The impact of increasing energy crop addition on process performance and residual methane potential in anaerobic digestion


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Abstract In a full-scale agricultural biogas plant, the changes in process performance connected with the increasing energy crop addition were monitored. The substrates applied were pig manure, solid energy crops and agricultural residues. During the study, the organic loading rate and the volume-related biogas productivity were doubled to 4.2 kg VS/(m·3d) and 2.83 Nm³/(m³·d) respectively, by means of increasing the energy crop ratio in the feedstock to 96.5% (volatile solids). This resulted in an increase of the electrical capacity on a level twice as high as before. At the same time, methane yield and organic degradation rate decreased slightly to 0.35 Nm³/kg VSadded and 87.4%, respectively. The strongest impact observed was on the transfer of partly degraded organic material into the digestate storage and with this, an increase of the residual methane potential of the digestate. A maximum theoretical methane load in the digestate of 14.4% related to total methane production of the biogas plant was observed. This maximum level could be reduced to 5.5%.

Keywords Agricultural biogas plants; co-digestion; digestate quality; energy crops; organic loading rate

Introduction

The co-digestion of biomass and sewage sludge or manure is a simple way to increase biogas productivity of anaerobic digesters, especially in isolated rural zones. There are mainly two approaches to implementing biomass addition: to enhance biogas production in an existing digester or to substitute annual feedstock fluctuations. In both approaches, the aim is to run a biogas plant more economically. However, as shown in the present study, those changes in the feedstock and/or the organic loading rate may influence digester performance also in a negative way. However, there is little information available on the consequences and the limits of energy crop addition into biogas plants which have been operated on liquid substrates such as sewage sludge or manure. The major part of the available data have been generated in laboratory-scale experiments. In 1980 Stewart had however published results of laboratory digestion experiments with silage of energy crops (Stewart, 1980) and Jarvis et al. carried out some studies in 1997 with grass clover silage (Jarvis et al., 1997), although the co-digestion of manure and energy crops did not come into focus until recent years. Angelidaki et al. (2005); Lehtomäki (2006) and Nordberg et al. (2007) presented experimental results on process performance and degradation efficiency applying different loading rates of energy crops. Furthermore, Lehtomäki carried out experiments on different energy crop ratios in the substrate mix, but whereas she stopped her experiments at a energy crop ratio of 40% (VS), in the present study a maximum ratio of 96.5% was applied. As a result of the former lack of information, in most biogas plants process parameters such as the...
substrate mix and the organic loading rate (OLR) were mainly based on proven experiences from existing plants. Data from the monitoring of agricultural full-scale plants presented by Weiland et al. (2004); Laaber et al. (2005) and Lehtomäki (2006) reflect this development. However, first positive experiences with the enhancement of already existing biogas plants, as in the present plant, showed very good results. Now, more and more operators are attempting to copy this development but ignoring the negative aspects.

The main objective of the present study was to investigate the impact of a change in the feedstock towards energy-rich substrates such as grains of maize or other cereals and the enhancement of the OLR on the digestion process. As well as the upper limits of an OLR increase, consequences in the process or in efficiency parameters such as the biogas yield or the organic degrading rate connected with the process enhancement should be retained. During the study, the electrical capacity of the plant was doubled, therefore some additional parts had to be integrated into the existing plant as is shown in Figure 1.

Material and methods

Full-scale equipment

The biogas plant where this study was realised is situated at a farm in Lower Austria. The plant started as a two-stage continuous stirred tank reactor (CSTR) with a main digester volume of 2,000 m³ (D1), a second digester step of 1,850 m³ (D2) and open effluent storage tanks of 3,800 m³. The average process temperature was 39 °C. The substrates applied during the present study were pig manure (VS approximately 4% VS) and solid energy crops: 37% silage from maize (approximately 30–35% VS), 49% ground grains from maize and wheat (approximately 65% VS) and 14% residues from vegetable and sugar processing (approximately 10% VS). The main part of the process enhancement was achieved by the dosage of silage from maize grains into D2. Biogas was used to generate electrical current and heat. In the beginning one combined heat and power unit (CHP) with an electrical capacity of 500 kW and a thermal capacity of 586 kW (GE Jenbacher, Austria) was run. Electricity was fed into the national grid and heat was used for a local heat supply in the neighbouring village. In the context of the capacity enhancement, a substrate dosage into D2 and a second combined heat and power unit with the same capacity as the first one were installed (Figure 1). These modifications resulted in a total electrical capacity of 1 MW and a thermal capacity of 1,172 MW.

Figure 1 Schematic of the studied biogas plant. Additional parts are pictured in grey
The operation of the studied agricultural biogas plant could be separated into three phases:

Phase 1: Operation as a two-step 500 kW biogas plant with a main and a second digester and a final uncovered digestate storage tank; dosage of substrates only into digester 1; energy crop ratio in the substrate mix: 50% of fresh matter (FM), 92.5% of volatile solids (VS).

Phase 2: Transition phase to 1 MW electrical capacity; dosage of substrates into both digester steps; final uncovered digestate storage tank; energy crop ratio in the substrate mix: 66% of FM, 96% of VS.

Phase 3: Final status: two main digesters followed by a first covered and final uncovered digestate storage tanks; energy crop ratio in the substrate mix: 66% of FM, 96% of VS.

Performance parameters of the plant and chemical parameters of the digesters and the digestate storage were recorded for each phase separately as average values of 6 months (phases 1 and 2) or 12 months (phase 3).

Sampling and chemical analysis
Samples of the digester content were taken every second week, in D1 out of a valve directly in the digester wall and in D2 out of a recirculation loop. The digestate storage was sampled monthly through a valve in the vertical part of the overflow tube out of D2 into the effluent storage. The sampling procedure always consisted of discarding the old content of the sampling tube, taking a sample of 15 L into a bucket and then taking a quota of 0.5 L out of the bucket. The samples were cooled down to 4°C immediately after sampling. Volatile fatty acids (VFA) were analysed using high performance liquid chromatography (Agilent 1100, RI-Detector). Total nitrogen (TKN), total ammonia nitrogen (TAN), pH, total solids (TS) and volatile solids (VS) were determined using standard methods (APHA, 1998).

Residual methane potential
The residual methane potential in the digestate was evaluated through anaerobic batch fermentation tests. These tests were carried out according to the modified norm DEV S6, DIN 38 414-S6 (DEV, 2005). Thereby, 500 mL of the sample was incubated at 35°C. Every batch fermentation test was carried out in three replicates. The experiments were continued until no more gas production was observed.

Calculation of performance parameters
The hydraulic retention time (HRT) was calculated according to Helffrich (2005) as a quotient of the daily feedstock mass (fresh matter; FM) and the total digester volume. The organic loading rate (OLR) is the quotient of daily mass of volatile solids (VS) in the feedstock and the volume of the liquid digester content. The organic degradation rate characterises the substrate degradation efficiency and was calculated in a mass balance between substrate input, effluent and biogas production. It is expressed as a percentage [%] of the VS-input. The volume-related biogas productivity is the quotient of the volume of daily biogas production and total digester volume and was used to assess digester efficiency.

Results and discussion
Process monitoring
Performance parameters. The development of the performance parameters was mainly influenced by the doubling of the electrical capacity of the plant maintaining the same
digester volume at the beginning of phase 2. Figure 2 shows the development of the electrical capacity and the volume-related biogas productivity. At the beginning of phase 3, a stable performance on the maximum electrical capacity was reached. The OLR also stabilised at twice the level compared to phase 1, after a maximum level of 5.5 kg VS/(m³·d) in phase 2. According to the studies of Weiland et al. (2004) and Laaber et al. (2005), which describe the performance of full-scale biogas plants in Germany and Austria, the applied OLR in the studied plant was higher than in the majority of the biogas plants. In Austria the median OLR was 3.39 kg VS/(m³·d) in 2004/2005 (Laaber et al., 2005).

At the same time, biogas yield, methane yield and power yield, all of them related to the organic loading of volatile solids, returned almost to former levels after a temporary decrease in phase 2 (Table 1). A permanent decrease in methane yield, as was observed by Lehtomäki (2006) after the increase of the OLR from 2 to 3 kg VS/(m³·d), could not be observed. The specific methane yield decreased during phase 2 and recovered to a level 10.3% below at 0.35 Nm³ CH₄/kg VS added. In comparison to data from Lehtomäki (2006) and Nordberg et al. (2007), who described 0.27 Nm³ CH₄/kg VS added, and Jarvis et al. (1997) who observed 0.30 Nm³ CH₄/kg VS added in the digestion of energy crops, the observed methane yield in this study was higher, even during process enhancement. This indicates a long-term adaptation of the microbial population to the feedstock.

While Lehtomäki (2006) observed a decrease in the methane yield already at an energy crop ratio higher than 40% in the co-digestion with manure, the data in this study show that an energy crop ratio of 96.5 (VS) in the feedstock was feasible without any decrease.

One of the most important parameters describing plant efficiency is the organic degradation rate. In phase 1 an average level of 89.7% was observed. As a consequence of the change from a two-step to a one-step process and the strong increase of the energy crop-OLR in phase 2, the degradation rate decreased to 82.8%. Similar observations were made by Andersson and Björnsson (2002), who recorded decreases in COD reduction of 10–20% after increasing the OLR in different digester designs. In the final status with
the covered digestate storage, a degradation rate of 87.4% was calculated. The differences between phases 2 and 3 shown in Table 1, can be traced back to the covering of the first digestate storage which lengthened the total effective HRT in the gas tight biogas system from 82 to 132 days.

Chemical parameters in the digesters. Chemical parameters inside the digester represent the composition of the substrate mix. As can be seen in Figure 3, three to four hydraulic retention times are needed to map changes in the substrate mix and to establish a new chemical balance. As a consequence of the increasing solid substrate addition at the beginning of phase 2, chemical parameters inside the digester changed significantly. In D2 these changes between phase 1 and phases 2/3 were even larger than in D1, as there was no direct dosage of substrates at all in phase 1. After the installation of the direct substrate dosage into D2 the contents of VS and TS, as well as TKN and TAN, levelled off at a balance, regulated by the contents of these parameters in the substrate mix and the digestate of D1. As in D1 most values in phase 3 returned to levels between phase 1 and 2.

**Table 1 Development of process parameters**

<table>
<thead>
<tr>
<th></th>
<th>Phase 1*</th>
<th>Phase 2*</th>
<th>Phase 3**</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input solids (FM) [t/d]</td>
<td>14.05 ± 1.89</td>
<td>22.58 ± 2.76</td>
<td>29.35 ± 3.69</td>
</tr>
<tr>
<td>Input manure [t/d]</td>
<td>15.0 –</td>
<td>17.5 –</td>
<td>17.5 –</td>
</tr>
<tr>
<td>Input solids (VS) [t/d]</td>
<td>7.55 ± 1.11</td>
<td>16.85 ± 1.93</td>
<td>15.14 ± 1.99</td>
</tr>
<tr>
<td>Input VS (total) [t/d]</td>
<td>8.10 ± 1.07</td>
<td>17.64 ± 1.81</td>
<td>16.07 ± 2.07</td>
</tr>
<tr>
<td>Biogas production [Nm³/d]</td>
<td>5755 ± 446</td>
<td>10280 ± 1137</td>
<td>10908 ± 1169</td>
</tr>
<tr>
<td>Methane production [Nm³/d]</td>
<td>3132 ± 246</td>
<td>5154 ± 614</td>
<td>5601 ± 633</td>
</tr>
<tr>
<td>Biogas yield Y VS [Nm³/kg VS]</td>
<td>0.72 ± 0.11</td>
<td>0.59 ± 0.08</td>
<td>0.68 ± 0.08</td>
</tr>
<tr>
<td>Methane yield Y VS [Nm³/kg VS]</td>
<td>0.39 ± 0.06</td>
<td>0.29 ± 0.05</td>
<td>0.35 ± 0.04</td>
</tr>
<tr>
<td>Biogas productivity [Nm³/(m³·d)]</td>
<td>1.49 ± 0.12</td>
<td>2.67 ± 0.30</td>
<td>2.83 ± 0.30</td>
</tr>
<tr>
<td>Production of power [MWh/d]</td>
<td>11.42 ± 1.00</td>
<td>20.52 ± 2.38</td>
<td>22.03 ± 2.61</td>
</tr>
<tr>
<td>OLR [kg VS/(m³·d)]</td>
<td>2.10 ± 0.28</td>
<td>4.58 ± 0.47</td>
<td>4.17 ± 0.54</td>
</tr>
<tr>
<td>HRT [d]</td>
<td>133 –</td>
<td>77 –</td>
<td>82 –</td>
</tr>
<tr>
<td>Degradation rate [%]</td>
<td>89.7 –</td>
<td>82.8 –</td>
<td>87.4 –</td>
</tr>
</tbody>
</table>

* Average of 6 months.
** Average of 12 months.

**Figure 3 Dynamic of chemical parameters in D2**
phase 2. In Figure 3 the development of the chemical parameters in D2 during the different phases is shown.

Generally, it can be summarised that after a transition phase during the enhancement of the biogas plant from 500 to 1,000 kW (phase 2), in phase 3 a stable balance between bacterial biomass and substrate dosage was established again. As in phase 1 the process was limited by substrate dosage as can be seen in the low concentrations of VFA.

Chemical parameters of the digestate. As in D2, the transition from phase 1 to phases 2/3 had a very strong impact on the chemical parameters of the digestate. In phase 1 the theoretical HRT of substrates in the digesters was 133 days. With the installation of the substrate dosage at D2 and the higher total OLR at the beginning of phase 2 the HRT in D2 was reduced to approximately 40 days and the total HRT of the plant to 77 days. These changes resulted in a strong increase of TS, VS and COD in the digestate due to an increasing transfer of partly degraded material into the digestate storage (Table 2 and Figure 5).

Residual methane potential

One of the critical parameters that changed considerably during the different phases, was the residual methane potential (RMP) in the digestate. The RMP is strongly connected to the organic load which is transferred into the digestate. In Figure 4 the daily VS load into the digestate storage, calculated on the VS content and the HRT, in comparison to the OLR, of the plant is shown. As can be seen, in phase 2 the organic load increased to a level three times higher than in phase 1, whereas the VS content and the OLR only doubled. A maximum daily VS discharge of 2.8–3.25 t was found. This corresponds to 17–19% of the daily substrate input. In phase 1 this was 11.2%. As a consequence of covering the first digestate storage the daily discharge of VS was reduced to 2.25 t, which corresponds to 14.0% of the input. It is very difficult to measure the real methane production from the digestate, as the temperature inside the digestate storage is mostly unknown. In the studied plant the average temperature inside the storage was 28°C depending on liquid level and season. To compare results with other studies the RMPs were calculated on the maximum achievable methane yield determined in batch fermentation tests at 35°C. Figure 5 shows the methane yields obtained from the digestate at 35°C at different sampling dates. In addition, one test was carried out at 28°C to represent the real situation in biogas plants.

Table 2 Development of the chemical parameters of the digestate during three years. Phase 3 represents the current status

<table>
<thead>
<tr>
<th></th>
<th>Phase 1*</th>
<th>Phase 2*</th>
<th>Phase 3 **</th>
<th>Phase 3** Maximum</th>
<th>Phase 3** Minimum</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH</td>
<td>7.83</td>
<td>7.79</td>
<td>7.75</td>
<td>7.84</td>
<td>7.66</td>
</tr>
<tr>
<td>COD [mgL⁻¹]</td>
<td>57.0</td>
<td>119.7</td>
<td>103.9</td>
<td>117.9</td>
<td>79.0</td>
</tr>
<tr>
<td>TS [%]</td>
<td>5.43</td>
<td>10.37</td>
<td>9.51</td>
<td>9.85</td>
<td>9.18</td>
</tr>
<tr>
<td>VS [%]</td>
<td>3.87</td>
<td>8.18</td>
<td>7.48</td>
<td>7.72</td>
<td>7.14</td>
</tr>
<tr>
<td>TKN [gL⁻¹]</td>
<td>6.50</td>
<td>9.35</td>
<td>9.33</td>
<td>9.79</td>
<td>8.53</td>
</tr>
<tr>
<td>TAN [gL⁻¹]</td>
<td>4.65</td>
<td>5.90</td>
<td>5.34</td>
<td>5.76</td>
<td>4.88</td>
</tr>
<tr>
<td>FAN (37°C) [mgL⁻¹]</td>
<td>396</td>
<td>511</td>
<td>375</td>
<td>486</td>
<td>295</td>
</tr>
<tr>
<td>Acetic acid [mgL⁻¹]</td>
<td>158</td>
<td>529</td>
<td>662</td>
<td>869</td>
<td>368</td>
</tr>
<tr>
<td>Propionic acid [mgL⁻¹]</td>
<td>31</td>
<td>83</td>
<td>81</td>
<td>186</td>
<td>26</td>
</tr>
<tr>
<td>Total VFA [mgL⁻¹]</td>
<td>230</td>
<td>661</td>
<td>772</td>
<td>1063</td>
<td>394</td>
</tr>
<tr>
<td>TAN in TKN [%]</td>
<td>71.5</td>
<td>63.1</td>
<td>57.2</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>VS in TS [%]</td>
<td>71.3</td>
<td>78.9</td>
<td>78.7</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>

* Average of 6 months.
** Average of 12 months.
As can be seen, the RMP in phase 2 increased to maximum values 10 times higher than in phase 1. In phase 3 the RMP decreased to a medium level again. This observation has already been made by other authors. Lehtomäki (2006) observed a residual methane potential of 2.9–7.7 m³ CH₄/t FM at 35°C after increasing the OLR from 2.0 to 3.0 kg VS/(m³d).

Weiland et al. (2004) observed a residual methane potential in operating biogas plants in Germany (n = 11) which was mainly lower than 10% but did reach 25% (20°C). Such alarming levels were only observed in one-stage CSTR systems. Angelidaki et al. (2005) recommended, therefore, the integration of the effluent storage into the gas proof biogas collection system of the plant, and furthermore a minimum temperature in the storage of 20°C to avoid methane emissions.

When calculating the mass flow of the digestate a theoretical daily methane production of 750 m³ from the digestate, which corresponds to 14.4% of the total methane production...
of the biogas plant (Figure 4) was calculated. In phase 1 this part was 1.1% and in phase 3 it was 7.9% when entering the covered storage tank and 5.5% when leaving it.

The methane production of the fermentation test at 28°C was significantly lower than the 35°C tests. However, the daily methane production would correspond to 251 m³ or 4.8% of the total methane production of the plant. Above all, methane emissions out of the effluent storage should be avoided because of their global warming potential. In the design of further biogas plants this should be considered.

The agricultural usability of the effluent was affected in two ways. The ratio of TAN in TKN decreased from 71.5 to 57.2% due to the process changes. Furthermore, the higher content of VFA is a potential source of odour emissions. Other changes in the process due to the higher loading of solid substrates connected with the process enhancement, were an increase of the viscosity in the digesters and consequently a higher demand on the stirring system and the rise of the ammonium content up to 6.5 g.L⁻¹. This high nitrogen concentration could lead to ammonia inhibition with higher temperatures (Ahring et al., 1995; Strik et al., 2006). Therefore a cooling system could be necessary to prevent a temperature increase in the digesters due to the effect of self-heating (Lindorfer et al., 2006).

Conclusions

The results of this study show that the additional feeding of anaerobic digesters with energy crops is a simple way to increase digester efficiency. However, some consequences in the digester performance should be expected to accompany this process enhancement. These are changes of the chemical parameters in the digester content and in the digestate, such as an increase in solids and nitrogen. The most serious development connected to the enhancement is the rising transfer of partly degraded organic material into the effluent storage. This caused a strong increase of the residual methane potential in the effluent. To avoid methane emissions due to the increasing biomass addition, the digestate storage should be covered.

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