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# The optimal size for biogas plants

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ABSTRACT

The costs of biogas and electricity production from maize silage in relation to plant size are investigated in this paper. A survey of manufacturers' engineering data was conducted to derive a reliable relationship between the capacity of a combined heat and power (CHP) unit and its electrical efficiency. Then a model was developed to derive cost curves for the unit costs of biogas and electricity production and for the transport costs for maize silage and biogas slurry. The least-cost plant capacity depends to a great extent on the local availability of silage maize, and ranges in the model calculations from 575 to 1150 $kW_{el}$. Finally, the paper deals with the optimum operating plant size due to the investment support available and the graduated tariff for green electricity in Austria.



## 1. Introduction

The use of agricultural substrates to produce biogas and electricity has grown tremendously in Austria's recent past. The sizes of the associated plants (in terms of installed electric capacity) range from 18 to 1000 $kW_{el}$. As the size of the plant increases, the investment costs per kW of capacity fall. At the same time the electrical efficiency increases. The labour requirement grows at a less than proportional rate. An increase in plant size leads to a rise in the costs associated with delivering substrate to the plant and removing the biogas slurry. The availability of substrate varies according to region. The price paid in Austria for "green" electricity from plants licensed before the end of 2004 is graduated. Only plants up to 250 $kW_{el}$ in size qualify for an investment grant. In combination, the above factors determine the most cost-effective plant size for any one particular site. This paper tackles this issue, expanding on relevant work previously published in this journal [1–3].

The following research questions are addressed with regard to a plant using silage maize as its substrate:

- How does electrical efficiency change with increasing plant size?
- How do the costs of biogas and electricity production change as plant size increases?
- As plant size increases, what happens to the cost per kWh of delivering substrate and removing the resultant biogas slurry?
- Which plant size is most cost-effective at different levels of substrate availability?
- In Austria, what effect do investment grants and graduated green electricity prices have on the optimal plant size?

The approach taken in answering these questions is briefly outlined below. Further details regarding the calculation of costs are given later within the relevant sections.

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**Nomenclature**

| | |
|---|---|
| $a$ | substrate supply area as a proportion of the total area |
| $c$ | the costs of biogas and electricity production (not including transport costs) (cents kWh$^{-1}$) |
| $d$ | distance-dependent part of transport costs (€ km$^{-1}$ tonne$^{-1}$) |
| $\eta$ | electrical efficiency of the CHP unit (%) |
| $k$ | electrical capacity (kW$_{el}$) |
| $I$ | investment costs (€) |
| $l$ | distance-independent part of transport costs for loading and unloading (€ tonne$^{-1}$) |
| $m$ | electricity production (kWh) |
| $Q$ | required amount of raw substrate (tonnes) |
| $\tau$ | tortuosity factor, the relationship between the actual transport distance and the direct distance |
| $t$ | tonne (1000 kg) |
| $T$ | total transport costs (€) for a particular plant size |
| $x$ | radius of the supply area (km) |
| $\bar{x}$ | average transport distance (km) |
| $y$ | maize yield (tonnes ha$^{-1}$) |

## 2. Approach

Both the costs of biogas and electricity production and those of transporting the silage maize and biogas slurry are calculated for plants varying in installed capacity from 25 to 2000 kW$_{el}$, in increments of 25 kW$_{el}$. It is assumed that the supply area is represented by a series of concentric circles featuring a constant proportion of silage maize crop area. Regression analysis on the results of the calculations is used to estimate cost functions which best fit the calculated average costs to describe the costs per kWh of electricity in relation to the total amount of electricity produced. The approach is drawn from the concept of the long-run average cost curve [4], but differs somewhat in that the function estimated through regression analysis does not represent an envelope curve for the short-run cost curves [5]. Thus, at selected points, the estimated average cost curve lies above the lowest possible costs for biogas and electricity production or the costs of transporting silage maize and biogas slurry.

The costs associated with both biogas and electricity production and transport of substrate and biogas slurry are largely determined by the assumptions used in the model calculations. These assumptions and other defining conditions are therefore described first. The relationship between plant size and electrical efficiency is drawn from manufacturers' own declarations. This underpins a calculation of the costs of biogas and electricity production in plants with different sizes (from 25 to 2000 kW$_{el}$). The regression function is then estimated from the results. There then follows an exploration of how the costs of delivering substrate and removing the biogas slurry change in relation to the amount of electricity produced. A comparison of the two cost curves reveals the most cost-effective plant size. Data from Austria are used to identify the impacts of investment grants and graduated green electricity prices on the economically optimal plant size. The sensitivity of the results to changes in the assumptions used is also evaluated. The paper ends with a discussion of the results and draws out some conclusions for decision makers.

## 3. Assumptions and data sources used for the model calculations

The biogas plant uses silage maize only in the fermentation process. The biogas is used to produce electricity and the electrical efficiency increases with the size of the plant. Revenues are earned solely through the sale of this electricity, with no purchaser for the heat produced. The biogas slurry is returned to the suppliers of the substrate. The plant operates at full load for 7000 h each year.

The supply of silage maize for a biogas plant in a particular region depends on the available proportion of arable land, market conditions and the demand for maize from livestock producers. In the calculations, three different levels of silage maize availability are used: 20%, 10% and 5% of the total area. The silage maize yield is 45 tonnes ha$^{-1}$, which is about the average yield in Austria [6]. There are 310 kg of organic substances in each tonne of silage maize. One tonne of silage maize yields 198 m$^3$ of biogas with an energy content of 900 kWh. Depending on the added water, each tonne of silage maize produces about 1 m$^3$ (about 1 tonne) of biogas slurry [7].

The field price for silage maize is independent of the size of the biogas plant and is calculated as €18 tonne$^{-1}$. The resultant biogas slurry belongs to the farmers supplying the silage maize. The silage maize is stored on-site at the biogas plant. The biogas slurry is applied directly to the fields once it leaves the biogas plant. The rates of a machinery ring are applied to calculate the transports of both the silage maize to the biogas plant and the biogas slurry back to the fields of the maize suppliers. The silage maize transport costs are €0.42 km$^{-1}$ travelled, plus €0.35 tonne$^{-1}$ for loading and unloading the material. For biogas slurry transport, the equivalent prices are €0.5 km$^{-1}$ and €0.5 tonne$^{-1}$ for loading and unloading. The tariffs charged by the machinery ring are higher for biogas slurry than for silage maize, even though the routes travelled by both are identical. Substrate costs per kWh fall as plant size increases, reflecting the commensurate increase in conversion efficiency.

The investment costs used in the calculations for plants up to a size of 330 kW$_{el}$ are drawn from a survey of Austrian facilities [8]. The investment costs for plants over 330 kW$_{el}$ are extrapolated from the survey data. Labour requirements for different plant sizes are taken from Keymer and Reinhold [9]. Labour costs are set at €20 h$^{-1}$. Other costs incurred by the biogas plant are assumed to be €100 kW$_{el}^{-1}$.

The construction of biogas plants can be supported in Austria using rural development funds, provided the plant's size does not exceed 250 kW$_{el}$ and provided the processed substrates are sourced from agriculture. The maximum subsidy available in these circumstances is equivalent to 30% of the investment costs [10,11]. Graduated fixed prices