Why do we make such bad biogas plants?

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There is a trend to construct larger and larger biogas plants to take advantage of improved economics. Over the past two years many German designers and builders are doing this by taking farm size plant designs and simply making them bigger. In Denmark though, there are processes and technologies which have been developed and operated for about 15 years which are better suited for big plants. By focusing on their own experiences engineering offices and plant developers have not kept up with the optimal technology available. It is the intention of this paper to change this old thinking and raise awareness for the basics of optimal large scale fermentation approaches.

Introduction

In Denmark, large biogas plants have been constructed since the mid 1980's. These are mainly central biogas plants, where the liquid manure from the surrounding farms along with any cofermentation materials is digested to produce biogas. The typical Danish system includes a large upright steel tank equipped with a single mixer mounted in the center of the roof. Heat for the process is added by an external heat exchanger.

At the same time biogas plants were being constructed in Germany. The majority of these are agricultural, on farm facilities in which a farmer processes the manure from his own farm together with coferments then distributes the digestate on his own fields. The typical design of the agricultural fermentation technology was based on a concrete tank with submersible directional mixers and is equipped with heating pipes installed inside the digester.

In reality both types and sizes of plants are found in Denmark and Germany. In both countries similar fermenting technologies are used depending on the application and the builder. In this article the terms "Danish technology" and "agricultural technology" are used as described above.

Technologies

This section describes the two fermentation technologies.

1. In Danish technology, fermentation is conducted in a double glass coated steel tank. The roof is usually glass coated as well or stainless steel to protect the structure against corrosion from biogas. The fermenters are built with volumes up to approximately 5,000 m³

(cubic meters). Diameters of 15 m (meters) and heights of more than 20 m are common. The mixing equipment is mounted centrally on the roof and hangs with its weight supported only by the roof. Unlike other mixing systems the top mounted central mixer (TCM) is not supported in any way at the bottom. The roof must then be constructed to withstand not only the weight but all torque and moments that develop from the rotation of the mixer paddles. The mixer runs continuously and provides a complete thorough mixing of the fermenter's contents. Heat is added to the digester via an external heat exchanger so that the new input material is heated as it enters the digester. Engine jacket water from the combined heat and power plant (CHP) is circulated to the heat exchanger where its heat is transferred to the substrate. Therefore the substrate already has the required temperature when it enters the fermenter. Heating is done in a carefully controlled manner to maintain the optimal fermentation temperature.

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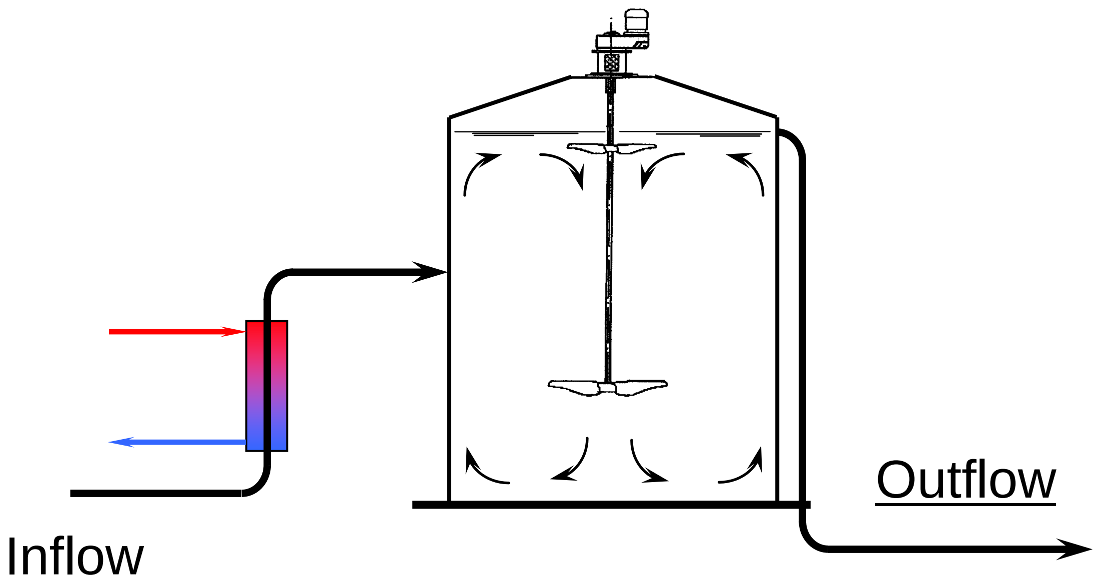

Figure 1 Fermenter "Danish Technology"

2. At the center of the typical German agricultural digester is a concrete container with a height of 4 to 6 m (meters) and a diameter of up to 20 m. Usual volumes range between 500 and 1,200 m³. Mixing of the digester contents is accomplished via one or more submersible directional mixers (SDM) usually mounted near the edge of the fermenter. In this technology, the mixers are only operated as needed and remain off part of the time. The mixers can be adjusted both in height and direction and should be inspected on an annual basis by removing them from the digester through a hatch in the roof. Typically heat is added to the digester by circulating engine jacket water from the CHP through plastic or steel tubes mounted on the interior of the tank wall.

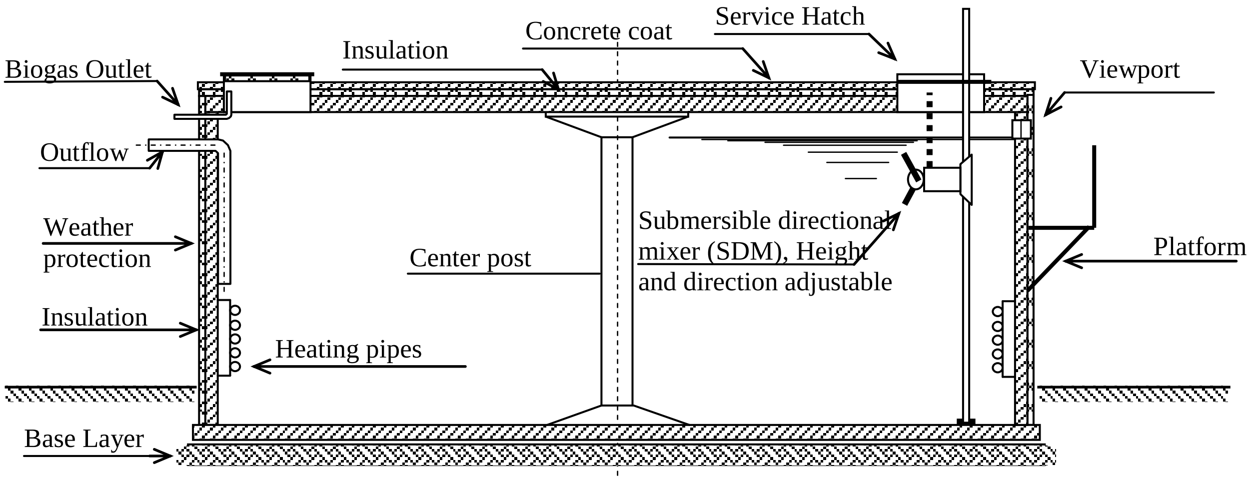

Figure 2. Agricultural Technology Fermenter

When comparing the two technologies the following table is the result:

	Danish Technology	Agricultural Technology
Tank	Steel	Concrete
Mixer	Top mounted Central (TCM)	Submerged motor mixer (SDM)
Mixing duration	Continuous	As required
Heating Method	External heat exchanger	Internal heating pipes
substrate input temperature	37/55°C	Ambient Temperature
Biogas Production	Identical	
Digestion extent	Identical	
Process stability	Identical	
Retention time (typical)	20 Days	40 Days

Table 1. Comparison of the fermenting technologies

In Denmark, almost all large biogas plants were operated initially at mesophilic temperatures (35 to 40 degrees Celsius) with a retention time of about 20 days. In some cases a reduction of the retention time to less than 15 days was possible. This was done at many of the Danish plants by converting them to the higher thermophilic temperatures (40 to 70 degrees Celsius) resulting in shorter retention times. This should play no role in the view discussed here however as this article focuses on design and dimensioning.

Agricultural biogas plants in Germany follow different approaches and retention times vary widely. Although different contractors apply similar technologies, the retention times fluctuate between 30 to 50 days. However to put the various technologies on equal footing, a typical retention time of 40 days was set for this study.

As shown in Table 1, there are clear and considerable technical differences which yield a significant different retention time between the two technologies. One must note that these different retention times – 20 days in comparison with 40 days – results in a doubling of the fermenter volumes between the Danish and the agricultural technology. It begs the question: Why did Germany develop agricultural fermenting technology that – for the same biogas production, the same digestion extent and the same process stability – requires twice the fermenter volume? Why have we built bad biogas plants? More to the point: why do we continue to use bad digestion technology?

In an attempt to answer these questions the mixing and heat addition systems are examined because they are the important parameters when designing a biogas plant. Other minor conditions such as charging rate play a role, however these are mainly dependent on the operation of the plant rather than its basic design and they are ignored here.

Mixing

Complete mixing of the contents of the fermenters is an important part of the plants which were evaluated. In the biogas industry, there are several systems in use to mix the digester contents. Devices used for stirring/mixing include: the mechanical mixers describe in this article, gas bubbles, pumps for circulation or other devices. According to estimations more than 1500 of the 1600 existing biogas plants apply mechanical mixers (no other mixing system) and therefore these mixers are the most important technology to consider.

Mixing the contents of a fermenter is done for several reasons:

- optimizing nutrient distribution
- avoiding temperature differences
- assisting the ascent of biogas bubbles
- prevention of sedimentation
- prevention of swimming layers

A good mixing technology performs all these tasks simultaneously. Mixing should be done in a way to enhance the growth of all essential microbial families. This can only be done with a flexible system that runs most of the time on slow, but can be sped up when needed.

In reality, there are large differences in mixing approaches but side by side comparisons are rare. One example of different mixing approaches and systems in use on identical fermenters digesting the same input substrate is found in the JOHANNESBURGS facility in Emsland Germany. Two fermenters with identical mixers were constructed in 1991 with a volume of about 500 m^3 each. Fermenter number one is equipped with two 11.5 kW submersible directional mixers (SDM) while the other fermenter has a 2.2 kW top mounted central mixer (TCM). They are operated on different cycles. The top mounted mixer runs continuously, round the clock seven days per week while the submersible directional mixers are operated 25 minutes on and 20 minutes off.

A study was conducted in mid 2001 to compare the organic loading rate of each fermenter. The results are summarized in Figure 3.

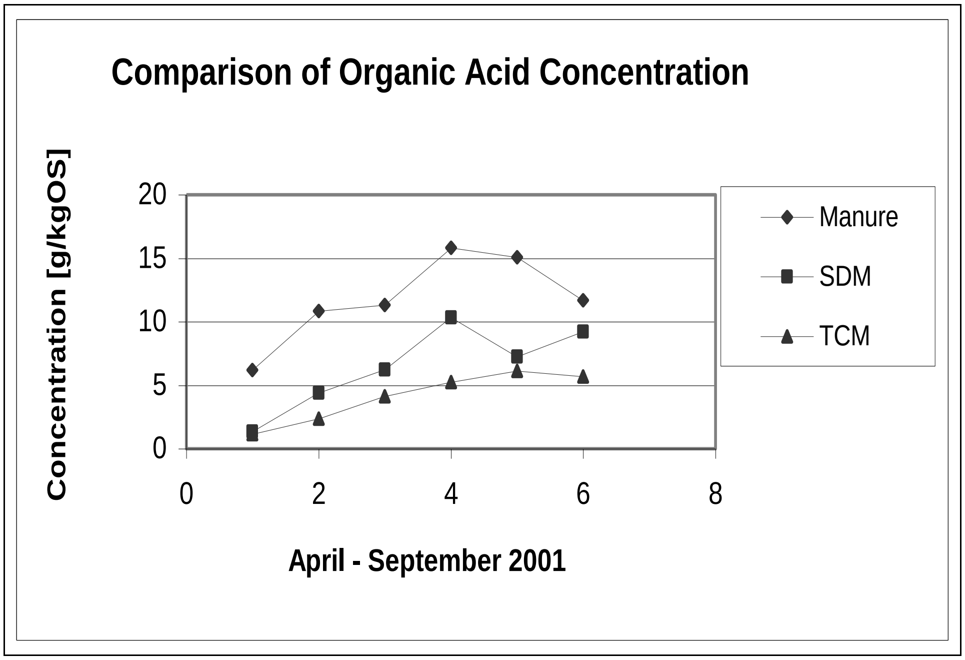

Figure 3: Comparison of fermentation data from two biogas plant digesters at the JOHANNESBURG facility.

This shows that the organic acid concentration in fermenter 1, with two submersible directional mixers is higher than in fermenter 2, equipped with a top mounted mixer. It is interesting to compare the operating times of the two different mixing systems. Although the SDM at this plant runs longer than normal for an agricultural biogas plant, it cannot achieve the same organic load as the continuously mixed fermenter.

One may assume that the motor power load is about 70% of the rated value for the continuously operated top mounted mixer while the corresponding value for the intermittently operated submersible mixers is 85% (in this case the substrate mass must be completely moved from a standing start each cycle). The above data was collected in the period from April 1 to September 31, 2001, during which about 47,572 kWh was consumed by fermenter 1 and only 6,764 kWh by fermenter 2.

Even though the owner invested seven times more for the mixing system in fermenter 1 he gets a poorer result than in fermenter 2. This provides some guidance for selecting an optimal mixing technology.

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Heating

Obtaining and maintaining the optimum fermentation process temperature is essential to maximizing the performance of the beneficial microorganisms. There are several ways to do this:

- External heat exchangers made of metal. These are generally in the form of a tube in tube or a double helix heat exchanger. In this device the input material is sent through one channel while hot water from the CHP is fed through a parallel channel in the opposite direction. While the feed material becomes warm the engine jacket water is cooled. The heat transmission rate and efficiency depends on the thickness of the metal, its conductivity, the fluid speeds and relative temperatures between them. In this approach, the substrate is warmed up in the feed line and arrives at the fermenters in a preheated condition. Then to achieve and maintain the optimal temperature the contents of the fermenter are pumped through the heat exchanger in between the feed in cycles as needed.

- Heating pipes mounted inside the concrete tank. Steel and PE pipes are used for this approach; the choice of material depends on the maximum temperatures used in the system. A pump circulates hot water from the CHP through the pipes. A good heat transmission can be obtained only if the digester's mixing equipment is operated at the same time. During the mixing down times, heat transmission is limited. Since the substrate is cold (ambient temperature) when fed into the fermenter it can lead to localized reduction in biological activity, especially during winter. The irregular and intermittent flow created by the mixers allows heat to enter the digester slowly or more quickly in an imprecise way.

- Heating pipes mounted outside of the steel tank surface. From a practical standpoint this is a technically sub-optimal type of heating system as the heat transmission is difficult to predict. It depends on how well the heating pipes are attached, how well the container is insulated and good mixing of the substrate inside the container to achieve an acceptable heat transmission.

External heating pipes that are positioned outside of the fermenters are the poorest possible system in use both for steel and concrete tanks. They are not considered in this comparison.

The first two systems were examined mathematically and the results used to form the basis for the following model fermenters.

Model Fermenters

A model to compare technologies should be based on elements which can be investigated and have an important effect on the investment and overhead of the facility. At the same time it is wise to use and compare the optimal fermentation applications for each technology. Finally the model must compare respectively identical biogas plants consisting of a receiving pit, a fermenter, a secondary digester with gasholder roof and a CHP.

For this model biogas plants with a minimum throughput of about 10,000 m^3/a, were included. The pre-processing and post-fermenting features, including a gas storage roof and CHP, are essentially identical. Only the fermenting technology including the tank, mixer and heating system conformed to either the Danish or agricultural technology. For the analysis the retention times discussed earlier are used. Some extrapolations were made regarding throughput.

Further, a few secondary conditions were established to fix a uniform starting point:

1: The input material consists in all cases of a mixture of liquid pig manure with a TS (total solids) content of 6% and liquid cow manure with a TS content of 9%. They are to be blended at a rate of 50% each to produce a mixture with a TS content of 7.5%.

2: This analysis does not take into consideration the relative quality or guarantee of the components. It is assumed that these elements are similar. In this paper the typical qualities of the respective fermenters are to be considered one to the other as if they were the same. In practice this is not the case, the corrosion protection in the double layered glass coated steel tanks is better than in concrete; the material quality in the top mounted central mixer tends to be better than the submersible mixers; external heat exchangers are easier to maintain and repair than heating pipes installed inside the tank; many components used in the Danish technology are better than those used in agricultural systems. These facts are irrelevant for this investigation, as this analysis will focus on a practical comparison of qualities that are usually applied.

3: The agricultural technology is based around two sizes of concrete digesters. The smaller concrete container, (type 1) has a diameter of 14.5 m and a height of 5.5 m. The usable volume amounts to 825 m^3 with a 0.5 m freeboard for a gross volume of 908 m^3. The larger concrete container (type 2) has a diameter of 17 m and a height of 5.5 m. This size was selected as the maximum meaningful size used for this type of fermenter. Taller tanks have been used but they are poorly mixed by the SDM's. Larger diameters have problems with heat distribution throughout the container. The volume of the type 2 agricultural fermenters is 1,135 m^3 net with a 0.5 m freeboard or 1,248 m^3 gross.

4: The Danish case is based on one fermenter per biogas plant.

5: All fermenters are equipped with a rigid top. The authors know that agricultural biogas fermenters are frequently topped with a single or double membrane roof. However, for this study, using fermenters with a concrete top made for a better comparison between the technologies.

6: The type 1 agricultural fermenters are equipped with an 11 kW submersible directional mixer (SDM); the type 2 agricultural fermenters have an additional mixer of the same size. Over a period of three hours the agricultural digester is mixed for fifteen minutes and the motors are working at 85% of nominal power.

7: The top mounted central mixer (TCM) in the Danish technology runs continuously, 24 hours per day seven days per week. The electrical consumption calculation was based on the motor drawing 70% of its power rating. A lower value was assigned to the top mounted mixer because the substrate mass is kept in continuous motion while the SDM motors must start with the mass at a standstill requiring a higher power load.

8: The process temperature is mesophilic.

9: In the heat transfer calculations, the temperature of the input substrate in the summer is fixed at 18°C and in the winter at 2°C, ambient temperature is set at 25°C in summer and -5°C in winter.

10: The free board in all tanks is set at 50 cm.

11: All tanks were complete including equipment and completely built.

12: There is no building height limitation.

Substrate throughputs used in the study are shown in table 2, they ranged between 7,500 m³/a and 52,700 m³/a, with feed rates from about 20 m³/d to 144 m³/d.

Agricultural Fermenter								
Case	Throughput	Amount	Typ	Diameter`	*Effective Height*	Height	Gross vol.	Net vol.
1	7.500 m³/a	1	1	14,50 m	5,00 m	5,50 m	908 m³	825 m³
2	10.000 m³/a	1	2	17,00 m	5,00 m	5,50 m	1.248 m³	1.135 m³
3	14.600 m³/a	2	1	14,50 m	5,00 m	5,50 m	1.816 m³	1.650 m³
4	21.000 m³/a	2	2	17,00 m	5,00 m	5,50 m	2.496 m³	2.268 m³
5	31.500 m³/a	3	2	17,00 m	5,00 m	5,50 m	3.744 m³	3.402 m³
6	41.000 m³/a	4	2	17,00 m	5,00 m	5,50 m	4.992 m³	4.536 m³
7	52.700 m³/a	5	2	17,00 m	5,00 m	5,50 m	6.240 m³	5.670 m³

Table 2: agricultural fermenters

Agricultural Fermenter					
Case	Number SDM/SDM	Power	Operation/d	kWh/d 85%	kWh/a 85%
1	1	11 kW	2,0 h	18,7 kWh	6.826 kWh
2	2	11 kW	2,0 h	37,4 kWh	13.651 kWh
3	2	11 kW	2,0 h	37,4 kWh	13.651 kWh
4	4	11 kW	2,0 h	74,8 kWh	27.302 kWh
5	6	11 kW	2,0 h	112,2 kWh	40.953 kWh
6	8	11 kW	2,0 h	149,6 kWh	54.604 kWh
7	10	11 kW	2,0 h	187,0 kWh	68.255 kWh

Table 3: Mixing energy consumption (Submersible Directional Mixers SDM/SDM) for agricultural fermenters

Danish							
Case	Throughput	Amount	Diameter	Height	Effective Height	Gross vol.	Net vol.
1	7.500 m³/a	1	8,50 m	7,75 m	7,25 m	445 m³	415 m³
2	10.000 m³/a	1	9,40 m	8,45 m	7,95 m	590 m³	550 m³
3	14.600 m³/a	1	10,25 m	9,90 m	9,40 m	815 m³	775 m³
4	21.000 m³/a	1	11,95 m	11,25 m	10,75 m	1.265 m³	1.210 m³
5	31.500 m³/a	1	13,65 m	12,65 m	12,15 m	1.860 m³	1.785 m³
6	41.000 m³/a	1	14,50 m	14,05 m	13,55 m	2.330 m³	2.245 m³
7	52.700 m³/a	1	16,20 m	14,75 m	14,25 m	3.045 m³	2.940 m³

Table 4: Dimension statistics for Danish fermenters

These values were used to send inquiries to different manufacturer of top mounted mixers. Motors for those mixers are only available in discrete power sizes and it is not possible to vary the power output of the motor continuously Therefore the motors quoted for case 2 and 3 are identical, but the mixer is equipped with different sized propellers to fit the purpose.

Danish Fermenter					
Case	Number of TCM's	Power	Operation/d	kWh/d 70%	kWh/a 70%
1	1	2,0 kW	24,0 h	33,6 kWh	12.264 kWh
2	1	5,0 kW	24,0 h	84,0 kWh	30.660 kWh
3	1	5,0 kW	24,0 h	84,0 kWh	30.660 kWh
4	1	6,8 kW	24,0 h	114,2 kWh	41.698 kWh
5	1	7,5 kW	24,0 h	126,0 kWh	45.990 kWh
6	1	9,2 kW	24,0 h	154,6 kWh	56.414 kWh
7	1	15,0 kW	24,0 h	252,0 kWh	91.980 kWh

Table 5: Mixing energy consumption (Top mounted Central Mixer) for Danish fermenters

This data was used to create the graph in Figure 4. It shows that the electrical energy required for agricultural digesters is lower than in the Danish fermenters with corresponding throughputs.

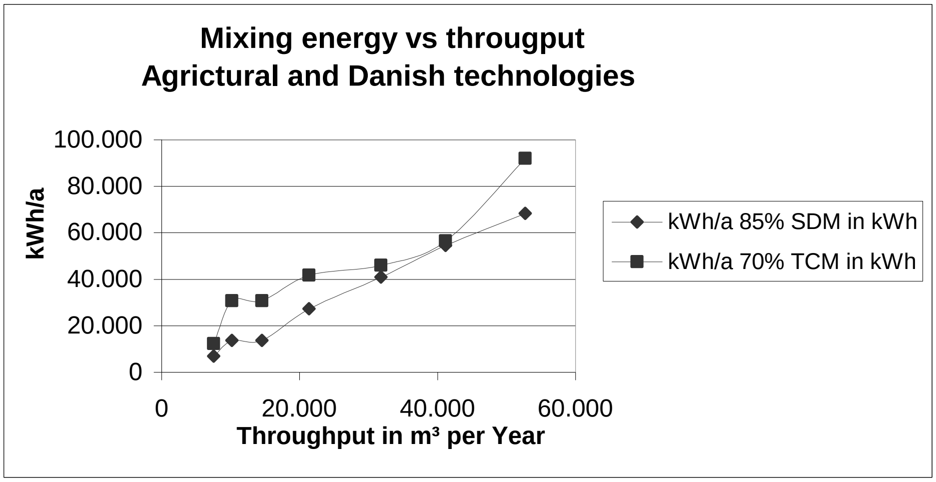

Figure 4: Mixing energy consumption comparison agricultural and Danish Fermenters

The Danish fermenters use more power than the agricultural digesters. In addition to the mixer operating continuously, they must have a pump to circulate the liquid manure through the external heat exchanger. The pumping power consumed in circulating the fermenter's contents to the heat exchanger is more than required for the agricultural fermenters. This pump power consumption, adds to the overall power disadvantage of the Danish system illustrated in figure 5 below.

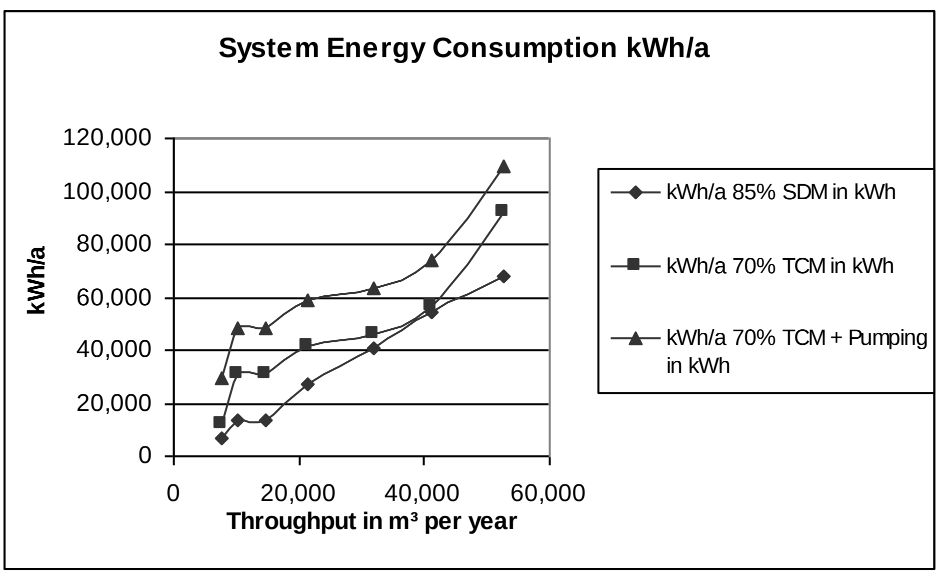

Figure. 5: System electric energy consumption comparison between agricultural and Danish fermenters

Next is a comparison of the process heat consumption between the two systems. Each has a unique approach to heating. In the Danish system the material is warmed from ambient temperatures as it enters the digester and in the agricultural system the input substrate is added to the digester and warmed within. Basically the heat consumption is identical between the two systems; the difference is the radiation heat loss from the overall systems.

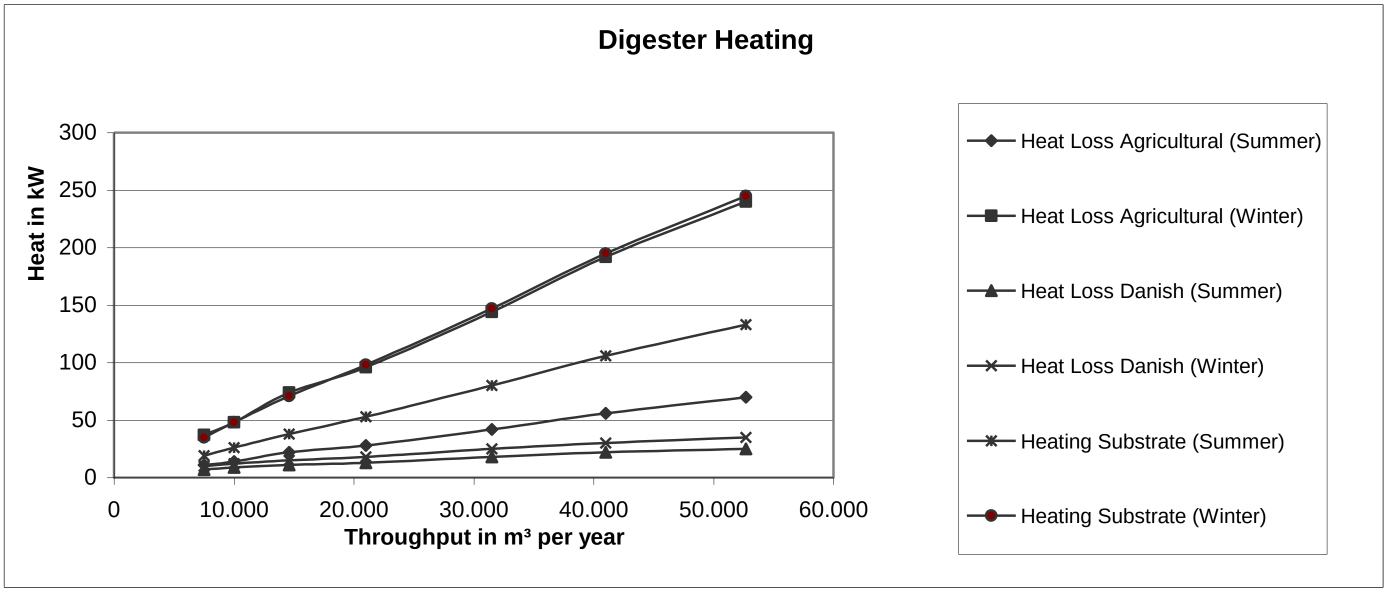

Figure 6: Warming heat requirement, summer/winter and agricultural/Danish

From figure 6 one can see clearly that more radiant heat is lost from the agricultural fermenters than those of Danish design. As these losses are mathematically directly proportional to the surface of the digester, it is obvious that they increase with a higher number of digesters and higher surface area at a given volume. Both factors are given with bigger agricultural plants. Although the real amount of heat loss advantage is dependent on the actual outside temperature at a given location, this result would recommend the use of the Danish technology for efficient heat utilization. The overall influence of this difference is difficult to measure, since in general more than enough 'waste' heat is available for either fermentation technology. For this reason heat use is not considered further in this comparison.

Independent of the energy consumptions shown above, the initial investment was considered for each type of fermenter. The fermenters listed in Table 2 and 4 above were compared on a cost basis. To create this comparison corresponding proposals were obtained for the tanks, mixers, heat exchangers, etc. The result is represented below in figure 7. It is evident that, based on initial investment, agricultural technology has the advantage below 20,000 m³/a and above this annual throughput level Danish Technology is preferred.

In addition to the higher construction and component cost the agricultural fermenter requires a more extensive automation and control technology (EMSR – SCADA). This is because it requires a more extensive piping and fittings building with a larger number of pieces (10-1) and higher power requirements of the mixers (110-15 kW)

It is important to note that the costs used above come directly from the individual components suppliers and no allowance for a general contractor has been made.

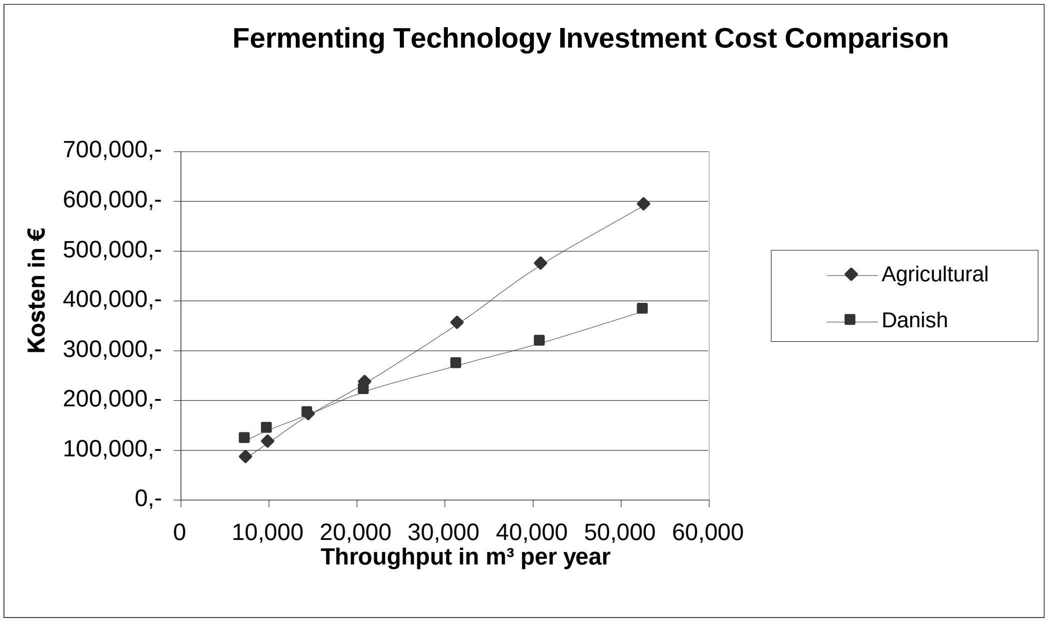

Figure 7: Investment comparison, agricultural/Danish fermenters

A direct comparison of the systems also requires comparing the operating costs, especially with respect to the electrical consumption. For comparing the ongoing operating costs the investment was divided into separate categories; the tanks, external heat exchangers and other equipment. The tanks were written off over 20 years, external heat exchanger over 12 years and other equipment over seven years. A 5% interest rate was assumed and the resulting capital values written off in a linear fashion. Planning and permitting costs were included with the investment values. The results of this are represented in figure 8

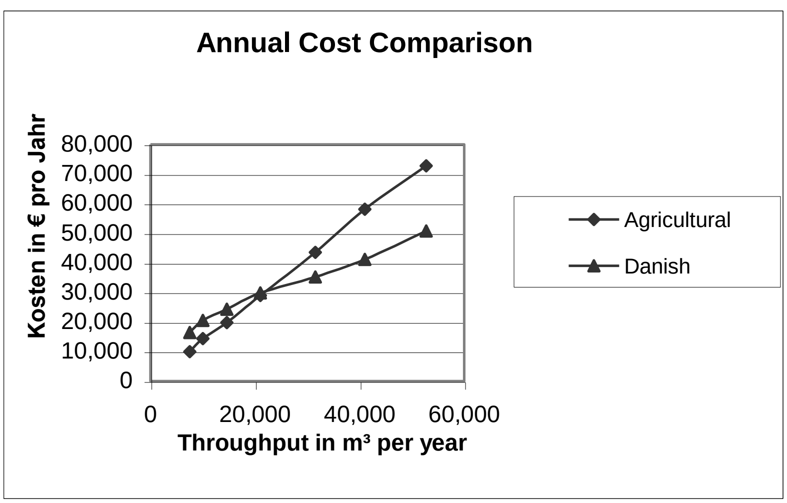

Figure 8: Annual cost comparison

Figure 8 clearly shows that the Danish technology has the advantage for throughputs over 20,000 m³ per year.

Conclusion

Considerable differences exist between the actual digesters in the field and the general model constructed above. The simple analysis in this paper cannot really consider the actual conditions and configuration of each digester. While using them would lead to different values regarding investments and operating costs for each of the cases used, it would not change the general conclusion. For the analysis carried out here between the basic agricultural and Danish technology the cross over point is approximately at 20,000 m³ throughput per year.

On the basis of this investigation relatively simple plants are recommended for throughputs under about 20,000 m³/a. At and above 20,000 m³/a one should take a close look at other process and fermenter technologies.

Therefore, "bad" biogas plant design is one that ignores the relative advantages of each technology. In practice most designers know this as there are few economical Danish fermenters with a throughput below 15,000 m³/a and same for agricultural digesters with feed rates above 25,000 m³/a.

The market for biogas plants is simply different between Germany and Denmark. This is the reason why over time different fermenting technologies developed in the two countries. It is natural that farm facilities are constructed using a simple technology. It is just as correct that large central biogas plants are built using a different approach. In this line of thinking there are really no "bad" biogas plants, however mistakes exist. This was recently reinforced in Germany when agricultural plants were constructed for large businesses. The agricultural technology was mistakenly just built larger. As a result the facility was not economic.

This conclusion depends on accepting several conditions which must be verified for each case. These optimization investigations should be dependent on the input material, the gas storage requirement, the feed rate, and the local conditions of each situation. It is reasonable to believe that biogas plants with over 25,000 m³/a, should not be constructed in the agricultural style. This is true so long as the total solids content in the mixture does not exceed 12%, or the maximum level which can be stirred by the mixers.

The investigations discussed here are limited to the two described fermentation technologies. It is recommended that a separate investigation of smaller plants with capacities below 10,000 m³/a be studied. In addition an investigation of other technologies such as plug flow, covered lagoons, and other agricultural fermenter types, is needed.

There is a significant need for research to determine optimal fermenting technologies. Other subjects to explore include retention times relative to gas production rates and how these times depend on the mixing intensity and heat addition technologies. At present, there are no publications on the technical basis of biogas plants. The value of laboratory investigations has not been given enough emphasis. In the future we will need more practical relevant data.