600</td>
<td>6</td>
<td>7</td>
</tr>
<tr>
<td>Reed canary grass‡</td>
<td>9–10</td>
<td>3,800–4,200</td>
<td>38–42</td>
<td>47–53</td>
</tr>
</tbody>
</table>

Table 1 | Annual dry matter yields (TS) of crops per hectare in boreal conditions, potential methane and gross energy yields per hectare and corresponding passenger car transport. Average consumption of 8 m$^3$ CH$_4$ 100 km$^{-1}$ passenger car

*Seppälä et al. (in preparation a).*

†Seppälä et al. (in preparation b).

‡Lehtomäki et al. (2008).
can in some cases be increased during storage, which thus acts as a pre-treatment step. The increase in CH$_4$ potential during storage is assumed to be caused by degradation of structural polysaccharides of plant material into more easily degradable intermediates (Egg et al. 1993). In the present study the role of biological additive in improving or preserving the CH$_4$ yield was not noteworthy, as was also the situation with grass and sugar beet tops (Lehtomäki et al. submitted) and whole crop maize (Neureiter et al. 2005).

Pre-treatments of energy crops

The rate limiting step in anaerobic digestion of solid materials such as energy crops and crop residues is usually hydrolysis of complex polymeric substances (Mata-Alvarez et al. 2000), such as lignocellulose. One way of improving the CH$_4$ production from lignocelluloses is pre-treatment of the substrate in order to break the polymer chains to more easily accessible soluble compounds. Pre-treatments can be carried out either physically, chemically or biologically, or as combinations of these.

Different pre-treatments were compared for their potential in increasing methane yields of sugar beet tops, grass and oat straw. The studied methods were enzyme treatment, composting, white-rot fungi treatment, incubation in water, autoclaving, peracetic acid treatment and treatment with two different alkalis (NaOH and Ca(OH)$_2$ + Na$_2$CO$_3$) (Lehtomäki et al. 2004). The only pre-treatment resulting in an increase in the methane yield from sugar beet tops was NaOH treatment (2%, 24 h) and this improvement remained at 10% per kg volatile solid (VS)$_{added}$ (Lehtomäki et al. 2004). For untreated grass, the methane yield was 0.23 m$^3$ kg$^{-1}$ VS$^-1$ and the greatest increases in methane yields were acquired with alkaline treatments (2% NaOH 72 h, and 3.0% Ca(OH)$_2$ + 4.0% Na$_2$CO$_3$ 72 h) that improved the methane yield by 17% per VS$^-1$. The methane yield of untreated straw was 0.23 m$^3$ kg$^{-1}$ VS$^-1$, and none of the studied pre-treatments increased the methane yield of straw. The alkaline treatments that offered some potential for improving the methane yield from grass and sugar beet tops are relatively simple to implement, and they could offer a cost-efficient solution for improving the methane yields in farm scale biogas production from plant materials.

**CO-DIGESTION OF ENERGY CROPS WITH COW MANURE**

Energy crops and crop residues can be digested either alone or in co-digestion with other materials and by employing either wet or dry processes. In the agricultural sector, one possible solution for processing crop biomass is co-digestion together with animal manures. In addition to the production of renewable energy, controlled anaerobic digestion of animal manures reduces emissions of greenhouse gases, nitrogen and odour from manure management. It also improves the recycling of the nutrients within agriculture (Amon et al. 2006; Clemens et al. 2006). Co-digestion of crops and manures, manures provide buffering capacity and a wide range of nutrients, while the addition of crops with high carbon content balances the carbon to nitrogen (C/N) ratio of the feedstock, thereby decreasing the risk of ammonia inhibition and potentially providing higher methane yields.

In the present study, the anaerobic co-digestion of grass silage, sugar beet tops and oat straw with cow manure was evaluated in semi-continuously fed laboratory continuously
stirred tank reactors (CSTRs). Reactor experiments were carried out in four parallel CSTRs, each with a liquid volume of 4 l, stirred continuously with magnetic stirrers and incubated at 35 ± 1°C. The digesters were fed semi-continuously (once a day, 5 days a week). The post-methanation potentials of the digestates were measured on several occasions during the experiment in triplicate batch experiments in 118 ml serum vials incubated in 5, 20 and 35°C for 100 days.

Initially, all reactors were fed for 27 days with manure at organic loading rate (OLR) of 2 kg VS m⁻³ d⁻¹ and hydraulic retention time (HRT) of 20 d. Subsequently, one reactor (R1) was run for an additional 28 days with manure alone whereas in the other reactors the feeding of crops along with manure was initiated by replacing 10% of the feedstock VS with crops, while maintaining constant OLR and HRT. The proportion of crops in the feedstock was then gradually increased up to 40% of the feedstock VS and, finally, the OLRs of the reactors co-digesting manure with grass and straw were increased first to 3 and then 4 kg VS m⁻³ d⁻¹, decreasing the HRTs to 18 and 16 days, respectively.

Co-digestion of manure and crops was shown to be feasible with feedstock VS containing up to 40% of crops. The highest specific methane yields of 268, 229 and 213 l CH₄ kg⁻¹ VS added in co-digestion of cow manure with grass, sugar beet tops and straw, respectively, were obtained during feeding with 30% of crop in the feedstock, corresponding to 85–105% of the total methane potential in the substrates as determined by batch assays. Volumetric methane production increased by 65, 58 and 16% in reactors fed with 30% VS of sugar beet tops, grass and straw, respectively, along with manure, compared with that in reactors fed with manure alone at a similar loading rate. After doubling the OLR from 2 to 4 kg VS m⁻³ d⁻¹ less methane was extracted per added VS, leading to a 16–26% decrease in specific methane yields, thus leaving more untapped methane potential left in the residues. The post-methanation of digestates sampled from CSTRs during co-digestion of manure and crops indicated that the digestates still contained degradable material with significant methane potential, which, if completely recovered, would in northern climatic conditions correspond to 0.9–2.5 m³ CH₄ t⁻¹ wet weight (ww) of digestate (calculated assuming post-methanation potential at 20 and 5°C each for 6 months of a year) and up to 12–31% of total methane production, being highest following co-digestion of manure with straw. If not recovered, part of this post-methanation potential can be lost as emissions to the atmosphere, thus contributing to the climate change, which emphasises the need for residual gas collection in covered storage tanks especially when high loading rates or short retention times are being applied. If the post-storage tanks were maintained at 20°C throughout the year, a post-methanation potential of 1.7–4.7 m³ CH₄ t⁻¹ ww of digestate could be obtainable, corresponding to 21–43% of total methane production.

**ENERGY BALANCE OF FARM SCALE BIOGAS PLANT FOR SELECTED CROP SPECIES**

Energy balance of a farm-scale “Biogas from energy crops”-system starting from cultivation of crops and ending up with biogas utilisation was determined in Finnish conditions (Figure 2A; Luostarinen 2007). Crop species studied were timothy grass, reed canary grass (*Phalaris arundinacea*) and forage oat which have relatively high yields in boreal growing conditions (dry matter yields: timothy grass 9 t ha⁻¹ a⁻¹, reed canary grass 11 t ha⁻¹ a⁻¹ and forage oat 6.1 t ha⁻¹ a⁻¹) and which can be relatively easily cultivated, harvested and stored with existing infrastructure and machinery. The energy balance optimization of “Biogas from energy crops”-system was made by evaluating the energy consumption of different phases of production chains of timothy grass, reed canary grass and forage oat. Moreover, biogas process using timothy grass was evaluated in more detail and with varying assumptions (Luostarinen 2007).

The capacity of the simulated farm-scale biogas plant was 1,000 m³, of which liquid volume was 80%, and operating conditions were mesophilic with an OLR of 3 kg VS m⁻³ d⁻¹. Digestate was separated with belt press into solid and liquid fractions which were returned back to the crop production. Inorganic fertilisers were used only for compensating the losses caused by leaching and denitrification (estimated annual nitrogen, potassium and phosphorous losses 10%). Cultivation was assumed to be made with
machinery and practices that are generally used on Finnish farms and transporting with Valtra tractor with a fuel consumption of 18 l diesel h⁻¹. Crops and solid digestion residue were transported in 10 ton trailer and liquid digestion residue in 15 m³ container, which returned empty. Average transport distance was assumed to be 4 km. Energy usage of seed and package production as well as production of farm machinery and construction of biogas plant were excluded from the study. As the model biogas plant capacity was defined beforehand as 1,000 m³, the produced energy and cultivation area changed between different crops (Table 2).

All calculations were made in primary energy. As the process has no by-products, all energy inputs can be allocated to biogas energy produced. Energy inputs and output are outside the system boundary (Figure 2A). Based on these allocations, energy balance was calculated as a percentage of how much produced energy was needed in the whole production process. Results were also expressed as output:input ratio, which was calculated as in formula (1).

\[
\text{Output : input ratio} = \frac{E_{\text{output}}}{E_{\text{input}}} \tag{1}
\]

where

\[
E_{\text{output}} = \text{Energy produced in the system}
\]

\[
E_{\text{input}} = \text{Energy consumed in the whole production process}
\]

Electricity used in the model was assumed to be average electricity produced in Finland. Technical data of machinery in biogas plant were obtained from full-scale plants and manufacturers. For traffic fuel use, biogas was assumed to be upgraded with pressure water absorption.

Production chains of timothy grass, reed canary grass and forage oat for biogas used 17%, 16% and 18% of primary energy, respectively (Luostarinen 2007). The energy

**Table 2** Methane and energy produced in the model biogas plant with different crops and the cultivation area needed for production (Luostarinen 2007)

<table>
<thead>
<tr>
<th>Crop Type</th>
<th>Methane production (m³ CH₄ a⁻¹)</th>
<th>Energy production (MWh a⁻¹)</th>
<th>Biomass needed (t a⁻¹)</th>
<th>Dry matter needed (t a⁻¹)</th>
<th>Cultivation area (ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Timothy grass</td>
<td>331,000</td>
<td>3,300</td>
<td>5,000</td>
<td>1,100</td>
<td>137</td>
</tr>
<tr>
<td>Reed canary grass</td>
<td>312,000</td>
<td>3,100</td>
<td>5,000</td>
<td>1,100</td>
<td>109</td>
</tr>
<tr>
<td>Forage oat</td>
<td>361,000</td>
<td>3,600</td>
<td>5,000</td>
<td>1,100</td>
<td>179</td>
</tr>
</tbody>
</table>
consumption in cultivation was 5% for perennial grasses and 7% for forage oat. If inorganic fertilisers were used as the only fertiliser (no digestate was used), the energy consumption of cultivation increased to 15–20% of produced energy, their manufacture being the biggest single energy user. Transporting used ~1% of produced energy and silage additives ~0.5% with all the crop species studied.

The effects of different process parameters and technical solutions on energy balance of the model biogas plant were simulated in more detail based on the timothy grass production chain. The energy output/input ratio for timothy grass in Finnish conditions with digestate recycling was 6.1. The major energy consumer was heat energy required for heating the feedstock and maintaining the digester temperature, using 9% of produced energy (Figure 2B). If heat exchangers were removed from the model system, the output/input ratio would decrease to 5.4. However, it has been previously reported based on experiences from full-scale digesters that all heat energy demand can be satisfied with metabolic heat when co-digesting energy crops and manure (Lindorfer et al. 2006; Weiland 2005). In boreal conditions, if half of the heat energy needed would be met with metabolic heat, the output/input ratio rises to 8.2. If only inorganic fertilisers were used, the output/input ratio would decrease to 3.5. If biogas upgrading to transport fuel was included in the system, the output/input ratio decreased to 4.1 as the purification of biogas for traffic fuel used 8.2% of produced primary energy as electricity (Figure 2B).

CONCLUSIONS

The present results show that biogas production from crops is feasible also in boreal growing conditions. The CH₄ potential of crops could be preserved well as silage during winter time, and the energy output/input ratio of grass silage based biogas plant was at least 3.5 when only inorganic fertilisers were used and even 8.2 when half of the heat demand of the system could be covered by metabolic heat. The major factor in determining the preservation of CH₄ yield during storage seems to be the loss of VS. Moreover, alkaline pre-treatments offered some potential for improving the methane yield from grass and sugar beet tops. The methane yields of manure based biogas plants could be enhanced by co-digesting crops; in co-digestion of manure and crops, up to 87% higher specific methane yield was obtained during feeding with 30% VS of crop in the feedstock than with the lower proportions of crop, while increasing the proportion of crop further led to a decrease in specific methane yields. The high post-methanation potentials observed emphasise the need for residual gas collection in covered storage tanks in order to prevent emissions of greenhouse gases from biogas systems to the atmosphere.

ACKNOWLEDGEMENTS

The authors wish to thank EU 6th Framework Programme (CROPGEN project SES6-CT-2004-502824) for providing funding for this work.

REFERENCES


Seppälä, M., Paavola, T., Lehtomäki, A. & Rintala, J. (In preparation a) Biogas production from boreal herbaceous grasses—methane potential and methane yield per hectare.

Seppälä, M., Laine, A., Tahvonen, R. & Rintala, J. (In preparation b) Methane production and yields of different forage and energy maize species in Finland.


Weiland, P. 2005 Results and bottlenecks of energy crop digestion plants–required process technology innovations. Available at: http://www.novaenergie.ch/iea-bioenergy-task37/Dokumente/utrecht/Peter_Weiland.pdf