Site-specific economic and ecological analysis of enhanced production, upgrade and feed-in of biomethane from organic wastes
J. Lindorfer and M. M. Schwarz

ABSTRACT
The present study analyses the cost structure and ecological performance of biomethane production and feed-in from organic wastes and manure in a site-specific approach for Upper Austria. The theoretically available quantities of biowaste and manure can feed representative biogas plant capacities resulting in relatively high biomethane full costs in the natural gas grid of at least 9.0 €-cents/kWh, which shows strong economies of scale when feed-in flows of methane from 30 to 120 Nm³/h are considered. From the ecological point of view small plant capacities are to be preferred since the environmental effect, i.e. the global warming potential (up to −22% of CO₂eq), is lower in comparison to higher capacities as a consequence of reduced transport in the evaluated scenarios. To enforce the combined energetic use of the biowaste fraction, co-operation between compost facility, gas grid and biogas plant operators is necessary to use existing infrastructure, logistics and knowledge to promote the production, upgrade and feed-in of biomethane from biowastes at attractive locations in Upper Austria and in the whole of Europe.

Key words | biomethane, economic analysis, feed-in, organic waste

INTRODUCTION
In addition to the disposal of residual waste, the treatment of organic household and garden waste is a substantial part of the waste management structure in Austria. The mobilisation of improvements in the field of eco-efficiency in dealing with bio-waste is therefore an important component of sustainable development in this field. In the present study of the Upper Austrian province, 48% of the households are provided with a pick-up system for biowastes whereby approx. 82 kg per capita per year are collected. A share of 5% of the households are connected to a bring system of composting facilities or collection points, which results in an average amount of 16 kg per capita per year. Consequently around 47% of the households are not connected to a collection system for biowastes. The declared target of the regional authorities is to increase the share of households connected to a collection system up to 60%. The combined use of organic waste in composting, biogas and biomass heating plants is the future goal. (Amt der ö6. Landesregierung 2010). The aim of the paper is to analyse key economic and ecological determinants for the viability of alternative organic waste management concepts in a regional context. The present study analyses the theoretically available quantities of biogenic waste from households and companies as well as agricultural manure for more than 30 geographical locations and regions with a diameter of around 10 km in the province of Upper Austria. The site-specific impacts of the utilisation of wastes in biogas plants of different capacity and the subsequent upgrading and feed-in of biomethane into the existing natural gas grid is evaluated in an economic and ecological comparison with respect to disposal of solid fermentation residues to nearby compost facilities. Liquid digestate is considered as fertiliser in agricultural applications. In digestate management, dewatering without drying was assumed to enhance transportation efficiency and not to deteriorate energy performance as no surplus heat is available in the proposed process configuration.

As a consequence, regional biomethane production costs are calculated for attractive disposal sites. On the one hand, the combined economic and ecological assessment is of systemic importance as growing plant capacities result in higher transport distances for substrate provision and induced emissions, and, on the other hand, growing plant capacities lead to stronger economies of scale.

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In January 2010, a total of 76 biogas plants were operated in Upper Austria, from which around 25 were digester facilities using 151,000 t organic waste, 94% of which originated from the province (Amt der oö. Landesregierung 2010). In Upper Austria there are currently two biogas plants and one sewage gas facility operating, which feed-in upgraded biomethane from animal husbandry, renewable raw materials and sewage to the natural gas grid. Since June 2005 the plant in Pucking has provided 6 m³/h biomethane. In January 2010 the sewage gas from the treatment plant in Asten was upgraded to 450 m³/h biomethane, and since the beginning of 2011 the facility in Engerwitzdorf has produced up to 125 m³/h biomethane (according to information from the operating companies ÖÖ. Gas-Wärme GmbH (www.erdgasooe.at) and Linz-Energieservice GmbH (www.linzag.at)).

METHODS

The individual methods illustrated in Figure 1 form the basis for the implementation-oriented analysis of an increased production and supply of biogas from organic wastes in Upper Austria.

The study included site analyses focusing on the differentiation potential of biomethane feed-in spots in the existing natural gas grid whereby load characteristics and technical conditions of gas supply were provided by the grid operators for investigated feed-in spots. The data on the resource potential of biogenic wastes were extracted from the study by Prammer et al. (2009) and disaggregated to the community level. The quantification of the resource potential of manure was based on a survey of livestock units in each investigated location. The analysis showed that in most of the locations only a relatively small proportion – usually less than 15% – of theoretically available manure quantities would be required as co-substrate to supply representative biogas plant capacities if all applicable biological waste quantities were used. Nevertheless, the available biowaste quantities in a diameter of about 10 km around the considered spots are not sufficient to fully utilise an economic plant size. The restriction to a small substrate supply area was chosen due to ecological concerns although the energy balance is only negatively assessed for transport distances above 22 km for cattle manure and 425 km for municipal solid waste in literature (Poeschl et al. 2010b). The structure of the site-specific calculation tool developed for the economic analysis is illustrated in Figure 2.

The reported amounts of organic waste flows and implemented technologies must have consistent system boundaries for scenario comparison. System barriers were defined for inputs concerning the available amounts of organic wastes and outputs regarding the feed-in of production and supply of biogas from organic wastes in Upper Austria.
biomethane and the transport of liquid digestate back to agricultural production as well as the transport of solid digestate to the nearest composting facility.

Disposal fees for organic wastes show a large variation due to regionally different waste management structures (Table 1). Currently the disposal is predominantly carried out by small composting facilities. From a technological point of view, three plant capacities for biogas production, treatment and feed-in (0.25/0.5/1.0 million m³ CH₄ per year) were considered for each investigated location whereby costs were received from plant engineering companies. Due to the highly structured feedstock, a plug-flow fermenter with high proportions of dry matter (around 4 kg VDS per m³ digester volume) and a separation of the digestate (10% DM) in a solid (30% DM) and liquid (5%) fraction was used (Mata-Alvarez et al. 2000). Chemical absorption with amines was chosen as upgrading technology, due to its high efficiency (> 99% CH₄) for feed-in (Ryckebosch 2003). The costs were verified based on data from the literature (Poeschl 2010; Patterson et al. 2011). Besides depreciation, all operational costs, such as thermal energy for the sanitation of leftovers and fermenter heating or chemicals and electricity for amine treatment, were calculated according to the yearly energy consumption to the disposal of solid and liquid digestate. The hygienic treatment requirements were established by the European Regulation (EC) No. 1774/2002. Transport expenses were considered per ton kilometre depending on the transport vehicle. By relating the costs to the kWh of provided energy, the comparison of various alternative-use pathways is possible. The cost calculation is divided into the three modules: substrate supply, biogas plant and upgrading, composting of solid and spreading of liquid digestate. In a sensitivity analysis, the influence of input factors on the results of site-specific biomethane production costs was evaluated. The environmental analysis and assessment was predominantly based on the life cycle approach according to ISO 14040 (Arvanitoyannis 2008). The conducted ecological assessment provides an inventory of all process steps from the transport of substrates to the biogas plant, or the system energy consumption to the disposal of solid and liquid digestate. Thus, information about the scenario could be derived concerning major environmental impact categories such as global warming potential (GWP in CO₂eq/t wet substrate), cumulative energy demand (CED for total energy use in MJ/t wet substrate), eutrophication (in kg PO₄³⁻eq/t wet substrate) and acidification (in kg SO₂eq/t wet substrate). The sources for the used emission factors for modelling are summarised in Table 2.

The characterisation of factors for the quantification of environmental impacts based on the emission inventory of the process chains was carried out according to international standard procedures (Guinée et al. 2002; Forster et al. 2007).

### Table 1 | Substrate characteristics as input factors for the analysis

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<tbody>
<tr>
<td>Cattle manure</td>
<td>8–11</td>
<td>75–82</td>
<td>2.6–6.7</td>
<td>0.5–3.3</td>
<td>200–500</td>
<td>60</td>
<td>+/ − 0a</td>
</tr>
<tr>
<td>Pig manure</td>
<td>ca. 7</td>
<td>75–86</td>
<td>6–18</td>
<td>2–10</td>
<td>300–700</td>
<td>60–70</td>
<td>+/ − 0a</td>
</tr>
<tr>
<td>Cattle dung</td>
<td>ca. 25</td>
<td>68–76</td>
<td>1.1–3.4</td>
<td>1–1.5</td>
<td>210–300</td>
<td>60</td>
<td>+/ − 0a</td>
</tr>
<tr>
<td>Pig dung</td>
<td>20–25</td>
<td>75–80</td>
<td>2.6–5.2</td>
<td>2.3–2.8</td>
<td>270–450</td>
<td>60</td>
<td>+/ − 0a</td>
</tr>
<tr>
<td>Chicken manure</td>
<td>ca. 32</td>
<td>63–80</td>
<td>5.4</td>
<td>n.a.</td>
<td>250–450</td>
<td>60</td>
<td>+/ − 0a</td>
</tr>
<tr>
<td>Organic household waste</td>
<td>40–75</td>
<td>50–70</td>
<td>0.5–2.7</td>
<td>0.2–0.8</td>
<td>150–600</td>
<td>58–65</td>
<td>+55b</td>
</tr>
<tr>
<td>Leftovers</td>
<td>9–37</td>
<td>80–98</td>
<td>0.6–5</td>
<td>0.3–1.5</td>
<td>200–500</td>
<td>45–61</td>
<td>+108b</td>
</tr>
<tr>
<td>Shrub cuttings</td>
<td>ca. 12</td>
<td>85–92</td>
<td>2–3</td>
<td>1.5–2</td>
<td>550–680</td>
<td>55–65</td>
<td>+51b</td>
</tr>
<tr>
<td>Slaughterhouse waste</td>
<td>12–15</td>
<td>75–86</td>
<td>2.5–2.7</td>
<td>1.05</td>
<td>250–450</td>
<td>60–70</td>
<td>+174</td>
</tr>
<tr>
<td>Trap grease</td>
<td>2–70</td>
<td>75–95</td>
<td>0.1–3.6</td>
<td>0.1–0.6</td>
<td>700</td>
<td>60–72</td>
<td>+62b</td>
</tr>
</tbody>
</table>

DM ... dry matter, VDS ... volatile dry solids, FM ... fresh mass.

aFor manure and dung only transport costs were calculated.
bDisposal revenues including exemplary transport costs.
cFachagentur für Nachwachsende Rohstoffe e.V. (FNR) (2006).
dOwn calculation based on requests from three different disposal companies operating in Upper Austria.
RESULTS AND DISCUSSION

The production costs of biomethane as full energy costs without consideration of feed-in or investment incentives range in the high variation margin of 9.2–20.3 €-cents/kWh for around 35 site-specific investigations. The results of economic evaluation for one location are given in Figure 3 wherein negative costs are illustrated as revenues for bio-waste disposal, and positive costs predominantly typify depreciation and operation costs of the biogas plant and upgrading.

Based on the sensitivity analysis, the following main influencing factors on specific bioenergy costs could be identified.

- Specific methane yield (m³ CH₄/t wet substrate): in connection to the inhomogeneous properties of biowastes, the reported methane yield differs up to +/–90% from the average value in selected literature (Fachagentur für Nachwachsende Rohstoffe e.V. (FNR) 2006; Kuratorium für Technik und Bauwesen in der Landwirtschaft e.V. (KTBL) 2008) with high influence on the whole process chain.
- Revenues from the disposal of organic wastes (€/t wet substrate): depending on the type of biowaste, different disposal fees are collected.
- Investment hygienisation, fermenter, digestate depot (€/MW): substrates with low energy density or high hygienisation requirements and low methane yields result in higher specific investment costs.

Table 2 | Inventory for ecological assessment

<table>
<thead>
<tr>
<th>Inventory</th>
<th>Source</th>
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<tbody>
<tr>
<td>Dry matter content and biogas yield of manure and organic waste</td>
<td>Fachagentur für Nachwachsende Rohstoffe e.V. (FNR) (2006)</td>
</tr>
<tr>
<td>Collection of manure and organic wastes, spreading of digestate and compost</td>
<td>Swiss Centre for Life Cycle Inventories, ecoinvent-database (Swiss Centre for Life Cycle Inventories)</td>
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<tr>
<td>Austrian electricity providing system</td>
<td>GaBi 4 professional database</td>
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Figure 3 | Results of the economic evaluation of selected sites: specific costs of feed-in biomethane related to plant capacity (€-cents/kWh).
• Upgrading of biogas to natural gas qualities (€/kWh biomethane): depending on the applied upgrading technology different investment and operational costs occur (Petersson & Wellinger 2009; Urban et al. 2009). In the presented example of Figure 3 the costs for upgrading of biogas to natural gas qualities contribute 20–30% to the running costs.
• Regional factors as transport distances of substrates and digestate (€/t wet substrate or digestate).

The results show a clear trend for all investigated locations: those sites with higher availability of biowaste input material show lower production costs as a consequence of negative charges in the area of substrate supply. The annual costs of the biogas plant including upgrading to natural gas quality (depreciation plus operating costs) are identified as the major cost driver, thereby creating strong economies of scale. Therefore, the biomethane production costs ranking is more influenced by the production size of the plant as by the plant location and its associated resource potential. The modelled co-fermentation of organic household wastes and manure results in high costs for pre-treatment on the one hand and high hydraulic loads and required fermenter volumes on the other hand, due to the lower energy content of manure in comparison to renewable raw materials like maize silage. It should be mentioned that the transport distances and related transportation costs for substrates showed no influence, given the equally chosen zone for substrate supply. The substrate transport loses influence in this regard.

From an ecological point, the small production capacity scenario investigation showed an impact for GWP (in CO₂eq/t wet substrate), reduced by 22% compared to the high production capacity (see Figure 4). The collection of substrates represents the highest contribution to GWP in the analysed scenarios within the system boundary. An extended investigation of possible carbon credits resulting from the substitution of fossil energy by the feed-in biomethane can also result in lower GWP for higher production capacities as a consequence of higher specific savings than additional emissions related to the provided biomethane. The biomethane from organic waste implies a reduction in GWP of 85–90% compared to natural gas in the investigated scenarios. The investigated impact categories of eutrophication and acidification showed similar results as for the GWP. For CED the opposite effect was observed as a consequence of the high specific contribution of the biogas-upgrading process. Future technology development should focus on optimising this step in the process chain.

CONCLUSIONS

The economic analysis promotes large biomethane delivery systems based on biowastes since the resulting biomethane costs are lowest due to strong economies of scale. However, from the perspective of global warming, small plant capacities are to be preferred since the CO₂-equivalent emissions are lower as a consequence of reduced transport requirements in the investigated site-specific scenarios. In
order to characterise the full environmental profile for the assessed biogas production capacities an extension of the analysed environmental impact categories, for example according to the CML method (Guinée et al. 2002), is required. The inclusion of the utilisation of the biomethane for heat and for electricity for mobility applications can result in greenhouse gas offsets which affect optimal scale and technology configuration.

The chosen feedstock of biowastes from households and manure as agricultural by-product implies no extra cropping as compared to maize-biogas for example, and thus minimises land use impacts. In other environmental investigations concerning biogas production, the input energy crop mixture accounts for more than 50% of all ecological effects (Hartmann 2006; Stucki et al. 2011). In the long run, current arable land-based biogas feedstock will compete with food and material production for productive areas, and consequently increase pressure on other environmental impact categories such as land use, soil erosion, eutrophication and acidification (Graebig et al. 2010). Sustainable biogas production requires closed nutrient cycles (Poeschl et al. 2010a). This encompasses the complete recycling of digestate, and consequently the nutrient demand of agricultural land available for spreading of liquid digestate is a limiting capacity factor as a result of the economic and ecological assessment.

From a strategic point of view, the composting or the fermentation of biogenic material is not seen as competition in any case. For composting facilities where wet, easily degradable waste is processed in large quantities, an add-on biomethane production can help to overcome odour and quality problems in the composting process. Composting and anaerobic digestion can therefore be seen as complementary systems wherein composting is the method of choice for lignin, woody wastes. To enforce the combined energetic use of biowaste fractions, co-operation between compost facility, gas grid and biogas plant operators is necessary to use existing infrastructure, logistics and knowledge in order to promote the production, upgrade and feeding of biomethane from biowastes in attractive locations in Upper Austria and in the whole of Europe.


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