A SURVEY OF ANAEROBIC DIGESTION IN DENMARK.

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ABSTRACT

Stabilisation of organic resources requires reducing the potential for biological activity, either by reducing the content of the most readily degradable organic constituents or by reducing the water activity so that biological activity is suspended. Biological stabilisation is practised widely and many have opted for aerobic processes (composting) to convert degradable carbon to carbon dioxide. Composting is also practised in Denmark but anaerobic processes that convert this unwanted degradable carbon to useful methane that provides renewable energy are considered to have a better life-cycle cost/benefit. Centralised plants co-digest animal manure, domestic and industrial organic wastes and sewage sludge to produce biogas and nutrient rich soil improver. Biogas is burnt in combined heat and power plants; electricity is sold to the grid and heat for district heating. Digestion controls the risk of odour nuisance so the digestate can be moved from livestock production areas to arable farming areas and used at agronomic rates to substitute for mineral fertiliser. This paper will describe sites where this approach is being applied.

KEYWORDS

Anaerobic digestion, animal manure, biodegradable wastes, biogas, CHP, composting, LCA, renewable energy, source separation, sustainability, thermal hydrolysis

INTRODUCTION

Denmark has looked closely at the question of sustainable management of organic resources and concluded that anaerobic digestion has a better environmental footprint than composting for some streams [(1)]. Denmark places a high priority on substituting renewable energy for fossil energy. It is Europe's leader in deployment of windmills. When selling electricity to the gird the average price is about 0.2 DKK/kWh but for decentralised electricity generation there is a premium price (presumably because there is minimal transmission cost) of 0.33 DKK[*]/kWh. The situation in the UK is currently 1.6 p/kWh base price plus 4.7 p/kWh (Renewable Obligation Certificate, ROC). ROC is awarded even if the electricity is used on site so thus avoiding the nonsense of selling green and buying back grey. Currently 3-year contracts are paying 4 p/kWh and 10-year contracts 4.7 p/kWh for ROCs. The combined green electricity price in the UK is nearly 25% greater than in Denmark.

[*] DKK Danish Krone approximate conversion: 11.76/£ 7.43/EUR

Denmark has factored biogas from anaerobic digestion into its long-term energy strategy (Table 1). It is one of the largest exporters of meat and livestock products; this animal production generates large amounts of manure (including slurry). Careful use of this manure is essential to protect groundwater in the shallow sand aquifers and legislation and infrastructure started to be introduced during the 1980s. Avoidance of odour nuisance has arisen as another driver that has led to anaerobic digestion of manure, often in centralised co-digestion facilities that derive income from multi-waste streams. This innovative approach was the background and driver to examine the situation more closely to see what could be learned and how much was uniquely Danish and how applicable it is outside Denmark.

Edelmann et al. [(2)] compared, different processes for treating biogenic wastes in plants with a treatment capacity of 10,000 tons/year of organic household wastes. They found from measurements at compost plants that the methane emissions were greater than had been assumed and showed by LCA (Life Cycle Analysis) that AD was better than composting, incineration or a combination of digestion and composting, mainly because of AD's improved energy balance. Baldasano and Soriano [(3)] concluded AD scores much better than other options in terms of climate change and the total electrical energy produced exceeds the amount of energy used for the erection and operation of the plant. Tilche and Malaspina, [(4)] concluded that a plant treating 15,000 tons/year of organic fraction of MSW (OFMSW) by composting uses around 0.75 million kWh/year, whereas by AD the net production is approximately 2.40 million kWh/year. The exact yields depend on the quality of the OFMSW treated.

Denmark has an infrastructure that enables best use of biogas in that district heating is well established with a network of lagged pipes for distributing hot water serving most urban areas. Frequently the biogas is piped from the AD plant to the local town where there is a CHP engine that generates electricity for the grid and water for the district heating.

Two AD facilities for manure, domestic and industrial wastes, one AD for sewage sludge, domestic and industrial wastes, two sewage sludge AD with retrofitted thermal hydrolysis and one mechanical biomass extraction facility were visited and will be reported briefly.

AD FOR FARM ANIMAL MANURE

Why would farmers want to invest in AD for manure? AD has been attempted for manure since about 1980 or before but never really took hold in the UK. The latest high profile application is at Holsworthy in Devon, south-west England. The plant will use 146,000 tonnes of liquid slurry a year from 50 dairy farms. As well as generating an estimated 1.4 megawatts for the National Grid, the plant will provide hot water to heat local public buildings. Co-digestion of waste was always in the plan but when it came to it an officer at the EA ruled that ‘waste in equals waste out’ and therefore application to land falls under waste licensing. Hopefully this will be resolved.

The first obligation for Danish farmers to be able to store manure was in 1987. In 2000 the obligation became more stringent and farmers are now required to have 9 months' storage for the manure from their livestock. They are also obliged to have sufficient land on which to spread the manure from their livestock according nitrogen limits:

- Farms with <250 livestock units[*] are required to own or rent land sufficient for 50% of the manure and to have 3 year contracts with people who control land sufficient for the remaining 50%.
- Farms with >250 livestock units are required to own or rent land sufficient for 65% of the manure and to have 5-year contracts with people who control land sufficient for the remaining 35%.

No spreading is permitted between harvest and 1st February, neither is spreading on frozen ground. Farmers are obliged to have at least 65% of their land in green crop through winter. Farmers are limited on the amount of N from organic sources because the whole country has been designated a "nitrate vulnerable zone". Farmers are also required to have a fertiliser plan that is compatible with their IACS returns[†]. If farmers exceed the recommended nitrogen use they pay a tax. In this fertiliser plan the total N in pig manure is counted as being 60% available, cattle manure 55% and composted waste 10%. So if a farmer applies pig manure at $170kgN_{total}/ha$, it counts as 102kgN/ha from the total fertiliser recommendation for the crop. Soon the figures for pig and cattle manure will be raised to 65% and 60% respectively. Anaerobic digestion makes the manure N more available and therefore the 102kgN/ha allowance is more nearly equivalent to fertiliser-N. By comparison the UK fertiliser advice is that the N in cattle slurry is 33% available and the N in solid pig farmyard manure is only 10% available. Thus it can be seen that farmers gain a real cereal yield advantage from having their animal manure digested. The main season for applying liquid digestate is April and May when it is used as a top-dressing on winter wheat. As in the UK the number of active farmers is decreasing as farming operations consolidate through land-purchase and rental and contractual agreements.

In summary, farmers have the manure storage infrastructure that enables storage until the time when the nutrients can be used to maximum value. There is also a financial incentive to digest because it enhances the crop yield resulting from manure. Digestion reduces the risk that they will create odour complaints when they spread manure. The biogas plants operate a tankering service, free of charge to farmers, that collects raw manure and returns digestate (i.e. tankers run full both ways). Manure digestion yields about $20Nm^3/t$ biogas, which just about balances the cost of tankering but it doesn't repay the capital investment. A benefit to the AD plant is that effectively the farmers provide the sales and marketing function for the digestate.

[*] A "livestock unit" means 1 bovine or soliped, 3 swine or 7 sheep or goats
[†] Integrated Administration and Control System – for administering payments under the Common Agricultural Policy

Animal welfare is less of a concern in Denmark than in the UK and therefore animals are not usually bedded on straw. However where there is straw bedding it is a problem for the AD plants and when it becomes more common some form of straw fragmentation will be essential.

AD FOR WASTES

Industrial wastes

The market for treating industrial wastes has become quite sophisticated and competitive. Gate fees are not linked to the cost of landfill or to incineration; they are related to the biogas potential. Thus plants will actually pay for clean wastes with the highest biogas potential and charge for wastes with low yield or with added costs of removing physical contaminants. Stomach content from abattoirs is charged at 60 DKK /t (£5) flotation sludge for food industries at 100 DKK /t (£8) and source-separated domestic waste at 250 DKK (£20). These prices appear very modest by comparison with charges in other countries. Waste was being delivered from Germany, Sweden, Belgium and other countries.

Municipal Waste

The OFMSW (excluding garden waste) has a high moisture content (60-75%) and despite the best endeavours there is often more physical debris in source separated household waste than is acceptable in useful compost. Denmark has a large existing infrastructure of municipal waste incineration capacity such that 95% can be burnt. Apparently incinerators have been around for so long that the public accepts them and emissions are not a matter of concern. However incineration is taxed at 330 DKK /t where there is CHP (combined heat and power) and 380 DKK /t where there is no energy recovery (respectively £28 and £32/t). Even the high moisture content organic fraction has a small positive net energy contribution. However when it is removed to a biogas facility, the net energy from incinerating the residual fraction plus the net energy from the biogas is much greater than when whole waste is incinerated, also the tax burden has been reduced. This is a double win. However as will be seen the Danish experience, which is also being admitted by others, is that there is an unacceptably large amount of physical contamination in source separated domestic waste.

SITE REPORTS

Aarlborg

Aarlborg started as a farmer co-operative and is still operated by part-time farmers. The plant is telemetered and can be controlled from operators' homes. The plant has 2 glass-lined steel $800m^3$ thermophilic anaerobic digesters. Retention was said to be 11 days but it was also said that the combined input was $170m^3/d$ which suggests that the digesters were only fed 6 days per week. The primary digesters are mixed with slow-speed 3.5kW paddle mixers; the height of the paddle in the digester was said to be critical to preventing sedimentation. The primary digesters are fed 6-times per day on a remove then fill basis. The digesters run at pH 8 and 500mgVFA/l.

Hot digestate is transferred to a 9000m^3 concrete secondary digester with a fabric cover said to give an HRT of 50-60 days. The secondary is stirred with four 17kw submersible mixers. The temperature in the primary digesters was 52-53ºC and in the secondary 40ºC. The biogas yield was 50% from the primary and 50% from the secondary. A small amount of air was bled into the headspace of the secondary digester to support aerobic bacteria that converted H_2S to sulphate.

Biogas is typically 65% methane; it is used for on-site CHP using a 500kW Jenbacher set and also piped 2km to the local village where there is 2MW CHP capability. The on-site engine has run for 20,000 hours without problem. Total biogas production is about 17000m^3/d equivalent to about 1.5 MW electricity production.

The plant receives 125m^3/d manure by road tanker (50% pig slurry: 50% cow slurry) at about 8%DS. Source separated waste is received from 2500 households and supermarkets. This amounts to 20m^3/d with a weight of 5 tonnes. The waste is delivered to a hopper in the bottom of which there are two horizontal augers that open bags and reduce the particle size of the material so that it can be elevated from the hopper by a screw auger. This delivers the material to a pressure screen developed on the site. It is similar in principle to a StrainPress but develops 110 bar which is considerably greater pressure. The split of pulp to trash was 70:30. 1 tonne of household and supermarket waste yields 150m^3 biogas i.e. the domestic waste accounts for only about 5% of the gas produced. It is interesting to note that on average each household yields about 250kWh of green electricity from OFMSW per year. This compares with about 75-100kWh per year per household (3-4 people) from digestion of sewage sludge.

Liquid industrial wastes are discharged to a stirred 1000m^3 below-ground tank. There is a wide range of wastes, examples include 7000t/y from a chicken processing plant, restaurant waste (which is 30% fat and yields 300m^3 biogas/t) bentonite from cleaning oils (both edible and mineral) which also has a high gas yield, shampoo and alcohol waste. It had been found that wastes that “texts books say” will poison digesters (alcohol, high ammonia, etc.) can be digested provided that the population of organisms has time to acclimate. However an acclimated population can then take time to acclimate to a heterogeneous feed. Fortunately the bugs have not read the books.

Herning

Herning operates 2 manure biogas co-digestion plants and was one of the pioneers. Its experience was seminal for Denmark and has been an influence in EU policy. The first plant (Sinding, built 1988) was the model for the second (Studsgard, built 1996). The design was that source-separated municipal waste would be suspended in slurry, sanitised at 70ºC for 4h digested (53ºC) and that physical contaminants would be removed post-digestion. Both plants have recently discontinued treating source-separated OFMSW because of plastic accumulation in the digesters. At Studsgard 1200m^3 plastic accumulated in one 3000m^3 digester between the start of operations in 1996 and 2002 when it was emptied - about 35,000t OFMSW had been treated. Digester feed averages 7-8%DS, manure is 5%DS and the wastes vary between 10% and 50%DS, with an average to about 30%DS. Digesters run at about 53ºC, pH8 and 800VFA. They are mixed using slow-speed paddle mixers. Biogas is captured off all of the tanks but 95% of it comes from the primary digesters.

It was estimated that 18-23% of the total biogas energy is used for pumping and heating. The equivalent of 10kWh/t is used for transport (bought in diesel) and 0.5kWh/t is used for pumping. Examples of biogas yield are manure 20Nm^3/t, oil 1100Nm^3/t and bleach clay 500Nm^3/t. The overall average production is 1150Nm^3/h at 68-69% methane and 1500ppm H_2S. The H_2S is removed in a packed tower of polystyrene supporting bacteria. If overall 130k t/y are treated to yield 10M Nm^{3}biogas/y at 68.5%CH_4 with a gross energy of 10kWh/Nm^3CH_4 this equates to 530kWh/t waste treated. At 35% generating efficiency this yields 180kWh electricity per tonne waste treated. It is double expectations at planning.

Grindsted

This is a municipal wastewater treatment works. It serves 70k p.e. (10k people and a 35k pig abattoir). The sewage is dilute – the total flow is 10k m^3/d of which infiltration is estimated at 6k m^3 – sewer refurbishment is planned. The sewer network is long and flat; 15% loss of carbon in the sewers is estimated. It treats 5k t/y grease and oils at 100 DKK /t; off spec. product from a large food additives factory that employs 1000 people at 200 DKK /t and 1300 t/y source separated domestic waste at 800 DKK /t. It also treats 500t vegetable packing waste but this will cease because it is too random and unpredictable The source separated domestic waste is collected from households on alternate weeks in 9 litre paper sacks; the waste is about 32%DS. The bags comprise 10% of the weight of the waste. The authority landfills 2700t residual waste per year. The participating population is about 16k; they are issued with 48 bags per 3 months. 1k people are outside the scheme. People take their greenwaste to the landfill site where it is composted.

The plant is fully automated. All tanks and conveyors are under negative pressure and the air is vented through a humidified mineral-wool biofilter at 1cm/sec. It removes 75% of NH_3 and H_2S; the odour at the nearest property (500m from the boundary) does not exceed 3.3 odour units.

The works has primary settlement and surface-aerated activated sludge.

The waste tipping/reception area is elevated in order that waste passes through the bag-opening and size reduction by gravity. After the paper sacks are opened and contents loosened, the waste passes a magnetic separator it is sheared to 15mm. Liquid sludge and solid waste are combined in the ratio 9:0.9 by weight; the mixture at 4.3-4.5%DS is fed to one of two pasteurisers at 71ºC. The temperature of the exit sludge is dropped to 40ºC before feeding the 2800m^3 MAD digester at 140 m^3/d (23.3d

HRT) its contents is 2.3%DS. The digester produces 2200m^3 biogas per day; it is stored in a 500m^3 gasholder. The sludge is screened after digestion to produce approx. 2m^3 screenings per week.

The design concept was that plastic and other light contras would remain in suspension through pasteurisation and digestion and that the digestion process would release organic matter from the contras. However it has been found that contras stick to the inside of the overflow weir at the top of the digester and a floating mat builds out from this accreted "tide-mark" layer. Currently the digester is being opened every 14 days to scrape off and remove this accumulation! Whilst this is proving operationally very unsatisfactory it has not yet been possible to find an effective alternative.

Digested sludge is dewatered using a belt press to produce 3600m^3/y cake at 23-24%DS. It is pumped using a Mono pump to a storage shed with open ventilation that has 5700 m^3 (1½ year) storage capacity. The pump was installed in 1996 and the stator was not replaced until 2002, it develops 19 bar pressure, pumping removed the cake's structure. The smell in the shed was acceptable. Cake use on farmland is restricted to 30kgP/ha/y averaged over 3 years. The spread rate is 13t/ha. Farmers are paid 59 DKK /t to receive cake; delivery and spreading costs 75 DKK /t making a total of 134 DKK /t, which is considerably, less than incineration or landfilling.

Currently the annual income and the annual expenditure are equal at 22 DKK million, which means that the debt for construction of the plant is not being reduced.

Fredericia

Fredericia is a most unusual situation, if not unique. It is a great demonstration of the ability to retrofit thermal hydrolysis into an existing anaerobic digestion facility and the value that it can have even in the most demanding of situations,

The wastewater treatment works serves a residential population of about 90k and a combined population equivalent peak load of about 350k p.e. The non-domestic input comprises wastewater from a fertiliser factory, dairies, breweries, refineries for both mineral and edible oils and food industries. The sewerage is combined foul and surface water, and there is infiltration. Sludge treatment is designed for 8000tDS/y; currently 5000tDS/y / 5000tCOD/y are being treated. The standards required of the effluent are 15mgBOD$_5$/l; l.8mgN$_{tot}$/l; 1.5mgP$_{tot}$/l and 30mgSS/l.

The fertiliser factory produces ammonium nitrate. In order to remove the nitrate from the wastewater the first stage after grit and screenings removal is an anoxic carrousel in which nitrate is denitrified, this adds to the production of aerobic biomass. It is followed by settlement, bio-P removal, diffuse bubble aeration and denitrification, chemical P removal if necessary and final settlement/clarification tanks. The recovered water (effluent) is discharged at sea through a 700m outfall.

The wastewater (and hence the sludge) has a high chloride content (8000mgCl/l) as a consequence of treating wastewater from a refinery that processes North Sea oil. In order to resist this the Cambi thermal hydrolysis plant has been manufactured in high-grade duplex stainless steel

Originally only the sludge from the anoxic primary stage was digested; it was then dewatered using a high performance belt press. The sludge from the secondary treatment stage was dewatered raw using a plate and frame press because was so resistant to digestion. Both cakes were disposed to landfill at a cost of 1000 DKK /t; one was sloppy and the other was smelly, neither was suitable for beneficial use. Since retrofitting thermal hydrolysis all of the sludge is digested and the cake is delivered to a site where it is co-composted with greenwaste. The composter values the cake for its nutrient content and for its moisture which both accelerate the composting. The composter requires that the cake does not exceed 30%DS. Farmers are paid to collect and apply the compost. The total cost to the works for cake removal has reduced to 200-250 DKK /t. Thermal hydrolysis has meant that there is greater solids destruction in the mesophilic anaerobic digesters and that the resulting digestate dewaters better than previously, so not only does it cost less per m^3, there are also fewer m^3. From the data provided it appears that the quantity of cake produced is now only 57% of the former volume, biogas production has doubled, and there has been an annual saving of about 20 DKK million (£1.7 million) for cake removal (Table 1).

Thermal hydrolysis was retrofitted into the space between the digesters and the services building as a turnkey contract that cost £2 million. There are houses only 50m from this part of the works; they are separated from the works by a narrow belt of trees. Avoidance of odour nuisance was paramount.

The sludges are combined and thickened to 18%DS using a centrifuge. It is hydrolysed in one of the two $12m^3$ reactors, at 160ºC for ½-hour. The solids content of the hydrolysed sludge is less than that of the thickened feed sludge because of dilution with condensed steam and solubilisation of organic matter. A sludge-cooler heat-exchanger drops the temperature of the hydrolysed sludge to 40ºC in summer and 45ºC in winter for feeding the two mesophilic digesters alternately, ½-hour each. They are $2000m^3$ each with conical bottoms and operate at 39.5ºC. Heat is recovered within the process. 50% of the biogas is used for steam raising, digester heating, etc.; the other 50% is used for CHP. Foaming has never been a problem at this digestion site. Retrofitting thermal hydrolysis has had the effect of raising the pH in the digesters from 6.5 and 7.5, which has reduced the H_2S content of the biogas to such an extent that whereas the oil in the CHP engine used to be changed 2-weekly, this has now extended to 6-monthly.

There is a small amount of waste gas/steam from the thermal hydrolysis; this is laden with odorous compounds and is treated by being fed into the digesters where some of the odorants are degraded and others are burnt with the biogas in the steam boiler or the CHP engine. There was no hint of offensive odour on the works.

Næstved

Næstved wastewater treatment works was designed for 89,000 population-equivalent; it only operates at about ½ that capacity. It was commissioned in 1992 with primary settlement/clarification followed by surface aerated secondary treatment and iron dosing for P-removal. Primary sludge was anaerobically digested (1600m³ MAD digester) and dewatered, the secondary sludge was dewatered separately. The cakes were combined and used on farmland. Elements of the works have been rebuilt 3 times to improve environmental compliance and reduce environmental taxes. It operates 24/7 but is only attended 8/5 (h/day: days/week). The works is fully monitored and telemetered to an on-site control room. During the unattended hours the control room dials out alarms to the duty person's mobile phone which is linked to a laptop and from this the status of alarms can be assessed to see whether remote control is appropriate or whether it is necessary to go to the plant.

The re-builds eliminated primary settlement/clarification and flow now passes through anaerobic, anoxic and aerobic treatment for biological removal of N, P, xenobiotics (LAS and NPE degrade more than DEHP or PAH) and COD. Bio-P removal can still be supplemented by chemical precipitation of P as necessary but the amount of chemical dosing has reduced and the effluent quality has improved compared with the original operation. This meant that there was only one sludge stream but it was dilute so one of the belt presses was converted to thickening prior to digestion, by removing one of the belts and merely using the free-draining area. The second belt-press was kept for final dewatering. However the digestibility of the sludge was very low (29% of VS destroyed), it contained filamentous organisms and the digestate was difficult to dewater (18%DS cake). Solving the reduction of the tax burden and compliance created another problem - intractable sludge.

Næstved was the first thermal hydrolysis installation in Denmark. The plant was commissioned in May 2000. It was supplied as a turnkey contract that cost £1 million including linkage into the central control system. The total construction time was about 1 year. It is a single reactor (12m³) facility. The thermal hydrolysis sequence is similar to Fredericia. The performance of the thickening belt was increased by reinstating the second belt such that 18%DS sludge is fed to the pulper tank. Digestibility has increased to 50% VS destroyed. The final cake solids averaged 28.6%DS in 2001 (Table 3) though it was reported that 42% has been achieved recently. The cake on the stockpile area was friable, low odour and stacked to a high angle of repose. The digested cake is popular with farmers.

Holbæk

The purpose of visiting this site was to see an operational-scale development-plant (called Dewaster®) for separating the digestible fraction from domestic waste that had been only poorly separated at source. The site is adjacent to a landfill it also practises greenwaste composting by open windrows turned with a loading shovel, which appeared to be working very well, and has a housed in-vessel composting system that was intended for source separated OFMSW. However the latter has been abandoned because even with source separation the content of contaminants (mainly plastic) in the screened compost was excessive for use on land and the compost was being landfilled. It comprised under-floor-ventilated tunnels with temperature probes and irrigation. Residence time through this plug-flow system was about 3 weeks. The treated material was matured in windrows outside. The tunnels are located in a steel-framed building that shows the importance of having adequate corrosion protection - the steel was severely rusted. The difficulties of the site were reported in the local newspaper and when members of the public learnt that the compost was being landfilled they took even less care with source separation.

The Dewaster® system was developed by NLM Combineering (it “inspired” the equipment at Aårlborg). To test its efficiency an analysis of the input waste was made by careful hand sorting and compared with the fractions extracted by Dewaster®. Hand sorting showed 50% of the waste was biodegradable, Dewaster® achieved 45-48% extraction of the same fraction as a pulp from the same input waste. This is a very impressive achievement and two of the striking examples of the “gentleness” of the process were that batteries were removed undamaged at the magnetic separator and wine bottle corks came through unscathed and ended up in the rejects bin. It can be seen from Table 4 and Table 5 that the composition of the incoming waste varies considerably, but the quality of the biomass pulp appears to be very consistent.

The Dewaster® itself works on the same principle as a StrainPress but at greater pressure. The central screw conveyer is heavy-duty hard-faced steel and the outer shell forms a slotted screen with the slots parallel to the axis of the conveyer. The pulp is about 28%DS and is pumped to a demountable tank for delivery to a biogas plant. However at 28% it sticks in the tank and it is therefore diluted to about 20%DS in order that it can be tipped from the tank. The gas yield from the pulp delivered to the biogas plant is about 200Nm^3/t at 70%CH_4. The pulp appeared to be a smooth paste; there was no visible plastic or other physical contamination.

The reject appears very dry; it contains plastic, paper, fibres and other materials. It has a high calorific value and is suitable for incineration with heat recovery.

The energy used in the process averages 13.86kWh/t feed. The gas yield from the pulp delivered to the biogas plant is about 200Nm^3/t at 70%CH_4. The average pulp yield was 71% of the feed (Table 5), therefore the biogas yield was approximately 140Nm^3/t feed. Assuming 10kWh/Nm^3CH_4 and 70%CH_4 this represents a gross energy yield of 980kWh/t feed, which at 35% generating efficiency would be 343kWh electricity/t feed. The process only uses about than 4% of the electricity generated.

Overall the Dewaster® appears a very impressive answer for biodegradable waste that contains physical contaminants. It gives the opportunity for significant generation of non-fossil electricity and conserves plant nutrients in a digestate that can be used as a soil improver that is free from physical contaminants.

CONCLUSION

The initial objectives were to assess whether the applicability of anaerobic digestion for Denmark is because of some particular national factors and to learn from Danish experience. Denmark has a highly developed set of fiscal measures to encourage developments in line with environmental policies. However prices overall did not appear to be too much different from those in the UK. Gate fees for receiving wastes appeared to be much less than the market rates in other countries, and this was evidenced by wastes being sucked in from Germany, Netherlands, etc. The base price for selling electricity in the UK is 1.6p/kWh plus 4.7p/kWh "green premium" (Renewable Obligation Certificate ROC), which is about 25% more than the selling price seen in Denmark (2.8p plus 2.3p). However it is also possible to recover the value of the low-grade heat from the CHP engines by virtue of the district-heating infrastructure in Denmark.

Digestion of farm animal slurry and manure was a marginal activity and income from biogas balanced the operating cost but did not contribute to repaying the capital. It was assisted by the obligation for manure storage, the restricted application window, the calculation of fertiliser allowances and potential tax. When animal welfare demands dictate that housing animals on concrete is unacceptable straw could become a problem, but doubtless a solution will be engineered.

Capturing biogas from all of the digestate tanks appeared to be standard practice, in one case it made a 50% contribution of biogas and it reduced greenhouse gas emissions. Relatively inexpensive fabric structures were used for storage tanks.

In general the sites were highly telemetered, alarms were phoned out and could be assessed by remote computers, that could be used to apply corrective action if appropriate. The sites where Cambi thermal hydrolysis had been retrofitted showed its cost effectiveness and reliability. They also showed that it can be fitted into restricted areas and that odour and liquor loads were not problems.

The fallacy of relying on source separation[5] of the biodegradable fraction of municipal waste to control physical contaminants was demonstrated repeatedly. Even with source separation the treatment process must be engineered to cope with physical contaminants, especially plastic film. If this level of contamination in source-separated waste is inevitable is it really worth doing, or is the Dewaster® a more sensible alternative? This gives the minimum inconvenience to the public, gives good diversion of biowaste, and produces useful digestate and biogas rather than dirty compost that is only fit for landfilling.

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TABLES

Table 1 Potential energy from biogas in Denmark, production in 2000 and plan for 2030

	Estimated Potential PJ	Production in 2000 PJ	Danish energy plan 2030 PJ
Animal manure	24.0	0.56	14.0
Sewage sludge	4.0	0.86	1.5
Industrial waste, Danish	2.5	0.56	1.5
Industrial waste, imported		0.35	0.0
Organic household waste	2.5	0.01	2.0
Garden waste	1.0	0.00	0.8
Landfill gas	1.0	0.58	0.2
	35.0	2.91	20.0

Table 2 Comparison of performance indicators before and after retrofitting thermal hydrolysis (TH) at Fredericia

		Before thermal hydrolysis			With TH
		1° stage	2° stage	Total	Combined
Sludge production	tDS/y	4,423	3,322	7,745	7,745
	tCOD/y	6,237	3,654	9,891	9,891
Sludge feed to digestion	DS	4%			9%
	m3/d	303	0		236
HRT in MAD @2x2000m3	days	13			17
After digestion and dewatering					
Dewatered digestate	tDS/y	2,378	3,213	5,591	3,994
	DS	21%	27%	24%	30%
	tCOD/y	3,353	3,534	6,887	3,723
COD removed	tCOD/y	2,884	120	3,004	6,168
	%	46%	3%	30%	62%
Cake	m^3	11,324	11,902	23,226	13,313
Biogas	Nm^3/y	1,560,740	0	1,560,740	3,188,528
Methane		64.6%			63.0%
	Nm^3/y	1,008,238	0	1,008,238	2,008,666
Biogas per tCOD destroyed	$Nm^3/tCOD$	541.2			516.9
Unit cost of cake removal	DKK			1000	250
Annual cost of cake removal	DKK			23,226,000	3,328,250
				£2,019,700	£289,400
Annual saving on cake removal	DKK				19,897,750
					£1,730,200

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Table 3 Biosolids from Fredericia and Næstved applied to agricultural land in 2001

	Fredericia		Næstved			
DS	30.2%		28.6%			
N	4.18%		3.20%			
P	6.40%		4.97%			
K	1.70%				Danish limits from 1/7/00	
	mg/kgDS	mg/kgP	mg/kgDS	mg/kgP	mg/kgDS	mg/kgP
Cd	0.72	11.3	0.50	10	0.8	100
Hg	0.49	7.7	1.49	30	0.8	200
Pb	23	359.4	115	2314	120	10000
Ni	11	171.9	31	624	30	2500
Cr	26		33		100	
Zn	360		2700		4000	
Cu	290		415		1000	
Note: PTEs were extracted using the Nordic nitric acid method (not aqua regia)						
LAS	150		<50		1300	
DEHP	23		23.02		50	
NPE	3.2		4.46		30	
PAH	1.2		1.42		3	

Table 4 Analyses of samples of biomass pulp

	Biomass 1	Biomass 2	Biomass 3	Biomass average	Limits (DK)
DM [%]	27.8	27.5	27.9	27.7	
Loss in ignition [%]	80.6	78.5	78.1	79.1	
COD mg/kg DM	310,000	273,000	305,000	296,000	
N, total mg/kg DM	23,000	23,000	21,000	22,333	
P, total mg/kg DM	3,060	3,130	3,210	3,133	
NPE mg/kg DM	2.1	2.4	2.4	2.3	10
DEHP mg/kg DM	12.0	9.5	13.0	11.5	50

Table 5 Operating statistics for the Dewaster® plant at Holbæk

	Operating capacity t/h	Feed	Reject	Biomass	Biomass
		tonnes/month			%
Nov'01	1,52	140	34	106	71
Dec'01	2,13	130	57	73	56
Jan'02	1,95	330	109	221	67
Feb'02	2,00	170	49	121	71
Mar'02	1,40	80	14	66	82
Apr'02	1,69	200	44	156	78
May'02	1,69	180	63	137	76
Average	1.78				71

FIGURES

Figure 1 Co-digestion facilities in Denmark and sites studied (diamonds)