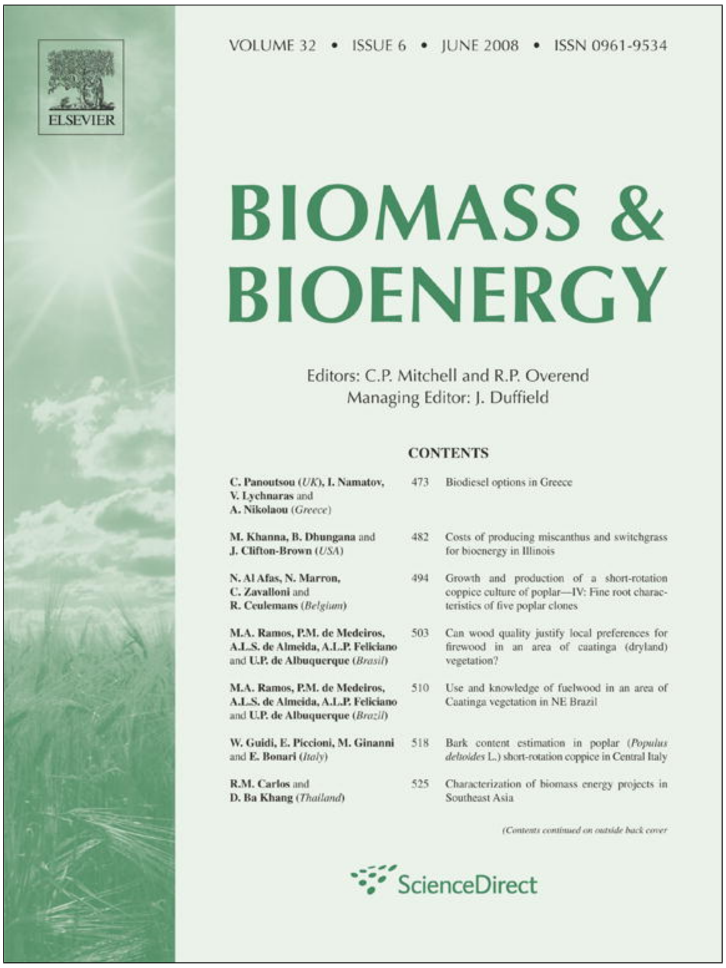
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BIOMASS & BIOENERGY

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} $tonne^{-1}$)
η	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)
τ	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 exist in Austria for green electricity produced by those plants licensed before 31.12.2004 and in operation by 31.12.2007. The prices are (per kWh) 16.5 cents for plants up to a size of 100 kW_{el}, 14.5 cents for those over 100 and up to 500 kW_{el}, 12.5 cents for those over 500 and up to 1000 kW_{el}, and 10.3 cents for those greater than 1000 kW_{el} [12].

4. The relationship between plant size and electrical efficiency

The declarations regarding the electrical efficiency of combined heat and power (CHP) units are taken from those manufacturers listed by the German Biogas Association (Fachverband Biogas) and in Information Service BOXER (Infodienst BOXER) and CHP-Info (BHKW-Info) [13–15]. Seventeen manufacturers responded to a written enquiry in August 2005 with information on conversion efficiency values for 65 different types and sizes of CHP units. The size of these cited CHP varied from 29 to 2425 kW_{el}. The plants were divided into six size classes, and the arithmetic mean electrical efficiency calculated for each class (Table 1). The results of the statistical analysis show that the greatest variations in electrical efficiency within a size class occur in the two smallest classes, namely plants with a size of up to 50 kW_{el} and those between 51 and 100 kW_{el}. The largest jump in the mean electrical efficiency occurs when moving from the size class 51–100 kW_{el} to the class 101–250 kW_{el}; the increase is 3.1 percentage points. The lowest conversion efficiency achieved by any one CHP within each class increases from 26% in the first size class (plants up to 50 kW_{el}) to 38% in the 1001–2425 kW_{el} class. The maximum efficiency attained by any one plant is found in the latter class, and is 42%.

When estimating the average cost curve for electricity production, conversion efficiency is not varied stepwise according to the size classes given in Table 1. Instead, it is varied continuously in order to avoid sudden jumps in the resultant average cost curve. To this end, the 65 data points provided by CHP unit manufacturers were subjected to regression analysis. The estimated regression equations for the relationship between electrical efficiency and plant size are given in Fig. 1.

5. The costs of producing biogas and electricity in relation to plant size

The costs of electricity production from biogas per kWh are calculated from the annual costs of the plant for producing the required amount of electricity. These annual costs are composed of the annual capital costs, substrate costs, labour costs and other costs (maintenance, insurance, administration, etc.). The costs of delivering the substrate and removing the biogas slurry are calculated separately.

The annual capital costs associated with a plant depend on the investment costs (I), the effective life of the plant and the discount rate. For each size of plant, the investment costs are calculated using the formula $I = 101{,}522{+}3500k$ [8]. As mentioned earlier, these investment costs have not been demonstrated empirically for those plants with a capacity exceeding 330 kW_{el}. The compulsory purchase (at fixed prices) of the electricity produced in a biogas plant is guaranteed by legislation for 13 years only. The effective life of a plant is therefore fixed at 13 years in the calculations. The CHP unit has to be replaced once in this period [16]. The discount rate is fixed at 5%. Table 2 presents the results of the calculations for plants of three different sizes.

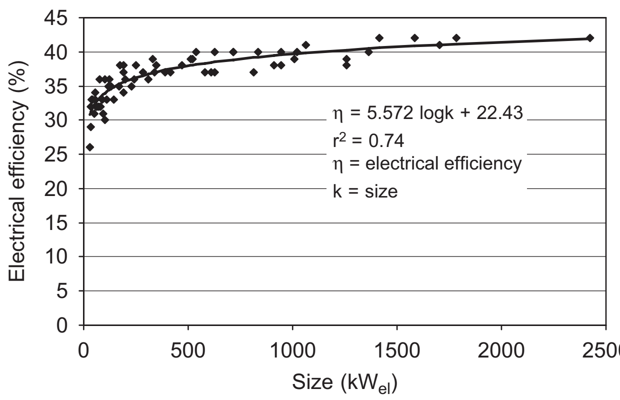

Fig. 1 – Data points describing the relationship between electrical efficiency and the electrical capacity of a CHP unit, and the shape of the resultant estimated function.

Table 1 – Electrical efficiency (%) in CHP units using biogas, for selected plant size classes

Measure	Size in kW_{el}					
	⩽50 $n = 6$	51–100 $n = 11$	101–250 $n = 14$	251–500 $n = 9$	501–1000 $n = 13$	1001–2425 $n = 11$
Mean	30.7	32.8	35.9	37.4	38.7	40.6
Maximum	33.0	36.0	38.0	39.0	40.0	42.0
Minimum	26.0	30.0	33.0	36.0	37.0	38.0
Standard deviation	2.7	1.9	1.7	0.9	1.3	1.5
Coefficient of variation	8.9	5.8	4.7	2.5	3.3	3.7

n = number of conversion efficiency data points (based on ISO 3046/I-1991).

Table 2 – Costs per kWh and other key figures for three selected plant sizes (without transport costs)

Size	100 kW_{el}	250 kW_{el}	500 kW_{el}
Electricity production in 1000 kWh	700	1750	3500
Substrate amount (tonnes $year^{-1}$)	2292	5368	10,246
Substrate production area (ha $year^{-1}$)	51	120	228
Electrical efficiency (%)	33.9	36.2	38.0
Investment costs (€)	451,522	976,522	1,851,522
Capital costs (€ $year^{-1}$)	53,130	116,025	220,710
Substrate costs (€ $year^{-1}$)	41,256	96,624	184,428
Labour costs (€ $year^{-1}$)	12,390	23,275	39,550
Other costs (€ $year^{-1}$)	10,000	25,000	50,000
Total costs without transport (cents kWh^{-1})	16.7	14.9	14.1

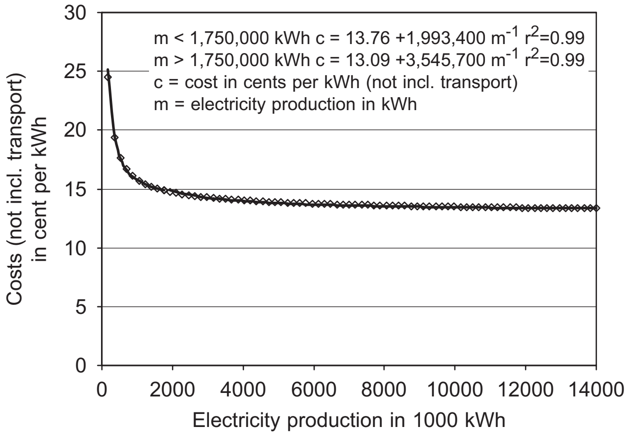

Fig. 2 – The long-run average cost curve (per kWh) for biogas and electricity production in agricultural biogas plants (transport costs are not included).

The costs per kWh for plants varying between 25 and 2500 kW_{el} were calculated for size increments of 25 kW using the system presented in Table 2. The investment costs and electrical efficiency were calculated and varied using the formulae described earlier. Regression analysis was carried out on the results to produce two functions to describe the average cost curve for biogas and electricity production. The first function describes the cost behaviour pattern for plants up to a capacity of 250 kW_{el} (producing 1,750,000 kWh), the second describes the equivalent pattern for plants with capacities between 250 and 2000 kW_{el} (see Fig. 2). The average costs initially fall rapidly as plant size increases. Once the size reaches 1000 kW_{el}, however, very few further cost benefits are gained through an increase in plant size.

6. Transport costs for silage maize and biogas slurry in relation to plant size

The transport costs for silage maize and biogas slurry were calculated for all plant sizes. The radius x of the area of supply was calculated for each level of silage maize availability using the formula $Q = ya\pi x^2$, where Q is the required amount of silage maize, a is the factor of silage availability (e.g. 0.2 for 20%) and y is the silage maize yield in tonnes per hectare, i.e.:

$$x = \sqrt{\frac{Q}{ya\pi}}.$$

The average haul distance ($\bar{x}$) between the biogas plant at the centre of a circle and the silage maize fields can be calculated using the formula given by Overend [17] and taking account of the tortuosity factor τ:

$$\bar{x} = \tfrac{2}{3}x\tau.$$

The average transport costs consist of the costs for loading and unloading (l) and the distance-dependent costs (d) per tonne (double the average field distance, given travel to and from the plant). In order to calculate the total transport costs (T) for a particular size of plant, the average transport costs per tonne for silage maize and biogas slurry need to be multiplied by the quantity of silage maize:

$$T = Q(l + 2\bar{x}d).$$

Given a haul distance of 0.8 km between the field and biogas plant, total transport costs would be €2.32 for each tonne of silage maize processed (€1.02 for silage maize and €1.30 for biogas slurry). Some relevant figures concerning transport costs and the results of the above calculations are presented in Table 3 for three selected plant sizes. If plant capacity is increased from 100 to 500 kW_{el}, then the transport costs per kWh rise by around 50%.

With the scheme described, the transport costs are calculated for plants with a size between 25 and 2000 kW_{el} and 7000 operating hours, in 25 kW increments and for each of the three levels of silage maize availability. Then the transport costs of silage maize and biogas slurry per kWh for plants between 25 and 2000 kW_{el} were calculated. Fig. 3 shows the transport costs per kWh for the transport of silage maize and biogas slurry in relation to the electricity production for each of the three levels of silage availability and accounting for increasing electrical efficiency.

7. The most cost-effective plant size

The most cost-effective plant size is the one where the costs of transport, biogas production and electricity production are

Table 3 – Transport costs for selected plant sizes (20% silage maize availability)

Size	$100\,kW_{el}$	$250\,kW_{el}$	$500\,kW_{el}$
Substrate (tonnes year^{-1})	2292	5368	10,246
Yield per hectare (tonnes)	45	45	45
Crop area required for substrate (ha)	51	120	228
Number of trips per year carrying silage maize	287	671	1281
Biogas slurry (tonnes year^{-1})	2292	5368	10,246
Number of trips per year carrying biogas slurry	191	448	854
Average transport distance (km) assuming a tortuosity factor ~133	0.8	1.2	1.7
Total transport costs (€ year^{-1})	5329	16,678	40,659
Total transport costs (€ tonne^{-1})	2.32	3.11	3.97
Transport costs for substrate (€ year^{-1})	2325	7337	17,981
Transport costs for biogas slurry (€ year^{-1})	3304	9341	22,678
Transport costs per kWh in cents	0.76	0.95	1.16

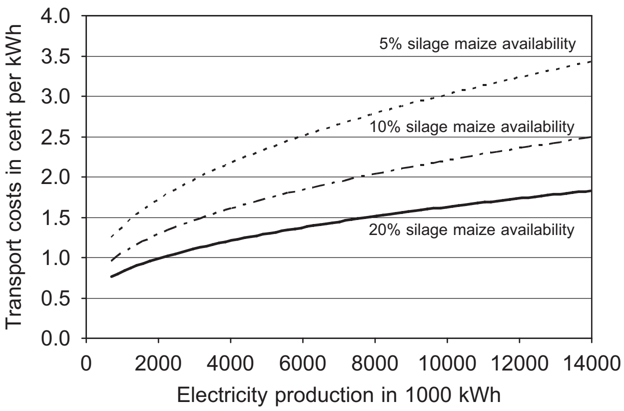

Fig. 3 – Transport costs per kWh in relation to electricity production and silage maize availability.

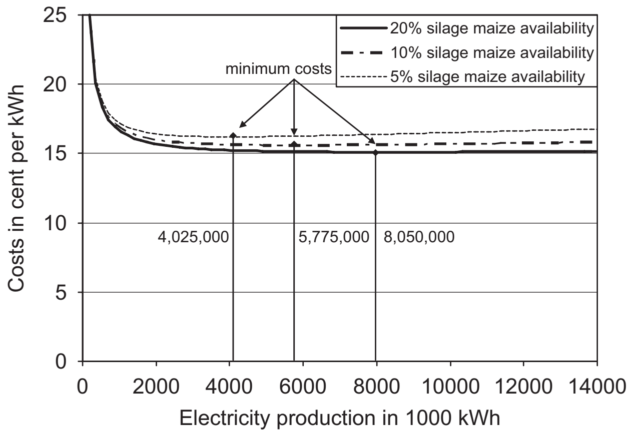

Fig. 4 – Minimum costs in relation to the electricity production and availability of silage maize (transport costs are included).

(per kWh) at a minimum. Fig. 4 shows the cost behaviour pattern (expressed per kWh) in relation to plant size according to the silage maize availability. This reveals that supply availability influences the size of plant that is most cost effective. Where 5% of available land is used for silage maize production, the lowest costs are incurred at 4,025,000 kWh, equivalent to a plant size of $575\,kW_{el}$. If 10% of the land is used for silage maize the most cost-effective plant size is 5,775,000 kWh ($825\,kW_{el}$), and 8,050,000 kWh ($1150\,kW_{el}$) if 20% of available land is used for silage maize production.

8. The influence of subsidies and graduated prices for green electricity on the optimal plant size

This paper has so far focused on costs only. As mentioned in the introduction, the graduated prices for green electricity need to be taken into account in Austria in order to identify the optimal plant size. Fig. 5 shows the change in electricity price as plant size increases. The costs per kWh (for biogas and electricity production and for transporting silage maize and biogas slurry) are also given in Fig. 5, and take account of

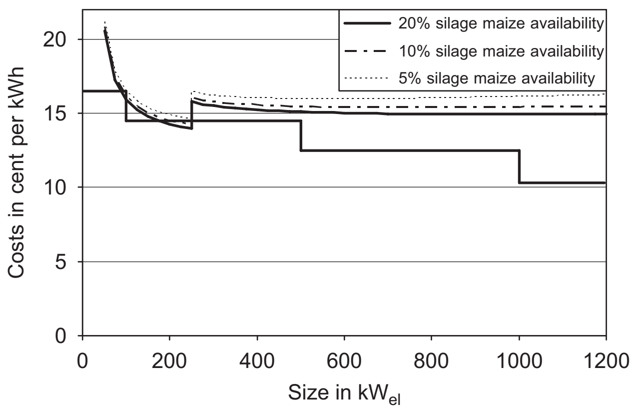

Fig. 5 – Changes in green electricity price and costs per kWh in relation to plant size and at three different levels of silage maize availability (accounting for investment grants in plants not exceeding $250\,kW_{el}$).

investment grants available for plants with a capacity of up to $250\,kW_{el}$. This support cut-off point explains the sudden jump in costs at this plant size.

It is clear that the investment grants and graduated prices for electricity are such that biogas plants with a size of 100 or 250 kW_{el} are able to operate at a profit. Plants with a size exceeding 250 kW_{el} cannot cover their costs given the assumptions used in the model calculations.

9. Sensitivity analysis

There are opportunities to reduce the costs assumed in the calculations. As well as reducing the substrate costs (through, for example, a lower price for maize, or the remunerative use of the slurry and other organic waste), plant costs could also be reduced through a longer effective life. Jenkins [2] used an effective life of 20 years in his calculations, while Keymer [9] used one of 15 years. The number of hours operating at full load could also be increased to more than 7000 per year. Caputo et al. [19] used 8000 operational hours in their calculations, Jenkins [2] however used only 6575 h. A greater availability of substrate with greater per hectare yields would also contribute to lower costs per kWh.

A reduction in silage maize prices only affects the substrate costs; transport costs remain the same. According to the assumptions used, an increase in effective life only influences the annual capital costs (possible increases in annual repair and maintenance costs are not considered). The increase in full-load operating hours (assuming the plant's effective life remains at 13 years) results in higher total substrate, transportation and other costs. An increase in yields with a constant silage maize price would reduce the size of the supply area and thus the transport costs. A 10% reduction in investment costs only reduces the annual capital costs (see Table 4).

10. Discussion and conclusions

As plant size increases, so the electrical efficiency of a CHP unit rises. According to manufacturers, the conversion efficiency in CHP units with a capacity of more than 1000 kW_{el} is evidently higher than that of plants with a capacity around 100 kW_{el}. This increase in efficiency means less consumption of substrate per kWh of electricity. It also slows the growth of both transport distances and transport costs.

The per tonne costs for transporting the silage maize and the biogas slurry are composed of a fixed cost for loading and unloading the material and a cost that is dependent on the required distances travelled. The transport costs thus increase more slowly than if the calculation was entirely based on distance-dependent costs, as is generally the case in the literature (e.g. [1,2,19]). In the model calculations, it is assumed that the biogas slurry is taken back by those supplying the silage maize substrate. The transport costs would fall if the biogas slurry could be sold to other farmers in the vicinity of the biogas plant.

Given silage maize yields of 45 tonnes ha^{-1} and an availability level of 5%, the decline in the costs of biogas and electricity production as plant size increases more than compensates for the increase in transport costs, up to a size of 575 kW_{el}. If the silage maize availability level is set at 20%, then the most cost-effective plant size is twice as big. The availability of silage maize is thus a key determinant of the most cost-effective plant size.

The calculations were based on a plant that only processes silage maize, for which cropland was made available (with the associated opportunity costs). Generating revenues from the excess heat produced in a biogas plant was not considered, reflecting the real situation for 75% of agricultural biogas plants operating in 2002 [18].

The sensitivity analysis quantifies the effects of some opportunities to reduce costs. Reducing the investment costs by 10% or increasing the full-load operating hours by 10% lowers the costs per unit below the relevant price tariff. A 10% decrease of the substrate costs results in costs per unit close to the relevant price tariff. A 10% increase in yield per hectare silage maize or an extension of the effective life of the plant to 15 years lowers the costs not enough to reach the price tariff. A mix of the opportunities analysed is possible in practice; thus, under favourable conditions costs per unit below the price tariff are realizable.

The analysis of the most cost-effective plant size relies on the concept of the long-run average cost curve, assuming for each point on the curve a realizable plant size and continuity of the transport costs. In economic reality, where specified

Table 4 – The impact of changes in different cost factors on the overall costs of a plant with a capacity of 500 kW_{el} (20% silage maize availability)

Costs	Substrate costs −10%	Effective life 15 years	Operating hours +10%	Yield per hectare +10%	Investment costs −10%
Investment costs (€)	1,851,522	1,851,522	1,851,522	1,851,522	1,666,370
Capital costs (€ $year^{-1}$)	220,710	205,590	220,710	220,710	198,643
Substrate costs (€ $year^{-1}$)	158,200	184,428	197,069	184,428	184,428
Transport costs (€ $year^{-1}$)	40,659	40,659	44,595	37,625	40,659
Labour costs (€ $year^{-1}$)	39,746	39,746	39,746	39,746	39,746
Other costs (€ $year^{-1}$)	50,000	50,000	55,000	50,000	50,000
Total costs (cents kWh^{-1})	14.51	14.67	14.47	15.06	14.47

plant capacities are offered, the plants are not at the centre of a circle and the tortuosity factors depend on the terrain. As a consequence, in practice the most cost-effective plant sizes vary from those indicated in Fig. 4.

The calculations also demonstrate the influence of political regulation on the economics of a biogas plant. As Fig. 5 indicates, the investment grants and price grades mean that only plants with a size of 100 or 250 kW_{el} can cover their costs through sales of electricity. Larger plants would need lower production costs than those resulting in the calculations if they were to turn a profit at the relevant electricity price. The sensitivity analysis identifies a few possibilities for such a cost reduction. Furthermore, selling some or the total excess heat would increase the revenue and thus contribute to lower the costs per kWh. Of the biogas plants established or proposed in Austria in 2003 and 2004, most have a capacity of 250 kW_{el} [20]. As such, practice matches the results presented here.

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