A dynamic model for integrated optimization of Biogas Production – A case study on Beet Root Biomass

Contribution for economic model and results

Draft July 10, 2014

Lise Skovsgaard[1,] Ida Græsted Jensen[1], Ida Kjærgaard[2], Kari-Anne Lyng[3]

[1] *Technical University of Denmark, DTU Management, Systems Analysis Division, Denmark, lskn@dtu.dk, idje@dtu.dk*
[2] *Knowledge Centre for Agriculture*
[3] *Østfold Forskning*

1 Contents

2 The economic analysis

Focus in the economic analysis is to find the Net income (NI) as a function of different levels of Costs and Income – looking at the potentials for economies of scale.
The potentials for economies of scale are considered both in the form of reduced production costs pr. handled ton of biomass or increased income potential pr. produced m3 biogas – in the form of upgraded biogas.

2.1 Scale

Each plant produces biogas with different shares of sugar beet and manure – more exactly the different shares are divided as in Figure 1

Sugar beet	0	12.5	25
Manure	100	87.5	75

Figure 1: Shares of sugar beet and Manure

Costs and revenue have been calculated for three different plant sizes:

- Small: Using 110 t. tonnes of biomass per year
- Medium: Using 320 t. tonnes of biomass per year
- Large: Using 500 t. tonnes of biomass per year

The choice of plant size is a combination of available data (primarily from former analysis), which plant sizes do we see in the Danish biogas sector, and which size do we expect to see in the nearer future.

Ratio\Scale tonnes		110,000	320,000	500,000
0.0	Sugar beet	0	0	0
1.0	Manure	110	320	500
Biogas yield in M3		1,043,103	3,034,483	4,741,379
0.125	Sugar beet	13.75	40	62.5
0.875	Manure	96.25	280	437.5
Biogas yield in M3		2,813,218	8,183,908	12,787,356
0.25	Sugar beet	27.5	80	125
0.75	Manure	82.5	240	375
Biogas yield in M3		2,212,644	6,436,782	10,057,471

Figure 2: Plant scale, Tonnes of biomass and biogas yield p.a.

2.2 Direct use vs. upgrade

Focus in this analysis is to examine the economic consequences of the different choices of input mix rather than to optimize a given biogas production. We therefore do not analyse different choices of biogas use, but decide beforehand what we do. In the case of direct use vs. upgrading, the assumption is that the biogas plant sells the biogas for direct use as long as demand for direct use is very nearby. In this case – looking at Maabjerg Biogenergy as a case – we assume, that a plant situated as Maabjerg Bioenergy chooses to send the biogas directly to the neighbouring combined heat and power plant (CHP), Maabjerg heat and power plant (at a distance of around 1 km) as long as the biogas production doesn't exceed their demand for biogas around 3.5 million m3 biogas (source: Lau Linnets master thesis p. 49). When the biogas production exceeds 3.5 million m3 it is assumed, that the biogas is upgraded for the net, also around 1 km from Maabjerg Bioenergy.

In the following sections the economic model will be presented.

3 The economic model

The overall objective is to find the total net income, $TNI(p_k, \mathrm{M}_j, M_k, \mathrm{r}_j, \mathrm{j}, \mathrm{k})$, which can be expressed by:

$$TNI(p_k, M_j, M_k, r_j, j, k) \ = \ TI(p_k, M_k) - TC(M_j, M_k, j, k)$$

Where $TI(p_k, M_k)$ is the total income as a function of the price of output k, p_k, and the mass of output k, M_k. $TC(M_j, M_k)$ is the total cost as a function of the mass of biomass j, and the mass of input k. The sets J and K represents the set of biomass (manure and sugar beet) and the set of output (gas and digestate).

The total income can be expressed as:

$$TI(p_k, M_k) = \sum_{k \in K} p_k M_k$$

M_k is the mass of output k resulting from using a specific mass of biomass j and a specific percentage of biomass j in the input mix.

The total cost is expressed as:

$$TC(M_j, M_k) = \ C_{trans}(M_j, M_k, GP_k) + \ C_{capex}(M_j, M_k) + \ C_{opex}(M_j, M_{gas,UP})$$

Where $C_{trans}(M_j, M_k, GP_k)$ is the total transport cost, $C_{capex}(M_j, M_k)$ is the cost of investments, and $C_{opex}(M_j, M_{gas,UP})$is the total operational costs.

In the model net income is calculated in Total Net income (TNI), while results will be presented as Net income pr. tonne input and net income pr. m3 biogas. When results from this analysis should be used in an energy context net income pr. m3 seems most relevant, while net income pr. tonne is more relevant, when focus is on the agricultural part of the value chain.

The model presented below will be in terms of total income (TI) and total costs (TC).

3.1 Income

The total income function consists of the sum of the price (p_k) paid for the different outputs times the mass of output (M_k). The mass of output depends on the tonnes of input as well as the specific input mix. The income function is presented below.

$$TI(p_k, M_k) = \sum_{k \in K} p_k M_k$$

3.1.1 Yield

There will both be a digestate yield and a biogas yield. The specific yield is given in terms of a mass of output, M_k.

3.1.1.1 Digestate yield

Digestate yield is measured in tonnes, and the *value* of the digestate is considered as independent of the input mix. This means that the specific input mix depended nutrient level is *not* considered in the economic model. What determine the digestate yield are therefore the tonnes of input and how the input mix related process reduces the tonnes of output.

3.1.1.2 Biogas yield

As sugar beet has a higher biogas potential than manure, the first order effect of more sugar beet will be that the more sugar beet the higher biogas yield. With a certain share of sugar beets, the sugar beets will however have a dampening effect on the process, and the biogas production goes down.
In the economic model this process will not be described, but only appear as a figure – depending on the input mix and total mass in tonnes.

3.1.2 Prices

Income for the biogas plant is determined by sales of biogas and digestate, where biogas is a high value product and digestate is a low value product.

3.1.2.1 Digestate price

Digestate is basically treated/refined manure, with improved fertilizing features and reduced smell. At this point, there is no direct regulation in Danish agriculture forcing the farmers to have their manure treated before the manure is applied on the fields.
The value of the digestate therefore only corresponds to the value of saved fertilizer (which is not that expensive) and a subjective value of reduced smell in the area. The price of digestate is given by p_{dig}.

Organic farmers cannot use commercial fertilizers and therefore value the digestate higher. This however is not assumed to change the prices in this model.

The exact value of the digestate depends on the specific supplier agreement between the biogas producer and the farmers. Often there is a close link between what the biogas producer pay the farmers for the untreated manure, and what the farmers pays the biogas producers for the treated digestate.

In this analysis there will be scenarios, with an excess level of digestate, which will be sold to nearby plant producers.

Prices used are given by KCA, and we assume prices for the digestate are the same for animal farmers and plant producers.

3.1.2.2 Biogas price

Biogas is highly supported in Denmark. Therefore, the biogas price depends on the support level and who receives the biogas. In this model two potential receivers are in play.

a. Biogas is upgraded for the natural gas net

b. Local use in a local combined heat and power production

The final biogas price depends on the total biogas yield. If the yield is high enough, it's profitable to invest in a biogas upgrade facility. In the model it is defined, that all biogas is upgraded, when

$$M_{gas} > \overline{M_{gas}}$$

The price will be $p_{gas,UP}$ else the price will be $p_{gas,CHP}$.

Notice: In this model $\overline{M_{gas}}$ is entirely defined from investment and operational costs for an upgrading facility combined with capacity limits on gas input from the local CHP. In a more complicated model this will also depend on V and p^{MP}, see 3.1.2.2.2

3.1.2.2.1 When biogas is upgraded for the natural gas net

When biogas is upgraded for the natural gas net, price is determined by the market price on natural gas (p^{NG}), the support level (S) and a potential green factor (p^g), which is the market price for "being green", found from sales of green certificates.

$$p_{gas,UP} = p^{NG} + p^g + S$$

Where the support is given to the biogas producer before the biogas enters the natural gas system.

3.1.2.2.2 When biogas is used in a local CHP

When biogas is used at a local combined heat and power plant (CHP) price setting is a bit more complicated, as the price is often agreed on for a specific time period, depending on the natural gas price (p^{NG}), the support level (S), which is then given to the local CHP, and finally the heat and power value (V) of the received biogas. The heat and power value is depended on the type of CHP, but also how much heat the CHP has to let out to nothing during the summer period, as the biogas supply is almost constant during the year while the heat demand is depended on the season.

Finally there will be a market power value (p^{MP}), which also depends on the specific CHP, as either both parties are respectively monopoly user and supplier, or one part has an alternative supply respectively consumer. In this model p^{MP} is considered from the CHP point of view, as the CHP traditionally have had a market power advantage, leaving $p^{MP} > 0$

In this case the price is determined by

$$p_{gas,CHP}. = p(p^{NG}, S, V) - p^{MP}$$

3.2 Total costs

Total costs consist of Transport costs ($C_{trans}(M_j, M_k)$), Investment costs ($C_{capex}(M_j, M_k)$) and Operational costs ($C_{opex}(M_j, M_k)$), each part of the cost function is elaborated in the coming sections.

Overall it can be said, that costs are scale depended, the larger the plant, the higher the total costs, the hypothesis is, that costs pr. tonnes and cost pr. m3 is reduced, the larger the plant. This is however not expected to be the case, when transport costs are considered.

3.2.1 Transportation costs

Transport costs are the sum of transport cost for transporting biomass to the biogas plant and transporting the output away from the plant, given by:

$$C_{trans}\left(M_j, M_k, GP_k\right) = C_{trans,in}\left(M_j\right) + C_{trans,out}(M_{man}, M_k, GP_k)$$

The transportation costs to and from the biogas plant is presented in the following.

3.2.1.1 Transport to the biogas plant

Transportation to the biogas plant is a significant cost in the economic model. To define the transportation cost of the different plant sizes and ratios, it was decided to define concentric circles around the biogas plant to handle the need for different amounts of manure and sugar beet. This is illustrated in Figure 1.

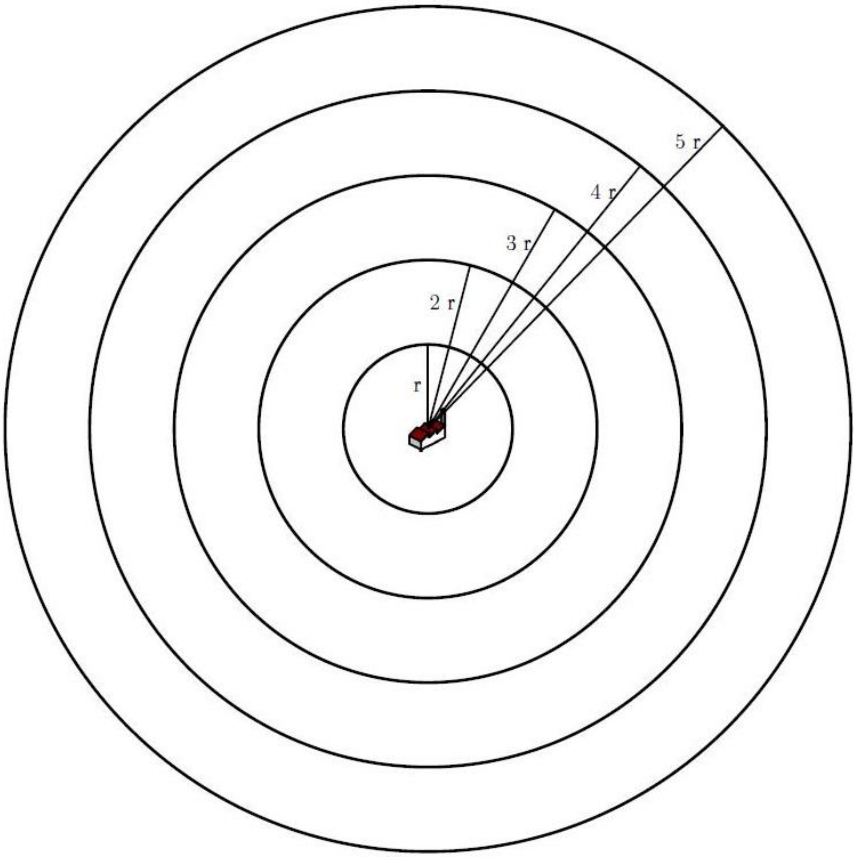

Figure 1: Division of the land for calculating average transportation distance

The available manure and sugar beet is divided into the amount available within the different radii and doing this, the average transportation distance (Δd) can be calculated by the following formula:

$$\Delta \mathrm{d}_j(M_j) = \frac{m_{1j}}{M_j} r_1 + \sum_{i=2}^{o(M_j)-1} \frac{m_{ij} - m_{i-1,j}}{M_j} r_i + \frac{M_j - m_{nj}}{M_j} r_n$$

Where m_{ij} is the mass of biomass j available in circle i, M_j is the total mass needed of biomass j for the specific setting of plant size and ratio, r_i is the radius of circle i, and $o(M_j)$ is the last circle needed for satisfying the requested demand.

After applying the formula for all plant sizes and ratios, the cost of collecting the manure and sugar beet can be calculated. The total cost, $C_{trans,in}$ [Euro], can be calculated by:

$$C_{trans,in}(M_j) = \sum_{j \in J} \left(2 \cdot \frac{M_j \cdot \Delta d_j(M_j) \cdot p_j^{trans}}{cap_j \cdot \rho_j \cdot v_j} + \frac{M_j \cdot (t_j^{load} \cdot p_j^{load} + t_j^{unload} \cdot p_j^{unload})}{cap_j \cdot \rho_j} \right)$$

The first fraction represents the cost of transporting the biomass, and the new parameters are: p_j^{trans}, the price for transporting biomass type j, v_j, the speed of the truck used for transporting the biomass j, cap_j, the capacity of the truck used for biomass type j, and ρ_j, the density of biomass type j. The fraction is multiplied by two, as the truck has to return to the plant after delivering the biomass. In case the trip is about manure transport, the trip out to the farmer will include delivering digestate.

The second fraction represents the cost of loading and unloading the truck, and the new parameters are: t_j^{load}/t_j^{unload}, the time for loading/unloading biomass type j, and p_j^{load}/p_j^{unload}, the price of loading/unloading.

All prices are based on renting trucks from an agricultural contractor and times for loading/unloading are estimated times delivered by KCA. The price for loading/unloading represents the cost for renting the relevant machines for doing the loading/unloading. The manure loading/unloading only uses the truck also used for transportation, while the sugar beet loading includes a front loader and the truck used for transportation. Loading sugar beet will therefore result in a higher cost per minute.

3.2.1.2 Transport from the biogas plant

The total transportation cost from the plant is given by the following equation:

$$C_{trans,out}(M_{man}, M_k, GP_k) = C_{trans,gas}(M_k, GP_k) + C_{trans,dig}(M_{man}, M_{dig})$$

Where $C_{trans,gas}$ is the transportation cost of the produced biogas, and $C_{trans,dig}(M_{man}, M_{dig}, \Delta M)$ is the transportation cost of the digestate as a function of the mass of manure and digestate and the digestate which cannot be sent back to the animal farmers.

3.2.1.2.1 Biogas

Biogas will be transported in pipes using a compressor generating the necessary pressure for the gas to move from the biogas plant to the destination point. The biogas cost is divided into two different costs and is:

$$C_{trans,gas}(M_k, GP_k) = C_{trans,gas_{CHP}}\left(M_{gas,CHP}, GP_{gas,CHP}\right) + C_{trans,gas_{UP}}(M_{gas,UP}, GP_{gas,UP})$$

Where

$$C_{trans,gas_{CHP}}\left(M_{gas,CHP}, GP_{gas,CHP}\right) = 0, when\ C_{trans,gas_{UP}}\left(M_{gas,UP}, GP_{gas,UP}\right) > 0\ and$$
$$C_{trans,gas_{UP}}\left(M_{gas,UP}, GP_{gas,UP}\right) = 0, when\ C_{trans,gas_{CHP}}\left(M_{gas,CHP}, GP_{gas,CHP}\right) > 0$$

When the biogas is destined for local use, the transport costs will be defined by energy use for the compressor, which again is depended on the amount of gas (Yield) and the defined gas pressure (GP_{CHP}) for transporting the gas to the destination.

$$C_{trans,gas_{CHP}}\left(M_{gas,CHP}, GP_{gas,CHP}\right) = C_{GP_{CHP}}\left(M_{gas,CHP}, GP_{gas,CHP}, p^{pow}\right),$$

Where $C_{GP_{CHP}}$ is the cost for generating the necessary pressure at a certain power price with a specific amount of gas.

When biogas is destined for the natural gas net, extra costs are added to the transport costs. There will still be an energy cost for the pressure, which is expected to be higher in this case, as the pressure should match the pressure in the natural gas net. Further there will be a commercial cost for using the distribution and transmission net. This cost is defined as

$$C_{trans,gas_{UP}}\left(M_{gas,UP}, GP_{gas,UP}\right) = C_{GP_{UP}}\left(M_{gas,UP}, GP_{gas,UP}, p^{pow}\right) + p^{distr} \cdot M_{gas,UP}$$

Where p^{distr} is a unit price for transporting 1 m3 of gas in the distribution and transmission systems.

3.2.1.2.2 Digestate

As explained in the transportation to the biogas plant, some of the digestate can be transported back to the farmers who deliver manure. In our case, the amount that can be sent back to the farmer is set to 115% of the supplied manure from each farmer. For this amount, the cost of loading/unloading must be used as in the previous equation, but for the first 100% the transportation cost is already included in the transportation cost to the biogas plant. The rest must be added to the transportation of digestate.

The excess digestate which cannot be sent to the farmers must be sent elsewhere. It is expected that plant producers in the area will be able to take the excess digestate. The amount is found by:

$$\Delta M = \max(M_{dig} - 1.15 \cdot M_{man}, 0)$$

Where the index dig and man represents the digestate and the manure.

The average transportation distance can be calculated the same way as for transportation to the biogas plant. The density of the digestate is assumed the same as for the manure, therefore it is only necessary to include the 15% of the manure supply and the excess digestate, ΔM, in this calculation. The loading/unloading cost must be added and it is expected to be the same times used for digestate as for the manure as it is transported in the same type of vehicle. The loading/unloading must be done for the total mass of digestate. The total cost for transporting digestate out from the plant is thereby:

$$\begin{aligned} C_{trans,dig}\left(M_{man}, M_{dig}\right) &= 2 \cdot \frac{\left(0.15 \cdot M_{man} \cdot \Delta d_{man}(M_{man}) + \Delta M \cdot \Delta d_{dig}(\Delta M)\right) \cdot p_{man}^{trans}}{cap_{man} \cdot \rho_{dig} \cdot v_{man}} \\ &+ \frac{M_{dig} \cdot \left(t_{man}^{load} \cdot p_{man}^{load} + t_{man}^{unload} \cdot p_{man}^{unload}\right)}{cap_{man} \cdot \rho_{dig}} \end{aligned}$$

The first fraction represents the transportation cost and is based on the digestate transported back to the farmer and the excess digestate which goes to other farmers in the area. The second equation is the cost of loading/unloading and is on the whole mass of digestate. All variables express the same as in the equation for transportation to the plant but now use the index dig for digestate. As the vehicle used for transporting the digestate is the same as for manure, the index man is applied for data on the vehicle.

3.2.2 Opex

The operational expenditures consist of costs for buying input and the costs related to operating the biogas plant. This can be expressed by:

$$C_{opex}\left(M_j, M_{gas,UP}\right) = C_{opex,input}\left(M_j\right) + C_{opex,oper}\left(M_j, M_{gas,UP}\right)$$

These costs are presented in the following sections.

3.2.2.1 Input prices

The input prices for manure and sugar beet are given by KCA, and the calculation for the total cost of acquiring these are given by:

$$C_{opex,input}\left(M_j\right) = \sum_{j \in J} p_j^{input} \cdot M_j$$

Where p_j^{input} is the input price of input type j.

3.2.2.1.1 Input prices sugar beet

Sugar beet prices are given by KCA and are market based prices on a not completely competitive market.

3.2.2.1.2 Input prices manure

Input prices for manure is often a part of a complete deal, where animal farmers supplies the biogas plant with manure to a specific price, and in return receives the treated manure (digestate) at some other higher price. See section **Fejl! Henvisningskilde ikke fundet.**.

3.2.2.2 Operation – including additional cost for more sugar beet

The operational costs on the plant are divided into two parts. The first part is a basis cost based on previous plants in Denmark and depends on the size of the plant. For the different mixing ratios additional costs applies. These costs are divided into three, namely wear of the plant due to a larger amount of sugar beets, electricity as more sugar beets requires more energy, and man power as the sugar beets require time for cutting and preparing for feeding into the biogas plant. This approach is based on numbers available from [reference – not publically available yet]. The costs are calculated by:

$$\begin{aligned} C_{opex,oper}\left(M_j, M_{gas,UP}\right) \\ &= C_{basis}\left(\sum_{j \in J} M_j\right) + \left(C_{wear} + C_{pow} + C_{man}\right) \cdot M_{sug} \\ &+ C_{opex,UP}(p^{pow}, p^{water}, M_{gas,UP}) \end{aligned}$$

Where $C_{basis}(\sum_{j \in J} M_j)$ is the basis cost of a biogas plant with size $\sum_{j \in J} M_j$, C_{wear} is the price of wear per tonnes of sugar beet, C_{pow} is the price of power per tonnes of sugar beet, C_{man} is the price of man power per tonnes of extra sugar beet, and M_{sug} is the total mass of sugar beet. The last part is the operational costs of upgrading the biogas, $M_{gas,UP}$, which is a function of the amount of upgraded gas, and the prices on power (p^{pow}) and water (p^{water}), assuming that the upgrading technology will be a water scrubber.

3.2.3 Capex

Investment costs (Capex) depends on investment cost related to input, production and output. In this model it is assumed, that all transportation is rented, therefore there are no investment cost for trucks and other.

$$C_{capex}(M_j, M_k) = C_{capex,prod}(M_j) + C_{capex,output}(M_j, M_k)$$

3.2.3.1 Production

Investment costs for the production: $C_{capex,prod}(\ M_j)$

Consist of many different costs, all depended on the scale of the biogas plant. it is assumed, that the size of the digester is scaled after the scenario with no sugar beet, as this scenario has the largest density, and it is assumed, that the other scenarios doesn´t change the density enough to invest in another size of digester within the same level of biomass.
In this model there are five different categories all depended on the total level of biomass (M): Biogas plant, Process heat boiler, purchase of land, counselling and other. They appear in the model as one figure. The cost of the biogas plant includes a storage facility for manure.
For the scenarios including sugar beet an additional cost applies depending on the sugar beet mass. This cost includes a storage facility of sugar beet and a pretreatment facility.

3.2.3.2 Output

Investment costs for the output:

$$C_{capex,output}(M_j\ , M_k) = \ C_{capex,output,dig}(M_j\ , M_{dig}) + C_{capex,output,gas}(M_{gas,UP}, M_{gas,CHP})$$

Consists of two different sub categories: Digestate and biogas

3.2.3.2.1 Digestate

After digestion, digestate will have to be stored at the biogas plant, until transported out to the farmers. In the cases with a high level of sugar beet input, some of the digestate will have to be stored at the plant for approximately one year, until the plant farmers are expected to use the digestate, as they cannot be expected to have their own local storage. The price for storage therefore depends on M_j, e.g. the mix of sugar and manure as well as the amount of digestate:

$$C_{capex,output,dig}(M_j\ , M_{dig}) = C_{stor,dig}(M_j, M_{dig})$$

3.2.3.2.2 Gas

Investment costs related to the produced biogas can again be divided into two cost groups. First costs that are considered independent of the quantity of biogas:

- A small temporary (12 hours) gas storage, this will not be depended of the final use
- A biogas cleaner facility, where the size might be depended of the quantity of biogas, but not the final use

- A pipeline from the biogas plant to the usage destination. It is here assumed, that the distance from the biogas plant to the nearby local CHP is the same as the distance from the biogas plant to the natural gas net. This is a plausible assumption.

If the quantity of biogas is high enough, it is profitable to upgrade the biogas for the natural gas distribution net. In this case, there should also be investments in:

- an upgrading facility and
- an MR-station including a compressor

The price is thereby described by:

$$C_{capex,output,gas}\left(M_{gas,UP}, M_{gas,CHP}\right) = C_{stor,gas} + C_{clean,gas}\left(M_{gas}\right) + C_{pipe,gas}\left(M_{gas}\right) + C_{MR,gas}\left(M_{gas,UP}\right) + C_{MR,gas}\left(M_{gas,UP}\right)$$

3.3 Appendix

Symbol	***Description***
$\boldsymbol{I}$	Set of circles in which biomass can be collected
$\boldsymbol{J}$	Set of biomass: manure and sugar beet
$\boldsymbol{K}$	Set of output: gas for upgrade, gas for CHP and digestate
$\boldsymbol{TNI}(\mathbf{P}_{\boldsymbol{k}}, \mathbf{M}_{\boldsymbol{j}}, \boldsymbol{M}_{\boldsymbol{k}}, \mathbf{r}_{\boldsymbol{j}}, \mathbf{j}, \mathbf{k})$	Total net income
$\mathbf{TI}(\mathbf{P}_{\boldsymbol{k}}, \mathbf{M}_{\boldsymbol{j}}, \mathbf{r}_{\boldsymbol{j}})$	Total income
$\boldsymbol{TC}(\boldsymbol{M}_{\boldsymbol{j}}, \boldsymbol{M}_{\boldsymbol{k}}, \boldsymbol{j}, \boldsymbol{k})$	Total cost
$\boldsymbol{Y}_{\boldsymbol{k}}\left(\mathbf{M}_{\boldsymbol{j}}, \mathbf{r}_{\boldsymbol{j}}\right)$	Yield of output k
$\boldsymbol{C}_{\boldsymbol{trans}}(\boldsymbol{M}_{\boldsymbol{j}}, \boldsymbol{M}_{\boldsymbol{k}})$	Cost of transportation
$\boldsymbol{C}_{\boldsymbol{capex}}\left(\boldsymbol{M}_{\boldsymbol{j}}, \boldsymbol{M}_{\boldsymbol{k}}\right)$	Total investment costs
$\boldsymbol{C}_{\boldsymbol{opex}}\left(\boldsymbol{M}_{\boldsymbol{j}}, \boldsymbol{M}_{\boldsymbol{gas,UP}}\right)$	Total operational costs
$\boldsymbol{p}_{\boldsymbol{k}}$	Price for selling output k
$\boldsymbol{p}^{\boldsymbol{NG}}$	Market price for natural Gas
$\boldsymbol{p}^{\boldsymbol{g}}$	Market price for a green certificate
$\boldsymbol{p}^{\boldsymbol{MP}}$	Price reduction due to market power
$\boldsymbol{S}$	Biogas Support
$\boldsymbol{p}(\boldsymbol{p}^{\boldsymbol{NG}}, \boldsymbol{S}, \boldsymbol{V})$	The price received for selling biogas for CHP
$\boldsymbol{V}$	Heat & Power value
$\boldsymbol{M}_{\boldsymbol{j}}$	Mass of biomass j, input
$\boldsymbol{M}_{\boldsymbol{k}}$	Mass of digestate and gas k, output
$\overline{\boldsymbol{M}_{\boldsymbol{gas}}}$	Point, where the output level of gas is so high, that it is profitable to invest in an upgrade facility
$\boldsymbol{p}^{\boldsymbol{distr}}$	Unit price for transporting 1m3 in the gas transmission and distribution systems
$\boldsymbol{GP}, \boldsymbol{GPchp}, \boldsymbol{GPup}$	Gas Pressure
$\boldsymbol{C}_{\boldsymbol{GP,CHP}}, \boldsymbol{C}_{\boldsymbol{GP,UP}}$	Cost of getting a specific gas pressure
$\Delta\mathbf{d}_{\boldsymbol{j}}(\mathbf{M}_{\boldsymbol{j}})$	The average transportation distance
$\boldsymbol{m}_{\boldsymbol{ij}}$	The mass available of biomass j within circle i
$\boldsymbol{r}_{\boldsymbol{i}}$	The radius of circle i

$o(M_j)$	The last circle needed for satisfying the requested demand
$n_j(M_j)$	The truck loads needed for the requested biomass type j
p_j^{trans}	The price of transportation for biomass type j
v_j	The speed of the vehicle used for transporting biomass type j
t_j^{load}/t_j^{unload}	The time used for loading/unloading biomass type j
p_j^{load}/p_j^{unload}	The price of loading/unloading biomass type j
cap_j	The capacity of the vehicle used for transporting biomass type j
ρ_j	The density of biomass type j
ΔM	The mass of excess digestate
$C_{basis}(M)$	Basis cost of a biogas plant with input mass M
C_{wear}	Cost of wear per tonnes of sugar beet
C_{pow}	Cost of power per tonnes of sugar beet
C_{man}	Cost of man power per tonnes of sugar beet
p^{pow}	Price of power
p^{water}	Price of water used for water scrubbing
$C_{stor,dig}(M_j, M_{dig})$	Cost of storage of the digestate as a function of input and amount of digestate
$C_{stor,gas}$	Cost of a gas storage, 12 hours
$C_{clean,gas}(M_{gas})$	Cost of cleaning the gas, depended on the amount of gas
$C_{pipe,gas}(M_{gas})$	Cost of pipeline, depended on the amount of gas
$C_{upgrade,gas}(M_{gas,UP})$	Cost of upgrading facility
$C_{MR,gas}(M_{gas,UP})$	Cost of MR-station

Table 1: Nomenclature for the economy model

4 Gas quality

Before upgrading, biogas has significantly lower energy content than natural gas. Which can be down to 60% of methane, the biogas produced in this study delivers a higher quality with around 70% of methane.

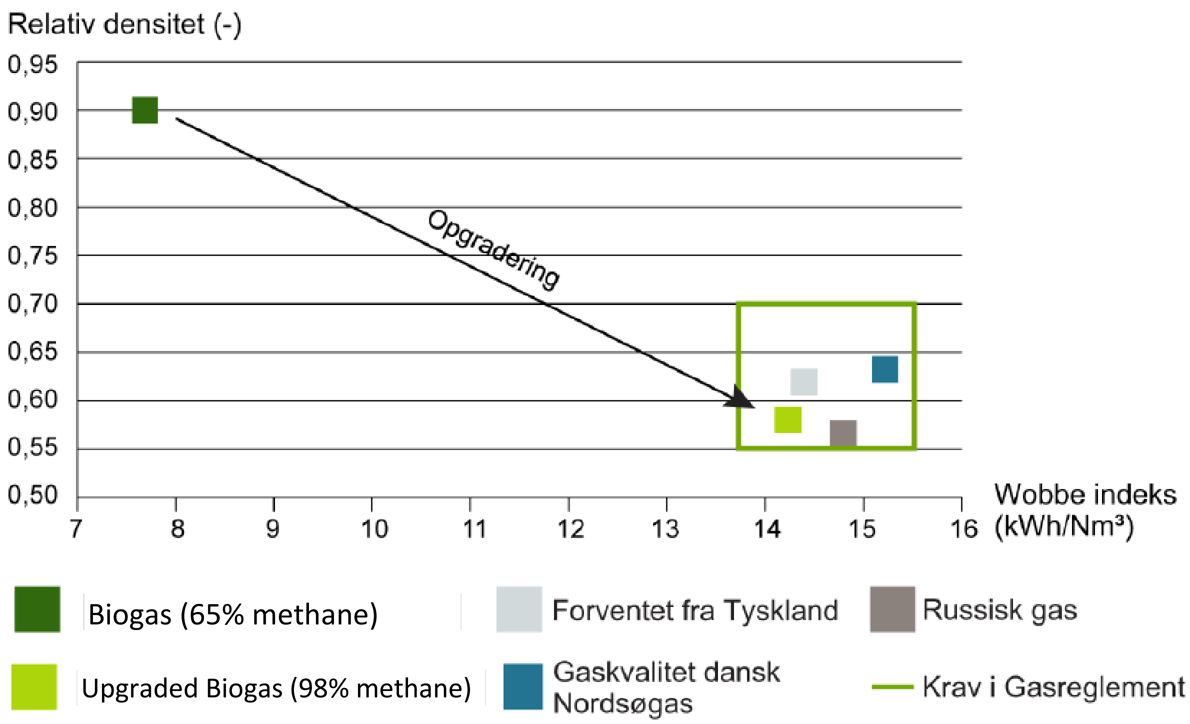

Figure 3: Gas quality - Biogas before upgrading related to upgraded biogas (BNG) and natural gas, Source: Presentation from Energinet.dk at a theme day on biogas in Skive: http://www.greengascluster.com/praesentationer/

While Natural gas typically contains a great variety of gassses, biogas primarily contains methane and carbon dioxide after clensing and upgrading.

Naturgas, biogas og bionaturgas		Nordsø gas (2009)	Biogas ('rå')	Bionatur gas	Bionaturgas med propan
Metan	%	86,6-91,8	55-70	97,3	92
Ethan	%	4,9-7,6	0	0	0
Propan	%	1,6-3,3	0	0	7
Butan	%	0,74-1,13	0	0	0
Pentan+	%	0,2-0,38	0	0	0
Nitrogen	%	0,25-0,40	0-2	0	0
Kuldioxid	%	0,32-1,16	30-45	2,7	1
Svovlbrinte	mg/m³n	0,4-4,1	~500	-	-
Ammoniak	ppm	0	~100	-	-
Øvre brændværdi	MJ/m³n	43,0-44,8	22-28	38,8	43,6
Nedre brændværdi	MJ/m³n	38,9-40,5	20-25	34,9	39,4
Relativ densitet	-	0,62-0,65	0,85-1,0	0,58	0,63
Wobbeindeks	MJ/ m³n	54,7-55,4	22-30	50,8	54,7

Figure 4: Gas content, Source: http://www.naturgasfakta.dk/copy_of_miljoekrav-til-energianlaeg/biogas

The results from our study are measured in methane production pr. tonnes of biomass. To calculate costs pr. m3 of biogas we therefore divide with 70%, reflecting the percentage of methane in our biogas. Giving the following results:

$$6.6\, CH4\, \frac{m3}{t} \Big/ 0.7 = 9.5 Biogas \frac{m3}{t}$$

When the biogas is upgraded for the gas grid, the methane concentration has been increased to 98%. While costs are calculated in m3 biogas, income is calculated in m3 BNG (Bio Natural Gas), the level of BNG m3/tonnes of input is calculated in the same way as biogas

$$6.6\, CH4\, \frac{m3}{t} \Big/ 0.98 = 9.7 BNG \frac{m3}{t}$$

Results for all three ratios are presented in Figure 5

Ratio	CH4 m3/t	Methane concentration %	Biogas yield m3/t	BNG yield m3/t
0/100	6.6	70%	9.5	6.7
12½/87½	17.8	70%	25.6	18.2
25/75	14	70%	20.1	14.3

Figure 5: Biogas yield

The yield is as such independent of scale, therefore the primary results can be seen in Figure 5 on the actual biogas output, two measures has been used primarily as Biogas yield in M3 and in m3/h. These result are depicted in Figure 6

Biogas yield, M3				
Ratio	M3/Tonnes	110	320	500
0/100	9.5	1,043,103	3,034,483	4,741,379
12½/87½	25.6	2,813,218	8,183,908	12,787,356
25/75	20.1	2,212,644	6,436,782	10,057,471

Biogas yield, m3/h			
Ratio	110	320	500
0/100	119	346	541
12½/87½	321	934	1,460
25/75	253	735	1,148

Figure 6: Biogas Yield on ratio and size - in m3 p.a. and m3/h

5 Results

Choice of technology: When to upgrade?

The choice of upgrading is made based on the demand limitations from the CHP plant (see 2.1). Only the annual demand is used as restriction. Thereby the two scales 320 000 tonnes and 500 000 tonnes both include the upgrade costs for cases with sugar beet. For the manure only case the 320 000 tonnes case does not include upgrading costs. The figures from Table 2 illustrate the scale effect within the upgrading technology as unit costs are the least for the 500 000 tonnes case. Compared to other costs (Table 5) these output related investment costs are small.

CAPEX, Investment costs, Euro/Tonnes p.a.				
Ratio\Scale		**110**	**320**	**500**
0/100	Gas, CHP	0.35	0.18	0.13
	Gas, upgraded	0.32	0.60	0.40
	Digestate	0.00	0	0
12½/87½	Gas, CHP	0.48	0.32	0.32
	Gas, upgraded	1.63	1.05	0.79
	Digestate	0	0	0
25/75	Gas, CHP	0.39	0.26	0.25
	Gas, upgraded	1.32	0.83	0.63
	Digestate	0.17	0.13	0.13

Table 2 Investment costs associated with outputs (biogas plant excluded, shaded cells not used for totals)

Scaling up the biogas plant reduces capital costs per amount of input for all input compositions. The addition of sugar beet adds capital costs from storage facilities part of the year, but the increase is less than 6% in the worst case. Table 3 include the investment costs associated with the biogas plant and the storage of inputs.

CAPEX, Investment costs, Euro/Tonnes			
Ratio\Scale	**110000**	**320000**	**500000**
0/100	4.82	3.46	3.09
12½/87½	5.02	3.64	3.27
25/75	5.17	3.79	3.42

Table 3 Total investment costs per annum per tonnes of input

Scale effect conclusion:

- Cost reducing effect in scaling biogas plant size 110 00 to 500 00 tonnes (capex per unit reduced 35%, 0/100 mix)
- Negative scaling effect on transport costs (increase 45% for manure and 96% for sugarbeet)
- Net effect (trade-off) result in equal costs per unit of the 320 000 t case and the 500 000 t case: the benefit of scaling to 500 000 t (biogas plant + upgrade capex) is outweighed by the increase in transport costs for both inputs and outputs

Transport, Euro/tonnes				
Ratio\Scale		**110**	**320**	**500**
0/100	Sugar bee	0.00	0.00	0.00
	Manure	1.12	1.45	1.62
12½/87½	Sugar bee	0.68	1.04	1.33
	Manure	0.95	1.22	1.38
25/75	Sugar bee	2.04	2.80	2.98
	Manure	0.79	0.98	1.14

Table 4 Transport costs per unit of input (unweighted)

All costs, Euro/Tonnes			
Ratio\Scale	**110**	**320**	**500**
0/100	15.89	14.75	14.87
12½/87½	20.69	20.91	20.91
25/75	25.90	26.60	26.95

Table 5 Total annual costs per tonnes of input

Purely based on the costs from Table 5 the options with 110 000 tonnes annually 12½% sugarbeet and seems the most competitive. However as the income from the upgraded biogas is slightly higher the options with upgrading become more attractive.

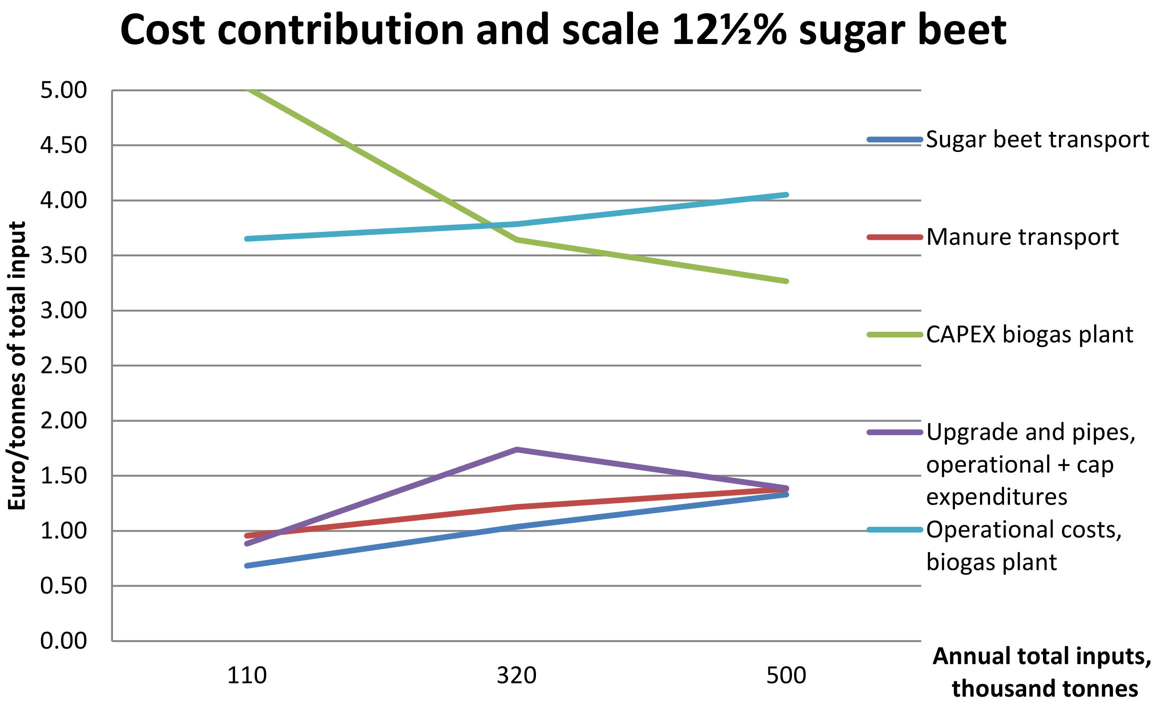

Figure 7 Trade off between rising operational costs (including transport) and reduced capital costs

The balance between increased operational costs and the reduced capital costs results in equal total unit costs for the 320 and 500 000 tonnes cases with 12½% sugar beet. As seen from Figure 7 this is a coincidence resulting from several counteracting effects. The drop in costs for upgrade and pipes etc. is a result of positive scale effects in the upgrading facility. The 110 000 tonnes case does not involve upgrading and therefore costs are lower here. The unit costs associated with transport do increase, and most for the sugar beet, but this is not severe enough to capture the capital cost benefits of increasing size. With the increasing operational unit costs of the plant the entire scale benefit disappears. As such the operational costs at the plant can be identified as an important factor in achieving profitability of increasing scale.

Overall economic results

Net-income, Euro/Tonnes			
Ratio\Scale	**110**	**320**	**500**
0/100	-0.42	0.72	0.78
12½/87½	3.99	**4.23**	**4.23**
25/75	-4.34	-4.68	-5.03

Table 6 Net annual result per tonnes of inputs

Based on existing subsidies, price assumptions for inputs and outputs and the production technology from section (biogas yield) the only viable input composition is 12½% sugar beet. Increasing the sugar beet input share reduces the biogas yield and the net earnings become negative. For the entirely manure based case the result is very close to break even. Scaling choices results in earnings for the 320 thousand tonnes/year scale being equal to the 500 thousand tonnes solution per input unit. Comparing the two different scales thus results in the preference for the highest absolute profit based on the 500 thousand tonnes solution.

Critical assumptions and main uncertainty related to:

1. Sugarbeet price (relative to manure)
2. Biogas yield (relatively between cases)

Sugarbeet prices are around 4½ times the manure price. The much higher yield provide for better earnings for the 12½% sugarbeet case, but the yield in the case with 25% sugarbeet is not high enough to balance the increased cost due to the larger input costs of sugarbeet. This is not a result of transport costs increasing but a result of the high sugarbeet price. Slightly lower sugarbeet prices could make the case of 25% sugarbeet also profitable.

Biogas yield is a very critical factor for profitability. The negative results for the 25% sugarbeet case are caused by the unexpected lower yield for the 25% sugarbeet compared to the 12½% sugarbeet case. The yield should have been somewhat higher for the 25% case to make this option more economical than the 12½% case.

Additionally the assumption about all subsidy from biogas used in the CHP plant accruing to the biogas plant is questionable for alternative ownership structures. We assume that either the CHP owns and builds the biogas plant as an additional activity or that the negotiating power of the biogas plant is sufficiently strong to secure the full subsidy. Alternative assumptions could change the attractiveness of upgrading relative to the CHP solution further.

Relating the results to actual production and profitability of Danish biogas plants is difficult as operational details are more complex than sketched here. Furthermore the economic condition and contracts are not always publicly available and depend largely on local condition. Basically the case with 12½% sugarbeet (our optimal production) produce biogas at a level that is at the lower end of what is actually produced annually at the Maabjerg plant.

6 Literature and data sources

1. Biogas taskforce reports: http://www.ens.dk/undergrund-forsyning/vedvarende-energi/bioenergi/afrapportering-biogas-taskforce
2. Ea energianalyse: "Anvendelse af biogas til el- og varmeproduktion ANALYSER FOR BIOGAS TASKFORCE"
3. Energistyrelsen: "Biogas i Danmark – status, barrierer og perspektiver"
4. Grøn gas erhvervsklynge: "Beslutningsgrundlag for Grøn Gas investeringer"
5. Energinet.dk, Niras: "Følgenotat_faktaark_final" and excelsheet: "Faktaark_biogas_2012_ver1", http://www.energinet.dk/DA/GAS/biogas/Sider/Biogasrapporter.aspx
6. Discussions with our project partner KCA
7. Maabjerg Bioenergy homepage (maabjergbioenergy.dk)
8. Master thesis: Lau Linnet p. 49
9. Master Thesis: Amalia Alonso (on cleaning and upgrading costs)
10. Offer from Spæncom on slurry tanks