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Codigestion of Manure and Organic Wastes in Centralized Biogas Plants

Status and Future Trends

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Abstract

Centralized biogas plants in Denmark codigest mainly manure, together with other organic waste such as industrial organic waste, source sorted household waste, and sewage sludge. Today 22 large-scale centralized biogas plants are in operation in Denmark, and in 2001 they treated approx 1.2 million tons of manure as well as approx 300,000 of organic industrial waste. Besides the centralized biogas plants there are a large number of smaller farm-scale plants. The long-term energy plan objective is a 10-fold increase of the 1998 level of biogas production by the year 2020. This will help to achieve a target of 12–14% of the national energy consumption being provided by renewable energy by the year 2005 and 33% by the year 2030. A major part of this increase is expected to come from new centralized biogas plants. The annual potential for biogas production from biomass resources available in Denmark is estimated to be approx 30 Peta Joule (PJ). Manure comprises about 80% of this potential. Special emphasis has been paid to establishing good sanitation and pathogen reduction of the digested material, to avoid risk of spreading pathogens when applying the digested manure as fertilizer to agricultural soils.

Index Entries: Anaerobic; centralized biogas plants; codigestion; thermophilic.

Introduction

In 1985, the Danish ministries of Energy, Environment and Agriculture launched a development and demonstration program in an effort to show the potential of large-scale manure-based biogas plants as suppliers of renewable energy, a method for better utilization of manure as fertilizer and for a more flexible manure distribution among farmers. The program

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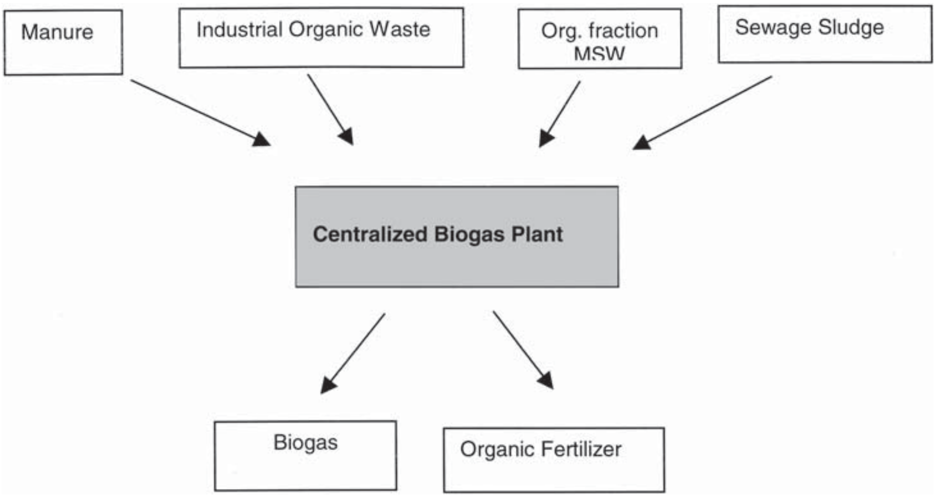

Fig. 1. Principle of codigestion in centralized biogas plants. MSW, municipal solid waste.

has included various reporting and follow-up activities, which have ensured a fruitful exchange of experience that will benefit development.

The program has since led to the construction of 22 plants of the centralized type, at present treating an annual amount of manure and other biomass of approx 1.5 million t/yr, producing a biogas equivalent of approx 39,000,000 m^3 of methane/yr. In addition to the centralized biogas plants, a large number of smaller farm biogas plants have been constructed. The farm biogas plants, however, represent only a small part of the total manure-based biogas production in Denmark. The potential amount of manure in Denmark could support a large number of new plants, and the continued growth of this sector is foreseen in the governmental planning as an important contribution to achieving a higher degree of sustainability in the energy and environmental sector.

In the centralized biogas plants, manure, mainly in the form of slurry, is transported from a number of farms to the plant, where it is codigested with other organic waste from food industries and municipalities (Fig. 1). After digestion the slurry is returned as nutritionally defined natural fertilizer, mainly to the farms that supply fresh manure, but also to farms that are engaged only in crop farming (Fig. 1).

Most of the plants are organized as cooperative companies with the farmers who deliver manure to the plants as cooperative members, a traditional type of organization in the Danish agricultural sector. Some plants (mainly connected to district heating networks of larger cities) are municipality owned and operated with farmers "attached" through a supplier group. One plant (Ribe) is organized as a share-holding company, with the farmers and a few external shareholders (both industry and institutional investors) as owners. Plants are usually financed by favorable long-term/low-interest loans based on a municipality guarantee.

The biogas produced is utilized with a high degree of efficiency. In most cases, the biogas is used for combined heat and power generation in lean-burn turbo-charged gas engines. Electricity is sold to the grid, while heat is used for district heating of towns and villages. District heating is quite common in Denmark.

Codigestion

Construction of large centralized biogas plants offers the possibility of efficient combined anaerobic treatment and utilization of livestock waste and several types of organic waste from the food-processing industry, sewage sludge, and household waste.

Organic industrial waste is usually characterized by high pollution loads and often contains high concentrations of rapidly degradable substrates such as saccharides, starches, lipids, and proteins.

Manure usually has a rather low total solids concentration (typically 5–7% total solids for pigs and 7–9% for cattle and dairy cows). In addition, manure contains a large fraction of lignocellulose, which makes up a large part of the fiber fraction in biogas reactors treating manure. This fiber fraction is highly recalcitrant to degradation and will often pass through the reactor mainly undigested. The high content of water, together with the high fraction of fibers in manure, is the reason for the low methane yields of manure, typically ranging from 10 to 20 m^3 of CH_4/t of manure treated.

However, manure is excellent as a "carrier" substrate to allow anaerobic digestion of concentrated industrial waste, which would be difficult to treat separately. The reasons for this suitability of manure to be used as "carrier" substrate are as follows:

1. The high content of water in manure acts as solvent for the more dry types of wastes, resolving problems of pumping and mechanical treatment of solid wastes.
2. The high buffering capacity contained in manure protects the process against failure owing to drop in pH in case of temporary volatile fatty acids (VFA) accumulation.
3. Manure is rich in a wide variety of nutrients necessary for optimal bacterial growth.
4. The large amount of manure treated dilutes concentrated waste and allows periodic supply of waste, which fits well into the manufacturing processes and transport logistics.

By combining different types of waste, such as manure, household solid waste, and organic industrial waste, a much higher gas yield can be obtained from biogas reactors because especially industrial wastes are more easily degraded and have a higher gas potential than manure. Since most types of industrial organic waste results in methane yields varying from 30 to 500 m^3/t, these sources constitute a very attractive substrate for biogas plants.

Economic analysis of existing biogas plants has shown that economic balance can be achieved when the average biogas yield is higher than 30 m^3 of biogas/m^3 of biomass (approx 20 m^3 of CH_4/m^3 of biomass). This biogas potential can be achieved by the addition of industrial waste with a high content of easily degradable organic matter. For evaluation of biogas production, it is necessary to know the concrete content of organic matter and its composition. The organic matter can be determined by several methods, but the most used method is measurement of volatile solids (VS), which gives the content of the organic matter. The theoretical maximum yield per gram of VS depends on the type of organic matter (see Table 1), in which a further characterization of the organic matter to its content of carbohydrates, proteins, lipids, and VFA can be necessary. Alternatively, one can estimate the biogas yield from the chemical oxygen demand (COD) measurement, in which 1 g of COD has maximum methane potential of 0.35 L of CH_4.

Table 1 lists the characteristics of a number of typical organic materials suitable for anaerobic degradation. Table 2 summarizes typical gas yields from different types of manure, organic industrial waste, sewage sludge, and household waste.

Besides increasing the yield, the addition of easily degradable material has been shown to stabilize the anaerobic digestion process if added in a controlled fashion. This effect could partly be owing to a higher active biomass concentration in the reactor, which results in better resistance against inhibitory compounds. Furthermore, the inorganic parts of some organic wastes, such as clays and iron compounds, have been shown to counteract the inhibitory effect of ammonia and sulfide, respectively.

Process, Plant Configuration, Operational Experience, and Results

Process Temperature

The first biogas plants were mesophilic plants, with a process temperature of 35–37°C and a hydraulic retention time (HRT) of 20–25 d. Thermophilic process temperatures (50–60°C) were known to be beneficial for the conversion rate but were originally feared to be more difficult to control *(1)*.

Since the conversion of one of the early plants (Vegger) to thermophilic operation, demonstrating the viability of thermophilic process temperatures, this process has gained a dominating position today. With a thermophilic process temperature, the HRT is typically reduced to approx 15 d, and the necessary veterinarian sanitation at temperatures above 50°C can be integrated into one single thermophilic methanization and sanitation process step. There are many benefits of the thermophilic anaerobic digestion process compared with the mesophilic one. These benefits are greater rates, higher sanitation effect, higher degradability of relatively recalcitrant organic matter, higher bioavailability of absorbed compounds for degradation, and higher solubility of hydrophobic compounds.

Table 1
Theoretical Methane Yields of Various Types of Organic Matter

Substrate type	Composition	COD/VS (g COD/g VS)	CH_4 yield (STP l/g VS)[b]	CH_4 yield (STP l/g COD)[b]	CH_4 (%)
Carbohydrate	$(C_6H_{10}O_5)n$	1.19	0.415	0.35	50
Protein[c]	$C_5H_7NO_2$	1.42	0.496	0.35	50
Lipids	$C_{57}H_{104}O_6$	2.90	1.014	0.35	70
Ethanol	C_2H_6O	2.09	0.730	0.35	75
Acetate	$C_2H_4O_2$	1.07	0.373	0.35	50
Propionate	$C_3H_6O_2$	1.51	0.530	0.35	58

[a]Calculations are based on the fact that all organic matter is solely converted to methane and carbon dioxide.
[b]STP is standard temperature and pressure (0°C and 1 atm).
[c]Nitrogen is converted to NH_3.

Table 2
Wastes Used in Danish Biogas Plants and Their Methane Yield *(9)*

Waste	VS (kg/t)	Methane yield (m^3/kg VS [STP])[a]	Methane yield (m^3/m^3 [STP])[a]	Ref.
Pig manure	48	0.29	13.9	*10*
Raw pig manure from				
Pigs	65	0.30	19.5	*11*
Sows	72	0.25	18.0	*11*
Pig dung	160	0.30	—	*10*
Cattle manure	64	0.21	13.4	*10*
Raw cattle manure from				
Dairy cow	89	0.20	17.8	*11*
Cattle dung	160	0.20	—	*10*
Stomach/intestinal waste				
Fra pig and cattle	150–200	0.40–0.46	—	*10*
Mixed manure				
Filskov biogas plant	75	0.32	24.0	*12*
Added straw	73	0.39	28.5	*12*
Chicken				
Manure	40	0.30	12.0	*10*
Dung	160	0.30	—	*10*
Straw				
Rye straw	855	0.36	—	*13*
Barley straw	846	0.20	—	*14*
Nonfood grain	731	0.18	—	*14*
Green barley (ensilage)	310	0.38	—	*14*
Wheat straw	873	0.15	—	*14*
Chopped straw	860	0.20–0.24	—	*11*
Nonfood grain	778	0.20	—	*14*
Hay	824	0.28	—	*14*
Industrial waste				
Flotation sludge	130–180	0.54	70–100	*10*
Concentrated sludge	150–200	0.25–0.35	50–70	*15*
Sludge	30–40	0.25–0.35	12–15	[b]
Bentonite-bound oil	400–450	0.80	320–360	[b]
Fish oil	800–850	0.60–0.80	480–680	*10*
Molasse	630	0.31	190	[b]
Vinasse	480	0.15	75	[b]
Meat and bone flour	565	0.57	325	[b]
Household waste	200–300	0.40–0.50	100–150	*10*
Source sorted	255	0.40	102	[b]
Garden waste				
Kerteminde local community	350	0.10–0.20	—	*11*

[a]STP is standard temperature and pressure (0°C and 1 atm).
[b]Unpublished results.

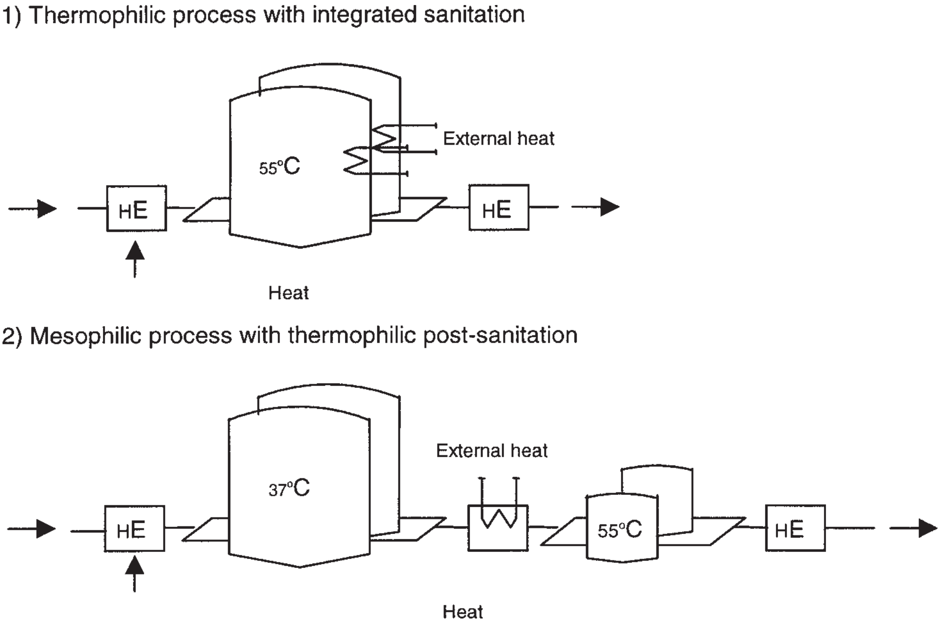

Fig. 2. Reactor configurations applied in centralized biogas plants.

The past 10–15 yr have proven that the thermophilic process is as stable as the mesophilic *(2,3)*. One reason for the negative reputation of the thermophilic process has been the problems associated with inoculation and startup; thermophilic organisms are not naturally present in high concentrations *(4)*. However, improved startup procedures, and now the opportunity to inoculate from well-established thermophilic processes, have eliminated this problem. In 2001, the first thermophilic plant based on Danish technology was started up on Hokkaido/Japan employing only a small amount of local thermophilic inoculum, generated in a laboratory while the plant was being established.

Veterinarian Aspects

When mixing and redistributing manure from several farms, it becomes important to adopt a sufficient level of sanitation, in order to prevent spreading of pathogens. The veterinarian requirements concerning manure are to ensure that the manure treated is kept at a thermophilic temperature (>50°C) for a minimum of 4 h. The required sanitation can be obtained directly in a thermophilic process by observing special pumping routines, whereas a mesophilic process requires a passive pre- or postsanitation stage (Fig. 2). A veterinarian follow-up program has documented that these requirements ensure an effective pathogen reduction, reaching a level equal to or better than 4 log units when using *Faecal Streptococcus* as an indicator organism. Certain types of supplementary waste, such as sewage sludge, require more strict sanitation. Originally, such types of waste required heating to 70°C for a minimum of 1 h.

The aforementioned veterinarian follow-up program has established a number of alternative temperature/holding time combinations to be as efficient as 70°C/h based on decay measurements of the most important animal diseases, both bacterial and virus types *(5)*.

For a thermophilic biogas process (minimum of 52°C), a guaranteed temperature/retention time of 52°C/10 h, 53.5°C/8 h or 55°C/6 h is considered equal to 70°C/h. The retention can take place in sanitation buffer tanks after the main reactor stage or directly in the reactor if pumping sequence allows the necessary pauses. For mesophilic biogas plants, slightly higher retention times are required and must take place in a separate tank (Fig. 2). Whereas inclusion of "problematic" waste in the past required a separate pretreatment step, all the biomass can now be sufficiently sanitated in a single thermophilic process, provided the longer guaranteed retention time is built into the design.

Process Tank Configuration

When applying heat exchanging, continuous feeding/pumping is often preferred in order to optimize the use of heat exchangers. In addition, to obtain the necessary guaranteed retention time for sanitation purposes, configurations with three reactors (or sanitation tanks) operated in parallel are often used. At a given time one is being fed, one emptied, and one resting, i.e., ensuring the sanitation retention time required. However, there are many alternative configurations with digesters and sanitation buffer tanks in combination with pumping routines that can be applied.

Startup Procedure

Startup of mesophilic plants has proven to be quite straightforward since manure has a natural content of the anaerobic microorganisms needed. It is possible to start up without any seeding material, although some initial seeding amount can speed up the startup procedure. Often near full load conditions can be reached within 3 mo.

For thermophilic plants, it is more necessary and efficient to obtain a suitable seeding material in a quantity as large as practical. Once this has been supplied to the plant and the temperature is reestablished, the initial filling can be loaded with approx 5% or more fresh material every day. The fed fresh material can gradually (i.e., in the course of 15 d) be regarded as activated and included in the loading calculation, thus gradually building up filling of the plant reactor(s). The level of loading can be adjusted in accordance with the concentration of organic acids in the reactor, which should not exceed approx 5–8 g/L during startup. Startup time depends on the initial amount of seed material. With a 1/6 initial seed filling, the time until full production is reached will typically last 3–5 mo.

Production Results

Figure 3 shows the average daily biogas production during the first operational period of the Thorsoe and Blaabjerg Biogas plants, two thermo-

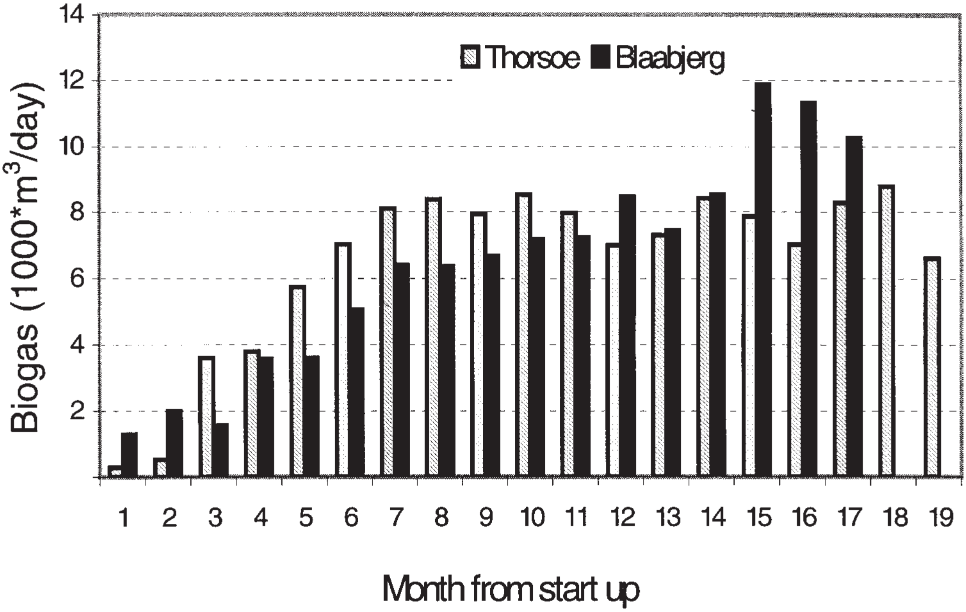

Fig. 3. Average monthly biogas production from thermophilic manure-based biogas plant: ▨, Thorsoe (1994); ■, Blaabjerg (1996).

philic plants, both with a biomass treatment capacity of 100,000 t of biomass/yr. Figure 3 illustrates the relative stability of the production, once normal operation is obtained. The sudden rise in biogas production of the Blaabjerg plant after mo 14 was due to the introduction of fish oil sludge as a cosubstrate.

Commissioning tests of these plants showed a process electricity consumption of approx 4 to 5 kWh/m^3 of biomass treated for mixing, pumping, control, and so on, and a heat consumption of 15–25 kWh/m^3 of biomass treated, including consumption for hot water and building heating. This should be compared to a biogas yield of approx 30 m^3/m^3 of biomass, corresponding to a calorific yield of approx 200 kWh; that is, only 10–15% of the energy produced is consumed in the process, and even less when organic industrial waste is used to increase biogas production.

Technical Developments

Although some technical troubles were experienced with the early plants, the practical experience over the years, combined with a relatively open exchange of experience and data among plants, companies, and research centers, has resulted in a number of important general developments that have gradually improved the technology.

Laboratory-scale experiments and the development of modeling tools *(6–8)* have improved basic process knowledge, helping to identify suitable or potentially troublesome waste types and to improve process control strategies to avoid process instability or failure. It is now standard to keep certain types of organic industrial waste in separate storage tanks with separate feed lines to be able to control the biogas process.

Improved techniques for slurry handling (such as pumping, mixing) with minimum electric consumption and service costs have also gradually been developed, centered on mixer types used for various applications and pump types/layouts minimizing handling problems. Other important developments have involved techniques to suppress and minimize odor emission through process air ventilation and treatment in compost filters or other types of odor filters and the use of a biologic oxidation process for reduction of H_2S without the use of additives other than air and buffer liquid already available at the plant. Another important area has been optimization and development of highly automated transport equipment, centered on vacuum tank trucks to minimize transportation costs.

The effect of these gradual developments can be seen in the plant statistics showing improved economical performance of the newer plants, although some level of support is still needed, mainly in the form of a "green electricity" premium.

Future Trends and Development

In the last few years only a few new plants have been established. This is mainly linked to the uncertainties related to the ongoing privatization of the electricity sector in Denmark and the European Union, creating some uncertainty regarding the future electricity price and "green energy" premium.

However, potential projects are still under consideration and research is ongoing. Once the future electricity market is in place and a satisfactory scheme for trading "green energy" is established, a second wave of centralized plants is expected, driven by tighter restrictions on manure handling and based on the technological advances of the past 10–15 yr within the biogas sector. Since the market is expected to become more competitive and government grants gradually reduce, development has focused on further improvements in plant costs and new sources of revenue.

Relatively large plants (>150,000 t/yr) or expansion of existing plants in animal-dense regions are foreseen to benefit from economy of scale. In such areas, posttreatment of the digested manure to remove excess nutrients for export/sale may also offer the opportunity for both farmers and plants to create additional revenue. Both technologies for selective recovery of certain nutrients (such as phosphorus) or complete separation into clean water/nutrient are currently being tested and developed.

Biogas in dual fuel biogas/natural gas engines (in regions covered by the national natural gas grid) is already in use in some plants and may improve utilization of the engine capacity installed, with biogas as base load fuel and natural gas as backup/top-up fuel. Recent investigations also suggest the use of serial digester coupling, with a large main digestion step and a smaller postdigestion step, as a way to slightly increase conversion efficiency of particulate/fibrous matter. This may be combined with pretreatment techniques to "open up" complex types of waste (such as energy crops), improving the biogas yield from such substrates. This may allow new types of cosubstrate to boost biogas productivity, since the traditional types of organic industrial waste are foreseen to become scarce if many new plants are established. Recently, larger trucks (trailer based) have also been introduced to further optimize transport economy, which is an important factor of centralized plants.

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