Programme Area: Bioenergy

Project: Energy From Waste

Title: AEA – Anaerobic Digestion Technology Landscape Review

Abstract:

This document is Appendix B2 (of 3) of the Energy from Waste UK Benefits Case (Deliverable 2 of 2 in Work Package 4).The ETI commissioned AEA to provide an up-to-date assessment of current development and demonstration activities in EfW technologies, including both Advanced Thermal Treatment (ATT) and Anaerobic Digestion (AD) technologies. This document is the review of Anaerobic Digestion technologies.

Context:

The Energy from Waste project was instrumental in identifying the potential near-term value of demonstrating integrated advanced thermal (gasification) systems for energy from waste at the community scale. Coupled with our analysis of the wider energy system, which identified gasification of wastes and biomass as a scenario-resilient technology, the ETI decided to commission the Waste Gasification Demonstration project. Phase 1 of the Waste Gasification project commissioned three companies to produce FEED Studies and business plans for a waste gasification with gas clean up to power plant. The ETI is taking forward one of these designs to the demonstration stage - investing in a 1.5MWe plant near Wednesbury. More information on the project is available on the ETI website. The ETI is publishing the outputs from the Energy from Waste projects as background to the Waste Gasification project. However, these reports were written in 2011 and shouldn't be interpreted as the latest view of the energy from waste sector. Readers are encouraged to review the more recent insight papers published by the ETI, available here: http://www.eti.co.uk/insights

A world leading energy and climate change consultancy

Energy from Waste Technology Landscape Review

Anaerobic Digestion

A Report for the Energy Technologies Institute

AEA in Confidence
ED45634.020/AD/FR01
Date 15/07/2011

Title

Energy from Waste Technology Landscape Review
Anaerobic Digestion

Customer

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1. Introduction and Methodology

1.1 Project Context and Scope

This review is part of a wider Energy from Waste (EfW) project, in which the Energy Technologies Institute (ETI[1]) is seeking to examine the technology development and demonstration needs required to allow a wide range of wastes to be used for energy production purposes. This Flexible Research Project (FRP) is currently being delivered by a Caterpillar-led consortium that includes Cranfield University, The Centre for Process Innovation (CPI), EDF Energy and Shanks Waste Solutions. Hereafter, the commissioner of this report is referred to as the Consortium.

1.2 Purpose and Structure of This Review

The Consortium's requirement for this project was an up-to-date assessment of current development and demonstration activities in EfW technologies, with reference to NASA's Technology Readiness Level scheme (see Section 1.3), which assigns a score from 1-9 to reflect the maturity of each technology.

The full scope of the project included reviews of both Advanced Thermal Treatment (ATT) and Anaerobic Digestion (AD) technologies. During the course of the project, it became clear that these two groups of technologies are at quite different levels of development, and that their reviews should accordingly focus on different aspects. For that reason, it was decided to write two parallel reports – one each on ATT and AD – and an overarching summary report pulling together conclusions and findings from the two technologies. Accordingly, this report focuses on AD technologies.

Through discussions between the Consortium and AEA, it emerged that the key requirements for the review were:

+ to create a "long-list" of all major "enterprises" (including companies, suppliers, distributors, technology providers, research institutes and universities) involved in EfW technology;
+ to determine criteria that could be applied to the "long-list", in order to obtain a short-list of about 20 enterprises to review in detail;
+ to make good use of AEA's extensive body of public and private resources (including project reviews, journals, papers, conferences, reports, site visits and supplier publications) in assessing the individual enterprises;
+ to assess the current TRLs of the key unit operations that constitute the enterprises; and
+ to conclude from the information provided the key opportunities and threats associated with AD as an EfW technology.

To deliver these outcomes, the rest of the document is structured as follows:

+ the rest of this section provides more detail on the information sources AEA used to support the analysis, and explains the short-listing process;
+ Section 2 presents a review of the key technological options for AD;
+ Section 3 presents learnings from existing plants, whether successful or not;
+ Section 4 presents AEA's review of future technologies; and
+ Section 5 draws conclusions from the review performed.

1.3 The Technology Readiness Level scheme

Technology Readiness Levels (TRLs) were developed by NASA, and the original definitions only included seven levels, though this was later expanded to nine levels. As might be expected, the NASA definitions have a clear bias to space technology, so Table 1 below presents the definitions that AEA used for this study.

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[1] http://www.energytechnologies.co.uk/Home.aspx

Table 1: AEA's Technology Readiness Level Definitions

Phase	TRL	Description
I	1	Basic principles observed and reported
	2	Technology concept and/or application formulated
	3	Analytical and experimental critical function and/or proof of concept
II	4	Component validation in laboratory environment
	5	Component validation in industry environment
	6	Subsystem model or prototype demonstrated in industry environment
III	7	Full system prototype demonstrated in industry environment
	8	Actual system qualified through test and demonstration in industry
	9	Actual system proven through successful operation

1.4 AEA's Body of Evidence

AEA is the UK's leading provider of technical environmental advice and support to UK Government, and is a trusted advisor to local government and the private sector. We have been operating in the UK, Europe, US and China for over 40 years and employ over 1,000 staff, many of whom are world-leading experts in their fields. AEA was voted Number One Consultancy for Climate Change and Renewables by our peers in the prestigious Edie Awards in 2006, 2007, 2008 and 2009.

AEA has worked on technology development, procurement, evaluation and delivery in both the thermal and biological areas for over 30 years, supporting developers, financiers, users and their contractors in designing solutions for waste treatment. We have assisted Government Agencies in evaluating new technology delivery, and in reviewing technology development and providing technical support to grant programmes designed to support technology advances.

Our team's technical and process technology expertise is underpinned by a thorough understanding of both the energy and waste markets, and associated data (e.g. feedstock availability and characteristics). Our market knowledge of new technology development was critical to the successful delivery of this assignment, enabling us to cut through the marketing literature on each technology and focus on their strengths and weaknesses, in order to short-list appropriate technologies on a robust evidence base. We know many of the technology providers and are in touch with numerous technology start-up companies and universities, having undertaken similar research assignments for several clients in the last two years. This insight has ensured that our scores and commentary are based on real evidence and visibility of the operations in question and not on the promotional literature available on the web.

That said, however, much of our work in the recent past has been on confidential studies, on topics such as feedstocks, technology options and process efficiencies for private sector clients including Hills, Shanks, Biossence, and Dairy UK. In addition, some of our on-going work for the International Energy Authority (IEA), DECC, Defra and WRAP is currently confidential. Although these studies are not publically available and so cannot be presented within this report, we have taken the lessons learned and the perspectives of the key technical staff who have worked on these projects to inform our technology appraisals. To give an idea of the extent of this body of evidence, the electronic "research" library within our system folder for this project contains almost 300 files, including reports, case studies and presentations.

Some examples of recent projects that have been utilised to inform our position on specific technologies include:

+ **Implementation of Anaerobic Digestion:** Multi-criteria optimisation for Defra (current). Development of a decision-making tool to identify the optimal type, scale and locations of AD plants in England and Wales.
+ **Monitoring of Anaerobic Digestion Demonstration Projects for WRAP (2010).** Monitoring of six innovative AD plants that are at commissioning stage.
+ **Secretariat and Lead Research Partner of the International Energy Authority's Bio-Energy Task Force** (see box)

+ **Evaluation of Energy from Waste Options for Hills Waste Solutions (2009).** A critical evaluation of current and near future thermal treatment technologies
+ **Analysis of Renewable Technologies Growth to 2020 for DECC (2010).** A review of renewable energy (including AD, liquid biofuels/bioethanol and energy from waste) deployment and projected development in the UK.
+ **An assessment for waste technology investment opportunities for Shanks Waste Management (2009/10).** A study to inform their five-year investment plan.
+ **UK and Global Bioenergy Resources and Prices, DECC (2010).** A study of the availability of bioenergy feedstock (including waste) in the UK.
+ **Bio-energy Review for the Environment Agency (2008).** Examination of the development of bio-energy in England and exploration of likely future development.
+ **Design of a Renewable Heat Incentive for DECC (2009-10).** Quantitative and qualitative cost benefit analysis to support the development of the Renewable Heat Incentive.
+ **Assessing cost-effectiveness scenarios for biofuel deployment options across the UK transport sector to 2020 and to 2050,** DfT
+ **An assessment of waste technology options for Essex Waste Partnership (2009/10).** As part of their PFI funded residual waste treatment procurement project.
+ **Management of two databases on behalf of DECC (current):** RESTATS, the UK's Renewable Energy STATisticS database, and REPD, the Renewable Energy Planning Database project that tracks the progress of new projects from inception to operation.

AEA was appointed as the secretariat and lead research partner of the International Energy Authority's Bio-Energy Task Force. IEA Bioenergy is an international collaborative agreement set up in 1978 by the International Energy Agency (IEA) to improve international cooperation and information exchange between national bioenergy RD&D programmes. IEA Bioenergy aims to accelerate the use of environmentally sound and cost-competitive bioenergy on a sustainable basis, to provide increased security of supply and a substantial contribution to future energy demands. The work within IEA Bioenergy is structured in a number of Tasks, which have well-defined objectives, budgets, and time frames. Recent tasks have included the

+ Promotion of information exchange and deployment of environmentally sound energy recovery technologies;
+ Stimulation of interaction between RD&D programmes, industry and decision makers, and
+ Identification and interaction with appropriate international organisations.

The scope of the project has continually evolved, with a number of new research themes identified, including:

+ Product Stewardship/Producer Responsibility
+ Greenhouse Gas balances for MSW Systems
+ Micro-particulate emissions – PM10
+ Mechanical Biological Treatment
+ Thermal Treatment of Sewage Sludge

AEA is responsible for peer reviewing all work done by the partners, co-ordinating visits, meetings and research, and for publishing the final reports.

1.5 AD Landscape Review Methodology

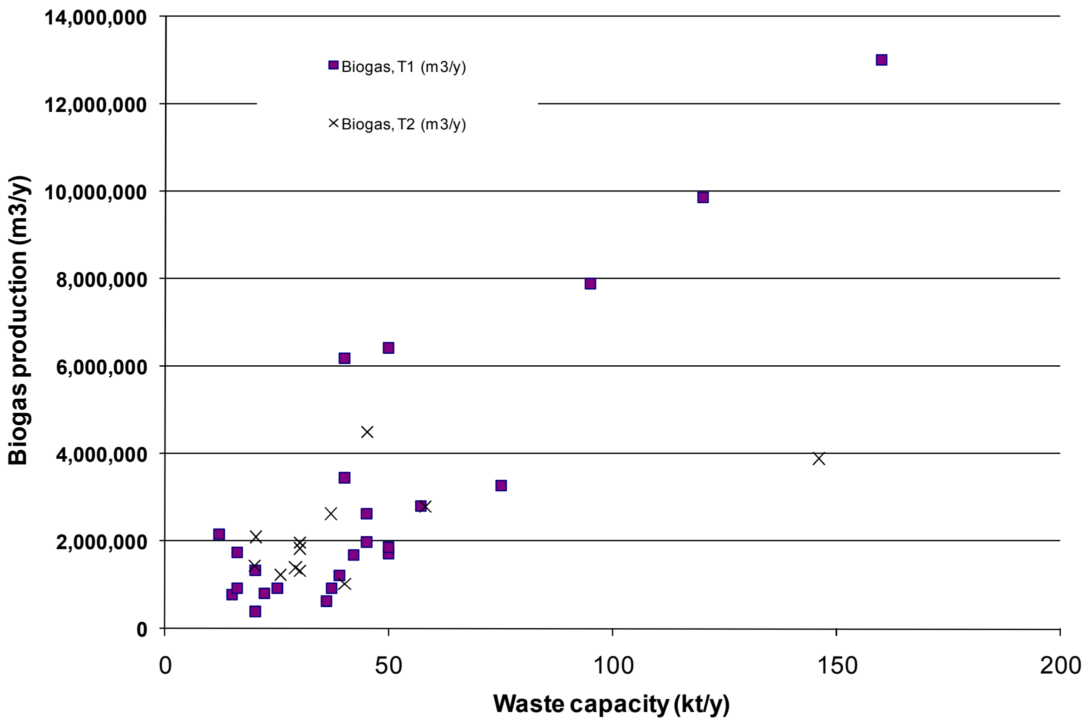
Around the world, a large number of technology providers have designed, built, commissioned and operated AD plants. In some cases, these plants have been operational for a significant number of years. Both the quality and the availability of data for the individual facilities vary significantly. Data on generic issues such as feedstock quantity and type, installed electricity capacity and end use of outputs are commonly quoted, but more specific plant data (such as information on feedstock composition, biogas composition and parasitic loads) are not so readily available.

Notwithstanding these constraints, information on key performance data was identified that enabled a picture of the operating AD plants to emerge. For example, there are examples of wet single stage, wet multi-stage and dry single stage operating plants. The wet multi-stage approach appears to be the most favoured amongst the AD plants for food waste processing. Additionally, there are examples of both mesophilic and thermophilic processes, but the number of mesophilic processes amongst the reference plants far exceeds the thermophilic processes.

Another operational parameter that determines the effectiveness of the AD plant is the residence time of the waste within the AD process and the overall plant itself. A key parameter from the digestion process is the biogas yield, and this is determined by a combination of factors, including the influence of the process feedstock and the residence time.

The biogas yields on actual AD plants, as a function of scale, is illustrated in Figure 1 for a selection of AD plants. It also illustrates that the majority treat less than 60,000 tonnes of waste or feedstock per year. This is in line with the Consortium's suggestion to look at the smaller plants where possible.

Figure 1: Biogas output in relation to scale of operation for selected plants



T1 and T2 refer to Type 1 and Type 2 facilities, as defined in Section 2.1.

1.6 Technology Selection Process

From our wide search, AEA identified over 60 operational AD plants for consideration for this project (see Annex I). The final column of the table in the annex details whether the plants are chosen for further consideration, according to the following criteria:

- **Y1** Yes, because the plant has a relatively high biogas yield
- **Y2** Yes, to provide coverage of the mix of different technologies
- **Y3** Yes, because the plant has suffered relatively poor performance

In most of the plants we identified, biogas is converted in CHP plant to produce electricity for export and heat for maintaining the process. However, in a few cases (for example Gustrow and Tilburg), the biogas is being produced for the purposes of injecting into the natural gas network. These were selected on that basis.

It should also be born in mind that a number of companies act as agents or are developing technology and expertise in the sector in their own right. We have taken these into account, to ensure that we select as many of the different technologies as possible from the international supplier list.

In devising the short-list, AEA tried to balance the requirement for access to relevant process data (which tended to favour UK plants, where much of our experience has been gained) with the desire to cover as many countries as possible. The final short-list of the plants is presented in Table 2, while Table 3 provides information on the geographical coverage of the short-list. This is clearly slanted towards Europe, but this also reflects the fact that it is in Europe that most AD development is occurring.

AEA's original short-list contained about 20 facilities, but, in researching the facilities in detail, we found that several plants did not have any information that we judged particularly noteworthy for the Consortium, so those plants were dropped from the final analysis.

Table 2: AEA Anaerobic Digestion Plant Shortlist

		Site Name		Technology	System
Y1	**21**	Pellmeyer Biogas Plant II	DE	UTS	Multi (2 Stage)
	24	Biogas Benet	FR	Entec Biogas	Wet: Multi (acidification, CSTR Digester, Post Digester)
	25	Nakasorachi	JP	Entec Biogas	Wet: Multi (2 stage)
	36	Cassington, Oxford	UK	Agrivert	Multi stage
	53	Selby Renewable Energy Park	UK	Entec Biogas	Wet: Multi (acidification, CSTR Digester, Post Digester)
Y2	**4**	Brecht II	BE	OWS (Dranco)	Dry: Single (Plug)
	14	Jessen	DE	Strabag	Dry: single
	23	Gustrow Bioenergy Park	DE	Envitec	Wet: Single
	26	Tilburg	NL	Valorga	Dry: Single (Plug)
	27	Waterschap Veluwe	NL	HoSt Bioenergy Installations	Multi (2 Stage)
	30	Barkip	UK	Xergi	Multi (2 stage)
	56	Twinwoods, Beds	UK	WELtec, BiogenGreenfinch	Single
	61	Tel Aviv	IR	ArrowBio	Wet
Y3	**42**	Holsworthy	UK	Farmatic	Wet: Single (CSTR)
	55	Stornoway	UK	Strabag	Dry

Table 3: Summary of the Selection

Country		Count	Y1	Y2	Y3	*Total*
AT	Austria	1				
BE	Belgium	3	1			*1*
CA	Canada	1				
CZ	Czech Republic	1				
DE	Germany	17	2	1		*3*
FR	France	1		1		*1*
IL	Israel	1	1			*1*
JP	Japan	1		1		*1*
NL	The Netherlands	2	2			*2*
UK	United Kingdom	33	2	2	2	*6*
Total		**61**	**5**	**8**	**2**	***15***

2. AD Processes – Key Technological Options

Before looking at the chosen plants in more detail, this section reviews some key technological options for the anaerobic digestion of waste materials, whose choice can have a significant bearing on the success or otherwise of the enterprise as a whole.

2.1 General

Anaerobic digestion (AD) involves the conversion of biodegradable organic matter to energy by microbiological organisms in the absence of oxygen. The biogas produced in the process is a mixture of methane and carbon dioxide, and can be used as fuel source for heating and/or electricity production. The treatment of waste leaves behind residues, generally in the form of semi-solid or liquor called digestate that can be used as fertiliser.

AD can be carried out in small scale systems located on the farm and operated by farmers, or in large centralised systems, operated as commercial concerns. The latter deal with a variety of wastes ranging from food wastes from household and C&I premises to livestock slurries from farms within the locality.

AD technologies for all these applications are largely demonstrated, although those at small scale are considered rather expensive for wide scale applications and require effort to commercialise them for wide scale applications. In order to identify areas for further development, it is useful to breakdown the AD plants into different scales and application types, and then to examine their constituents process units or equipments.

+ **Large-scale merchant AD plants (Type 1).** These are typically based on food waste from municipal and C&I origins but also accommodate other wastes such as livestock slurries. Over 100 such plants exist in Europe[2] and several are installed in England. The technology applied varies from CSTR to high solids plug flow systems.
+ **Medium-scale farm enterprise AD plants (Type 2)**. These are typically based on co-digestion of various feedstocks but the main component tends to be livestock slurry with energy crops. Thousands of such plants are installed in Europe, notably in Germany. These are also implemented or being implemented in several locations in England. The market for these is increasing.
+ **Small-scale on-farm AD plants (Type 3)**. These are defined as AD plants that deal with livestock slurry, agricultural residues and energy crops drawn from within the confines of the farm. While some 20 plants exist in the UK, this technology still requires development for wider acceptance and would perhaps offer greater scope for innovation.

AEA has come across some AD plants that, at first glance, match the definition of Type 3 (i.e. on-farm AD plants, dealing with wastes from within its confines), but seem to exclusively or largely deal with energy crops, and are in effect similar to Type 2.

2.2 AD Technology

Technologies developed to digest source separated food waste, mechanically separated organic fraction of municipal solid waste or any of the other wastes mentioned above fall into three distinct categories:

1. Wet or low solids digestion: 'operated at' dry solids content below 10% (but the feed could comprise much higher solids content, which is diluted upon entry);
2. Dry or high solids digestion: operated at between 15% and 35% dry solids content; and
3. One or multi-stage digestion, where the final methanogenic stage of the biochemical conversion is separated from the earlier stage, for optimisation.

[2] Luc de Baere, 2010; General trend of the AD technology implementation and their types in Europe'; paper presented at the Biowaste Conference, February 2010.

The overall plant is generally optimised to maximise the economic production of biogas. Any front end processing, including feed preparation stages, are related to the type of feed and digestion system, whereas the market outlet of the digestate requires its storage (for a minimum of 18 days) and any processing specific to the end user (e.g. fibre/liquor separation or concentrating if it is to be transported long distance). With the current trend in the collection of source separated food waste, the digestate is often made suitable for spreading on agricultural land. There is increasing effort in co-digesting food waste with other organic wastes that would allow the PAS110 (Quality Protocol) requirements to be met. As such, food waste from household is considered for digestion with livestock slurry, agricultural wastes as well as with commercial and industrial food waste.

Any biogas produced from AD plants generally has a composition of approximately 50% to 70% methane (CH_4) and 30% to 50% Carbon Dioxide (CO_2). There are often small amounts of other compounds such as Nitrogen (N_2), Oxygen (O_2) and Hydrogen Sulphide (H_2S). The overall composition is a function of the feedstock as well as operating conditions (such as pH). Varying degrees of cleaning need to be applied to the biogas, depending on its use.

There are many configurations of the actual AD process itself. The different designs are often based on addressing specific characteristics of the feedstock or overcoming the rate determining step (RDS) of the anaerobic digestion. The RDS can be different for different feedstock; for instance, in the case of garden waste it may be the initial hydrolysis or the need to overcome inhibition due to any toxics in the feedstock, whereas, for food waste, it is often the final stage of the biochemical conversion, where the fatty acids are converted to methane and carbon dioxide.

2.2.1 Retention Times

The most common digester design is a continuously stirred tank reactor (CSTR), which, as its name implies, is continuously mixed within a tank. The overall efficiency of the process is dependent on the efficiency with which it brings about contact between substrate and the microorganisms. There is no enhancement applied to retaining the microbial biomass, and the overall digestion or the biogas yield is influenced by the hydraulic retention time (HRT) within the digester tank[3]. In this design, a higher HRT usually leads to higher biogas yield but incurs higher capital cost (because the tank has to be larger to process the same amount of feedstock). This process is normally operated at mesophilic digestion temperature around 35°C and the central digestion process has HRTs typically between 20 and 30 days. However, much higher are also observed, especially with those dealing mainly with rich feedstock such as food waste. At times, the rather low HRT within the key AD process is compensated by long retention time within the subsequent storage tanks, from where biogas can be harvested as its production declines.

In ‘Contact Reactors’, a portion of the biomass in the effluent is recycled by adding it to the fresh feed. This allows de-coupling of the HRT from the microbial or biomass retention time, which is often then referred to as the sludge retention time (SRT). A longer SRT tends to promote higher methane yields and improve process stability.

2.2.2 Continuous Flow versus Batch Flow

The vast majority of digesters, especially those designed for energy production, tend to be continuous processes. In contrast, ‘fed-batch’ systems are rarely applied but do exist, in which the waste is fed as it arises and is allowed to accumulate over several months before emptying the whole content. Such an approach often combines the use of the digester alongside storage (e.g. on a farm). Loading the digester in this way can be quite labour intensive and its biogas generation will be highly variable, not least because the digester vessel may be opened to atmosphere during each loading.

Overall, batch flow reactors have the potential to provide a much higher biogas yield, but at a low or fluctuating rate. Where such an operation can be automated, the operating costs may be lower. This design could be used in a bank of digesters to overcome peaks and troughs in gas production.

2.2.3 Two or Multi-phase Digesters

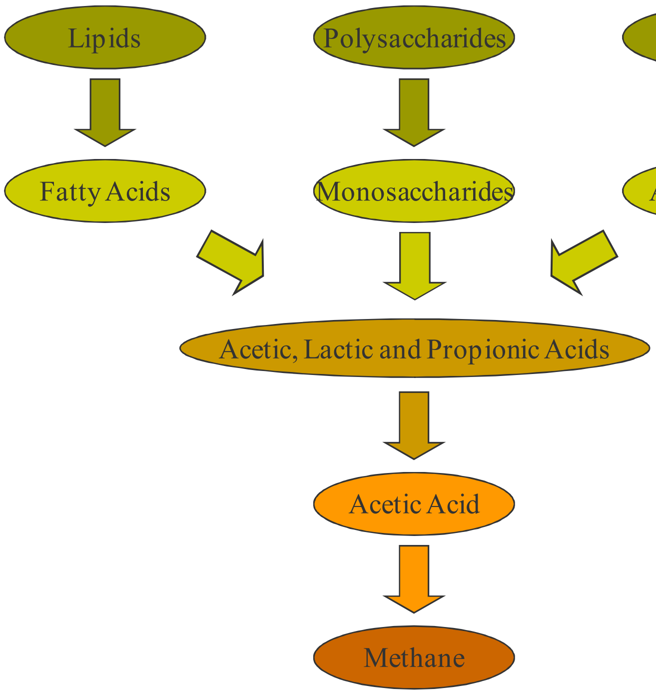
Two or multi-stage processes have been developed with the aim of improving the efficiencies of different stages of the digestion process, thus providing flexibility and better process control for the different stages of the anaerobic biochemical reactions. Figure 2 shows how complex organic materials are broken down to produce biogas.

[3] HRT = Tank volume / Volumetric Feed Flowrate

Typically, two reactors are used: the first for hydrolysis/liquefaction and acetogenesis stages, and the second for methanogenesis. The increased complexity, compared to a single stage AD process, is not necessarily about higher rates or yields, but about greater biological stability for AD plants that face fluctuating type of feedstocks and organic loading rates.

Some systems have multiple digesters to ensure each stage is as efficient as possible. The terms two- and multi-phase digestion are used to mean a variety of things. Scientifically, two- or multi-stage digesters should refer to optimisation of the overall reaction, giving higher biogas yields, higher biogas generation rates and/or greater process stability, but also resulting in higher capital cost, higher operating cost and require greater process control. In contrast, many AD plants based on CSTR (including most of the digesters in the UK) send the output to a holding tank where the methanogenic activity is allowed to gradually subside while still collecting the biogas from the headspace, before sending the digestate for direct use on agricultural land.

Figure 2: Breakdown of organic matter to biogas by key microbial groups



We understand that a 2-stage AD plant, based on BTA technology, was installed in 1991 at Elsinore, Denmark. It was designed to handle 20,000 t/y of source separated feed waste, and to maximise the biogas generation by adopting pulping together with alkali-acid pre-treatment to extract all possible sugars prior to digestion (see also Section 3.2.3).

3. Learning from Experience

3.1 Successful Plants

There are over 20 centralised AD plants operating in Denmark, with a further 20 farm scale operations. Feedstocks are mainly pig and cattle manure, but also include waste food, fat sludge and brewery wastes.

In Germany, over 200 companies are offering services in connection with biogas technology, e.g. consulting, planning, manufacturing and delivery of parts and components (pumps, stirrers, engines, tanks) as well as servicing. It is estimated that, together with the operating staff, 8,000 jobs are dependent on the services associated with biogas technology at present.

Initial developments in Germany, in the mid 1990s, were focussed on the treatment of organic wastes, primarily driven by the requirement to meet landfill diversion targets. The treatment capacity of some of the small plants (such as those developed by Pellmeyer farm, see below) was quickly exceeded. However, owing to the general flexibility of the process and the design of AD plants, capacities could be increased by converting secondary fermenter and digestate storage tanks into primary digesters, and adding extra secondary fermenter and digestate storage capacity. The rapid rise in the biogas generation took place in this manner, but later with dedicated and specifically designed AD plants.

Once the required landfill diversion targets had been met in Germany, the focus for biogas plants shifted from one of providing treatment capacity for organic wastes towards the generation of renewable energy using energy crops. Since 2000, the feed in tariffs associated with the German Renewable Energy Sources Act (EEG) have allowed the development of small to medium scale, farm-based AD plants, and thousands of such plants have been constructed across Germany[4]. This led to AD plants based largely on energy crops.

Below, we provide a summary of the technologies based on some of the successful plants operating in the UK and internationally. They were selected on the basis of their methane yields observed at operating plants. Comments on their suppliers and specific aspects of the plants are also given, especially with respect to their constituent parts in terms of pre-treatment, conversion process, post-treatment/clean up, energy and integration.

3.1.1 Pellmeyer Biogas Plant II, Germany

Technology	UTS	**CapEx**	€3M
Process Stages	Multi-stage (primary + secondary) AD process.		
Reactor Type	CSTR	**Annual Throughput**	20,000 t/y (Type 2)
Wet/Dry	Wet	**Biogas Yield**	220 m^3/t
Operating Temperature (M/T)	39-40ºC	**Energy prod'n/ Capacity**	2,810,949 m^3/yr
Feedstock	Energy crops, approx 3,600tpa plant silage (imported to the plant from adjacent farms) and approx 9,000tpa whole crop maize silage (grown on the farm) and other biomass sources locally.		

UTS Biogas Ltd is a UK subsidiary of UTS Biogastechnik GmbH of Germany. They offer design, construction, commissioning and operation services. They have installed over 60 commercial plants (to 20,000 t/a) throughout Europe. Currently, they are developing an AD plant at Glenfarg, Perthshire (UK).

The Pellmeyer Biogas Plant II is one of two plants at the Pellmeyer farm, in Germany, whose performance is given above. The plant is operated by Biomasse Kraftwerk Eggertshofen GmbH and Co, having been commissioned in 2006. The rationale behind this plant was to take advantage of the high tariffs offered by the German government for the generation of renewable energy using energy

[4] Key elements of the legislation can be found at: http://www.e-parl.net/eparlimages/general/pdf/080603%20FIT%20toolkit.pdf

crops. Appendix II gives a more detailed description of the plant and its operation. The feedstock used is high solids (around 33% total solids, comprising 95% as volatile solids) but the rate of feed ensures that it operates in a relatively wet state, with its operating total solids content (i.e. that within the digester itself) being around 10%.

UTS has over 60 commercial AD plants and their plants are seen as successfully design-engineered, with high performance (in terms of methane yield per tonne of feedstock), so it follows that the technology scores (TRL values) must be among the highest. AEA's assessed scores are as follows:

Unit Operation	TRL	Comments
Pre-Treatment	9	Silaging of maize and grass to preserve and use as feedstock throughout the year
Conversion Process	9	Fairly standard low solids digesters
Post-Treatment / Clean Up	9	Digestate held under cover (to collect methane initially but to then prevent ammonia volatilisation); biogas cleaned sufficiently for use in CHP.
Energy	9	High energy yield, which reflects the feedstock but the simple AD technology (low solids CSTR) is able to handle this well.
Integration	9	Very good overall integration of well established unit operations.

3.1.2 Biogas Benet, France

Technology	Entec Biogas	**CapEx**	nda
Process Stages	Multi-stage (acidification, CSTR digester, post digester)		
Reactor Type	CSTR	**Annual Throughput**	40,100 t/yr (Type 1)
Wet/Dry	Wet	**Biogas Yield**	86 m^3/t
Operating Temperature (M/T)	nda	**Energy prod'n/ Capacity**	3,462,000 m^3/yr (0.8 MWe)
Feedstock	Industrial and commercial food waste, including whey, milk products, bakery waste, dough, pet food, grease trap pumpings, glycerine, yeast		

Entec Biogas GmbH is an Austrian based organisation offering a full range of services, including pre-planning feasibility studies, design construction and commissioning. They have delivered over 100 commercial plants globally, varying in scale up to 350,000 t/a, including developing and commissioning the Selby AD plant in Yorkshire.

The Biogas Benet plant in France, detailed above, is a wet multi-stage plant with CHP units attached and has been operational since September 2010. Pre-treatment at the plant involves shredding and a de-packaging unit for food wastes packaged in paper and plastic. This plant was developed with SIFDDA, who also intend to install two further AD plants in France in 2011. Given the success of this supplier in delivering a large number of integrated AD plants, the technology scores (TRL values) are among the highest. As such, the overall AD plant together with their stages (pre-treatment, conversion process, post-treatment/clean up, energy and integration) are all considered to be at a TRL of 9.

3.1.3 Nakasorachi, Japan

Technology	Entec Biogas	**CapEx**	nda
Process Stages	2-stage		
Reactor Type	BIMA	**Annual Throughput**	16,000 t/yr (Type 1)
Wet/Dry	Wet	**Biogas Yield**	110 m^3/t
Operating Temperature (M/T)	nda	**Energy prod'n/ Capacity**	1,750,000 m^3/yr (0.4 MWe)
Feedstock	Residual MSW		

For the Nakasorachi plant in Japan, detailed above, Entec Biogas partnered with Mitsui Engineering & Shipbuilding Co. Ltd to install the plant. The facility is a wet, two-stage plant with CHP units attached, as well as a wastewater treatment plant of 130m^3/d, and has been operational since 2002. The plant has an 8m^3 capacity waste pre-treatment facility attached, which is required because a significant proportion of the incoming waste is in plastic bags, which must first be split and then removed.

As its name suggests, the Biogas Induced Mixing Arrangement (BIMA) technology involves agitating the reactor without the use of mechanical equipment. As such, the reactor is mounted vertically and uses the pressure of the digesting gas to provide agitation, which reduces maintenance and operation costs. The average hydraulic retention time of the feed in the BIMA digester is about 16 days before being drained to a storage tank from where tailing production of methane can be collected. This has been applied widely, not only by Entec Biogas but also other suppliers, including in the UK by Farm Gas in the nineties and by Greenfinch.

Consequently, AEA's assessment of this technology, supplied by Entec Biogas, together with its stages (pre-treatment, conversion process, post-treatment/clean up, energy and integration), is that all considered to be at a TRL of 9.

3.1.4 Cassington, UK

Technology	Biogas-Weser-EMS	**CapEx**	£9M investment plus grant funding from WRAP
Process Stages	Multi-Stage		
Reactor Type	CSTR	**Annual Throughput**	45,000 t/yr (Type 1)
Wet/Dry	Wet	**Biogas Yield**	100 m^3/t
Operating Temperature (M/T)	38ºC (M)	**Energy prod'n/ Capacity**	4,500,000 m^3/yr (2.0 MWe)
Feedstock	Municipal food waste, segregated at source and other types of solid and liquid organic wastes		

Biogas Weser-Ems is a leading supplier of AD plants. They quote over 250 plants that have been successfully developed and implemented, with a total installed capacity of around 140 MWe electricity. Its rapid growth in the last 12 years has been built on latest but tested and widely applied process units.

This AD plant near Oxford was designed by Agrivert in conjunction with Biogas-Wesser-EMS and became operational in October 2010. Agrivert has its origins in the farming community, and its waste solutions are always well geared to a local, agricultural solution for the final products. To an extent, they look first at means of making fertiliser for farmers, rather than means of treating waste.

There are three principal feedstocks; agricultural residues (including silage and maize) are added directly to the digesters, while liquid food waste and solid food waste are added via a hammer mill and pasteurisation stage. The process operation is unusual in that the material retention time is very high, typically around 140 days. Waste spends at least 50 days in one of three primary CSTR digesters, before being moved to storage vessels where further biogas is collected. Agrivert claim that maximising the gas yield (and concurrently minimising odour) by such a long residence time is worth the extra investment in tankage. Overall, their process is likely to last the course of time, but may well not prove to be as competitive as some other providers.

Given the success of this supplier in delivering over 250 integrated AD plants, the technology scores (TRL values) are among the highest. As such, the overall AD plant together with their stages (pre-treatment, conversion process, post-treatment/clean up, energy and integration) are all considered to be at a TRL of 9.

3.1.5 Selby Resource Efficiency Park, UK

Technology	Entec Biogas	**CapEx**	£20M, with ~£2M WRAP and £750k Future Energy Yorkshire funding
Process Stages	Multi-stage (acidification, CSTR digester, post digester)		
Reactor Type	CSTR	**Annual Throughput**	160,000 t/yr (Type 1)
Wet/Dry	Wet	**Biogas Yield**	81 m^3/t
Operating Temperature (M/T)	38 - 40°C (M)	**Energy prod'n/ Capacity**	13,000,000 m^3/yr (2.0 MWe)
Feedstock	Commercial food waste (restaurant and market waste), expired food and canned goods from supermarkets, food industry waste and non-contaminated slaughterhouse waste		

Whites Renewable Energy is the owner/operator of this Entec Biogas plant, situated at the old Tate & Lyle citric acid production site at Selby Resource Efficiency Park. The plant was commissioned in 2009. The wastes undergo mechanical waste pre-treatment and, following digestion, the high strength liquid waste is treated at the on-site effluent treatment plant for end-use agricultural purposes. The site also houses CHP units for the conversion of captured energy to heat.

AEA's TRL assessment of the technology supplied by this company was given in Section 3.1.2.

3.1.6 Brecht II, Belgium

Technology	OWS (Dranco)	**CapEx**	nda
Process Stages	Single		
Reactor Type	Plug	**Annual Throughput**	50,000 t/yr (Type 1)
Wet/Dry	Dry	**Biogas Yield**	35 m^3/t
Operating Temperature (M/T)	nda	**Energy prod'n/ Capacity**	1,708,200 m^3/yr
Feedstock	Biowaste (source-segregated biodegradable waste, not municipal solid waste), waste paper and industrial waste		

Organic Waste Systems nv. is a Belgian company offering design planning, construction, commissioning and operation services. They offer a range of technologies to treat both low and high solids material using either mesophilic or thermophilic processes. Their reference plants show the application of single stage systems. They have successfully installed over 20 AD plant across Europe, although none known to be installed in the UK at present. The company is famous for introducing an early version of the high solids plug flow AD plant that uses organic waste with a consistency of a cake (or toothpaste) like consistency – innovation that took place around the early nineties.

One exemplar of the use of large scale AD for MSW, detailed above, is the Brecht II facility in Belgium, which began operation in 2000 with a capacity of 50,000 tonnes per annum from the municipalities around the city of Antwerp. The plant is owned by IGEAN, a regional agency set up by those municipalities. The feedstock for the plant is mainly organics such as garden, kitchen and food waste, to which nappies, non-recyclable paper or cardboard can be added. 30% of the electricity produced is used within the plant, and 70% is sold at a renewable energy rate of 12.5cents/kWh[5]. The plant also produces 20,000 tonnes of compost, which meets the Flemish regulations for high quality soil amendment.

Given the success of this supplier in delivering over 20 well integrated high solids AD plants, the technology scores (TRL values) are among the highest. As such, the overall AD plant together with their stages (pre-treatment, conversion process, post-treatment/clean up, energy and integration) are all considered to be at a TRL of 9.

3.1.7 Jessen, Germany

Technology	Strabag (formerly Linde)	**CapEx**	nda
Process Stages	Single		
Reactor Type	LARAN Plug Flow	**Annual Throughput**	60,000 t/yr (Type 2)
Wet/Dry	Dry	**Biogas Yield**	77 m^3/t
Operating Temperature (M/T)	Thermophilic	**Energy prod'n/ Capacity**	4,599,000 m^3/yr
Feedstock	Energy crops		

Strabag Umweltanlagen GmbH is a Germany based company that includes the AD capability of Linde-KCA. They offer design, construction, commissioning and operation services with a broad range of AD technologies and have installed commercial plants up to 150,000 t/a scale located across Europe. They seem to focus on biomass based AD plants, with a proportion of wastes mixed in feedstock; these include sewage sludge; agri-waste; industrial food waste; source segregated waste and MSW. They have over 15 reference plants within Germany, France, Spain, Portugal, Italy, Austria and Switzerland. The company is not known to have installed any AD plants in the UK.

The AD plant detailed above is the Jessen AD plant in Dresden, Germany, which was commissioned in 2008 (first reactor) with a subsequent second reactor in 2009 for Agratec AG. The facility operates a thermophilic, dry digestion process for the digestion of energy crops.

Given the success of this supplier in delivering over 15 well integrated AD plants, the technology scores (TRL values) are among the highest. As such, the overall AD plant together with their stages (pre-treatment, conversion process, post-treatment/clean up, energy and integration) are all considered to be at a TRL of 9.

3.1.8 BioEnergiepark, Gustrow, Germany

Technology	EnviTech Biogas AG	**CapEx**	€100M investment (without cash assets or finishing costs)
Process Stages	nda		
Reactor Type	CSTR	**Annual Throughput**	460,000 t/yr (Type 2)
Wet/Dry	nda	**Biogas Yield**	100 m3/y
Operating Temperature (M/T)	nda	**Energy prod'n/ Capacity**	46,000,000 m^3/yr
Feedstock	Maize (380,000t/a), cereal (1,000t/a) cereal and whole plant silage (60,000t/a) and grass cuttings silage (8,000t/a)		

[5] http://www.lacitysan.org/solid_resources/strategic_programs/alternative_tech/PDF/AnaerobicDigestionFacility.pdf

The technology supplier is Envitec Biogas AG, who has become a leading player in the delivery of state of the art biogas plants worldwide. They have recently grown their water treatment capability, in order to focus on niche markets where more novel applications of technologies (applied elsewhere) are required. As such, they have ended up focusing more on the delivery of biomethane and on novel techniques in digestate treatment and management. They claim to have installed the world's largest biomethane plant, detailed above, that feeds into the natural gas grid. The company is also operating in some 20 countries worldwide but has only 2-3 plants in Europe.

The BioEnergiepark in Gustrow, Germany, claims to be the world's largest natural gas quality processing plant, creating energy for 50,000 households. It is certainly much larger than any of the other facilities reviewed in this report. The plant cleared planning in twelve months, and became fully operational in 2010. It produces 140,000 t/a of liquid manure, and a further 85,000 t/a of "press cake", which is spread to land by local farmers. Given the expansion of the renewable gas (biomethane) market, the above plant was designed to produce natural gas quality biomethane, which is fed into the national gas grid.

This is a technology supplier that is ambitious in capturing current niche, but developing, markets and some of the unit operations are relatively new on the above AD plant.

Unit Operation	TRL	Comments
Pre-Treatment	9	Fairly standard mixing and matching of feedstock
Conversion Process	9	Well established and tried AD process (HRT ~65 days)
Post-Treatment / Clean Up	7	Application of flocculation, ultra-filtration and reverse osmosis to refine digestate into fibre, fertiliser and permeate which can be re-used as process water.
Energy	8	Biomethane production from biogas
Integration	8	Excellent integration of individual unit operations

3.1.9 Tilburg, Netherlands

Technology	Valorga	**CapEx**	€16M, including Novem grant of €1.4M
Process Stages	Single		
Reactor Type	Plug	**Annual Throughput**	57,000 t/yr (Type 1)
Wet/Dry	Dry	**Biogas Yield**	49 m^3/t
Operating Temperature (M/T)	37-40ºC (M)	**Energy prod'n/ Capacity**	2,800,000 m^3/yr (0.4 MWe)
Feedstock	Municipal vegetable, fruit and garden waste		

Valorga International SAS is a French company that offer design, construction, commissioning and operation services dealing with a broad range of AD technologies but with a focus on relatively high solids systems. They have over 15 commercial scale AD plants (up to 120,000 t/a) located in Europe and internationally but they are not known to be present in the UK.

The AD plant detailed above is that based at Tilburg in The Netherlands, operational since 1994. It incorporates pre-treatment via mechanical sorting and post-treatment composting and air maturation. Development partners Stork Protech together with Valorga are responsible for this plant on behalf of the client G.F.T. Verwerkingsinstalatie.

Waste is pre-treated by means of shredding, screening and iron separation. The digested material is processed into compost by dehydrating and sand separation. Before using the compost as a soil structure improving material, it needs to be further processed (maturing, screening). The waste water is partly re-used as processing water, with the remainder drained to a nearby waste water treatment plant. Residence time in the plant is about 24 days, producing about 18ktpa of digestate.

The anaerobic digestion plant includes the following units:

- Waste preparation unit, including: reception of waste, inert removal and size reduction.
- AD unit, including: mixing of waste, pumping into the 3,300 m^3 digesters, biogas buffer storage, compression and stirring system, digested matter extraction and the mechanical de-watering.
- Process water treatment unit, including: compost storage unit, which includes a completely closed building in which the digested matter is kept for a seven days period, and an open building under which compost can be stored one more week before being transferred to users.
- Extraction and treatment installation dealing with foul air coming from the compost storage unit and other installations.

Given the success of this supplier in delivering over 15 well integrated AD plants, the technology scores (TRL values) are among the highest. As such, the overall AD plants, together with their stages (pre-treatment, conversion process, post-treatment/clean up, energy and integration) are all considered to be at a TRL of 9.

3.1.10 Apeldoorn, Netherlands

Technology	HoSt Bioenergy Installations	**CapEx**	Nda
Process Stages	2-stage		
Reactor Type	nda	**Annual Throughput**	50,000 t/yr (Type 1/2)
Wet/Dry	nda	**Biogas Yield**	38 m^3/t
Operating Temperature (M/T)	nda	**Energy prod'n/ Capacity**	1,881,648 m^3/yr (1.432 MWe)
Feedstock	Various organic wastes, include ABPR Category 3 materials		

HoSt has been established since 1996 when it focused on the development of its own technology for the gasification of biomass fuels. With expertise in gas treatment, water, gas turbines, gas engines and low NOx incinerators, it has recently extended its services into the design, engineering and delivery of AD plants. The company focuses on agricultural and industrial markets using well known and established unit operations. They have installed numerous AD plants.

The plant detailed above is based at Apeldoorn in the Netherlands, and was developed by HoSt Bioenergy Installations for Waterschap Veluwe. Construction began in September 2008 and the plant was operational by February 2009. It is operated by the local authority and is located on a municipal wastewater treatment plant. The electricity generated at the AD plant is more than sufficient to supply the treatment plant process and the heat is utilised in a new district heating system supplying an eco village ("Zuidbroek") with 1,100 houses.

The technology used by this supplier is tried and tested as far as the overall AD plant is concerned and therefore all stages (pre-treatment, conversion process, post-treatment/clean up, energy and integration) are all considered to be at a TRL of 9.

3.1.11 Barkip Landfill, UK

Technology	Xergi, Zebec Biogas	**CapEx**	£13.5M investment, including a £2.2M Zero Waste Scotland grant
Process Stages	2-stage		
Reactor Type	nda	**Annual Throughput**	75,000 t/yr (Type 1)
Wet/Dry	nda	**Biogas Yield**	44 m^3/t
Operating Temperature (M/T)	High temperature	**Energy prod'n/ Capacity**	3,285,000 m^3/yr (2.5 MWe)
Feedstock	Food waste, manures, fats and greases, industrial organic effluent sludges, energy crops (grass silage)		

Xergi A/S is a Danish company operating in the UK through its subsidiary Xergi Ltd. It offers design, construction, commissioning and operation services in wet systems (in both the mesophilic and thermophilic temperature ranges). The technology is well developed and commercial (applied at up to 230,000 t/a scale) with over 25 reference plants in Europe and the USA. In the UK, Xergi is the technology provider for Scottish & Southern Energy's Barkip AD facility.

The Barkip AD plant was due to be commissioned in June 2011. The project was co-developed between Xergi, Zebec Biogas and Scottish Southern Energy Ltd (SSE), with a 25-year deal for 37,000 tonnes per annum feedstock supply with William Tracey Group. Of the £13.5M investment, £6.9M of this went to the technology provider and the grant of £2.2M from Zero Waste Scotland came from their Organic Capital Grants programme. SSE claims that this will be the first AD plant to incorporate a rather novel digestate processing stage for capturing the CHP generation heat to concentrate the liquid fraction of the digestate into nutrient rich liquid fertiliser[6]. This is a well tried and tested stage but is generally more costly so it tends to be applied where access to raw digestate market is limited.

Given the success of this supplier in delivering some 25 well integrated AD plants, the technology scores (TRL values) are among the highest. However, AEA considers that the novel digestate processing stage probably merits a TRL of 8. Otherwise, the overall AD plant together with their stages (pre-treatment, conversion process, energy and integration) are all considered to be at a TRL of 9.

3.1.12 Twinwoods, UK

Technology	WELtec, BiogenGreenfinch	**CapEx**	£5M investment
Process Stages	Single		
Reactor Type	CSTR	**Annual Throughput**	42,000 t/yr (Type 1)
Wet/Dry	nda	**Biogas Yield**	40 m^3/t
Operating Temperature (M/T)	40ºC (M)	**Energy prod'n/ Capacity**	1,695,060 m^3/yr (1.29 MWe design capacity)
Feedstock	Pig slurry, food waste (12,000t/a of slurry as liquid fraction for the AD)		

WELtec BioPower GmbH is a German company that has a number of sales partners in the UK. The company has also supplied the technology for a number of plants in the UK. It offers design, construction, commissioning and operation services in a range of AD technologies and has over 200 reference plants (scale to 50,000 t/a) in Europe and internationally.

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[6]http://www.scottish-southern.co.uk/SSEInternet/index.aspx?id=22180&TierSlicer1_TSMenuTargetID=1368&TierSlicer1_TSMenuTargetType=1&TierSlicer1_TSMenuID=6

The Twinwoods facility in Bedfordshire, UK, is a good example of the technology, which is seen in the UK as an efficient use of local waste streams. The 42,000 tpa facility is fed on pig slurry and food waste; of this 22,000 tonnes is pig slurry provided by Bedfordia Farms and the remainder is food waste. Some of the digestate is recycled as the liquid fraction to retain active population of the methanogens in the two digesters. During the 2003 planning process, there was reportedly much public opposition on the grounds of visual impact and odours associated with the plant, however the scheme was approved at committee in July 2003 (following application in April 2003). The then plant operator, Biogen, has since joined forces with Greenfinch, to form BiogenGreenfinch, currently the most prolific UK AD company, with at least three operational plants, and several more are at planning and construction stages. Biogen has also been involved in a number of research and development projects on topics such as bio-digestion of kitchen waste, farm-scale biogas and composting to improve bathing water quality, ryegrass research and CROPGEN project.

Given the success of this supplier in delivering some 25 well integrated AD plants, the technology scores (TRL values) are among the highest. As such, the overall AD plant together with their stages (pre-treatment, conversion process, post-treatment/clean up, energy and integration) are all considered to be at a TRL of 9.

3.1.13 Tel Aviv, Israel

Technology	ArrowBio	**CapEx**	$22.8M investment
Process Stages	2-line		
Reactor Type	UASB	**Annual Throughput**	91,800 t/yr (Type 1)
Wet/Dry	Wet (hydro-mechanical process)	**Biogas Yield**	100 m^3/t
Operating Temperature (M/T)	nda	**Energy prod'n/ Capacity**	10,200,000 m^3/yr
Feedstock	MSW (segregated or not)		

ArrowBio is an Israeli company that is renewing the type of technology that was being tried out in the nineties, especially in the UK. They currently have two plants that take in mixed municipal solid waste (i.e. un-segregated).

The plant detailed above is based in Tel Aviv and operated by ArrowBio (parent company being ArrowEngineering). It is designed to treat residual MSW, and uses a relatively novel approach. Bags of mixed waste are split and the waste is tipped into a large tank of water (not unlike a swimming pool), in which the light waste fractions (paper, light plastic, etc) float and are scooped off, while heavier materials, such as metals, soil, grits and glass, fall to the bottom, are removed and further processed to retrieve valuable materials. Meanwhile, any papers and organics are soaked and mixed into the water, which is drained and sent to a wet anaerobic digestion process. The output digestate is made into soil conditioner.

There has been a low take up of the ArrowBio system, which suggests that investors are wary of the technology. This may stem from the fact that the EU is encouraging source separation of wastes in order to increase recycling. In addition, the digestate or the soil conditioner made from this process is likely to be more contaminated (with respect to heavy metals) and unlikely to meet the PAS110 criteria needed for unrestricted agricultural or horticultural use in the UK.

Although this technology is referred to as relatively novel, it has been working for some time, and is based on accepted techniques in conversion of biodegradable fraction by AD, post treatment, energy yields and overall integration. AEA has some concerns about the reliability of the waste suspension stage, so that is marked down to an 8, but all other aspects are considered to be at a TRL of 9.

3.2 Unsuccessful Plants

Many AD plants stand out as good practice. However, some of the early adopters have suffered, and a couple of examples are provided below. While it may be arguable whether the plants are strictly "unsuccessful", the difficulties they have had present some useful learnings.

3.2.1 Holsworthy, UK

Technology	Farmatic	**CapEx**	£7.7M, including £3.85M EU grant
Process Stages	Single (dedicated biomass)		
Reactor Type	CSTR	**Annual Throughput**	146,000 t/yr (Type 2)
Wet/Dry	Wet	**Biogas Yield**	27 m^3/t
Operating Temperature (M/T)	37ºC (pasteurisation 70ºC)	**Energy prod'n/ Capacity**	3,900,000 m^3/yr (2.1 MWe)
Feedstock	80% farm waste (mixture of cattle, pig and poultry manure collected from 30 farms in a 5-6 mile radius of the plant); 20% food waste (parasitic load 10%)		

Summerleaze Ltd, at Holsworthy, Devon was the UK's first centralised AD site, and opened in 2005 for the digestion of livestock slurry from some 30 dairy farms. The facility ran into financial difficulties, having to pay for its feed collection whilst being unable to generate any revenue from sales of its digestate – farmers were permitted to collect the digestate for free with their own transport. The problems associated with generating working capital for new plant and equipment eventually led to the German plant suppliers, Farmatic, going into liquidation.

However, the advent of the Animal By-Product Regulations (ABPR) created a demand for outlets for animal wastes previously applied to land, and the plant became commercially viable. It now handles organic wastes from bakeries and food processors, abattoirs, fish processors, cheese producers, biodiesel manufacturers and local councils, in a system currently capable of processing 80,000 tonnes per annum currently[7].

The facility also incorporates a Sepamatic de-packaging machine for food waste de-packaging. The methane produced is used to generate 2.1MW, with approximately 10% of this used to run the plant and the remaining 90% exported to the National Grid.[8] One advantage of accepting food waste is that it attracts higher gate fees than agricultural waste, encouraging the feasibility of the site. The plant employs around 15 people (5 managers/engineers, 5 on-site technicians and 5 drivers) with an operating cost of around £450,000/yr.

Overall, the Holsworthy Biogas plant is an interesting example of how the commercial viability of a facility can sometimes depend critically on legislative drivers. Although this plant initially struggled, the supplier has now delivered some 50 well integrated AD plants, so its technology scores are among the highest. As such, the overall AD plant together with their stages (pre-treatment, conversion process, post-treatment/clean up, energy and integration) are all considered to be at a TRL of 9.

3.2.2 Stornoway

Technology	Strabag (formerly Linde)	**CapEx**	£10M
Process Stages	2-stage		
Reactor Type	Nda	**Annual Throughput**	2,000 tpa (Type 1)
Wet/Dry	Dry	**Biogas Yield**	nda
Operating Temperature (M/T)	57°C (T)	**Energy prod'n/ Capacity**	0.23 MW (design)
Feedstock	Residual MSW, Source-separated MSW, food fish wastes		

The Western Isles Integrated Waste Management Facility in Scotland is a waste treatment centre incorporating recycling and MBT, in-vessel composting and the EarthTech AD plant. This plant also

[7] Holsworthy Biogas Plant, Case Study 2, http://www.devon.gov.uk/renewable_energy_guide_case_study_2.pdf and "UK's largest" AD plant permitted to take more food waste, 2008, **http://www.letsrecycle.com/do/ecco.py/view_item?listid=37&listcatid=333&listitemid=10429**
[8] Andigestion, Holsworthy, http://www.andigestion.co.uk/content/holsworthy

has a CHP system incorporated into it, which is designed to heat the AD system itself. Before installing this plant, the local council's MSW arisings were predicted to be about 20,000 tonnes per annum[9]. However, in 2010, it processed only around 3,200 tonnes of organic waste, sourced mostly from households (approximately 14,000) in the Western Isles. Of the collected organic waste, just over 2,000 tonnes is sent to the AD process, the reason being that, in most of rural Western Isles, they collect waste paper along with the household food waste and garden waste, and process the <60mm fraction in the AD and the >60mm comprises mostly of paper is disposed off site.

At present, the AD plant is running at approximately 15-20% capacity. The facility's IVCs were intended to process up to 4,000 tonnes per annum of the residual waste. It was assumed that, despite requiring all householders to place all their food and garden waste into the organic bin, some organic matter losses would be lost to the mixed residual waste bins. The original intention was that this waste would be coarsely screened to capture the compostable organic matter (with a degree of contamination) and it would be processed in the IVCs. In the event, the IVCs have failed to meet the required temperatures to be able to divert the compost like output (CLO).

The facility is an example of how a plant can fail to operate as intended if its waste feedstock is outside the limits expected by the designers, and points to the value of designing plants that can accept a range of waste materials. Moreover, the plant cannot really be said to have failed; it has simply not been fed as much waste as anticipated. Given the success of this supplier in delivering several AD plants of this design, the technology scores (TRL values) are among the highest. As such, the overall AD plant together with their stages (pre-treatment, conversion process, post-treatment/clean up, energy and integration) are all considered to be at a TRL of 9.

3.2.3 Other Plants

Unsuccessful plants are very rarely reported on, as any information about performance or design is guarded by the technology suppliers and/or respective users.

In Section 2.2.3, a 2-stage AD plant, based on BTA technology and installed in 1991 at Elsinore, Denmark was outlined. Although seen as State of the Art, the plant was found to be expensive to run, not least because the operator found it difficult to find outlets for the digestate (due to its chemical content from the acid-alkali pre-treatment). The plant also developed odour problems that could only have been resolved by investing in rather expensive odour abatement and control features due to its close proximity to dwellings. The plant has not been operating since the mid nineties.

3.3 Summary of Plant TRL Scores

As can be seen, the difficulty with the TRL analysis was that, because all the plants are operational, they must merit the award of the full 9 score, associated with "actual system proven through successful operation". Even for the two projects cited as "unsuccessful", Holsworthy is now performing well enough on a different feedstock under a different model, while we believe that the Stornoway plant is coping with its waste, but over-capacity for what it is being fed.

The above examination demonstrates that AD technology is at an advanced stage of development and in many respects considered mature and operating well as long as the plants have been designed to specific needs. However, there are some alternative means of delivering some of the unit operations in the overall AD plant that are still at TRL 4-6 levels, whose improvement would help to increase scope for AD in the future. The next section therefore seeks to identify those opportunities that will increase the uptake of the technology.

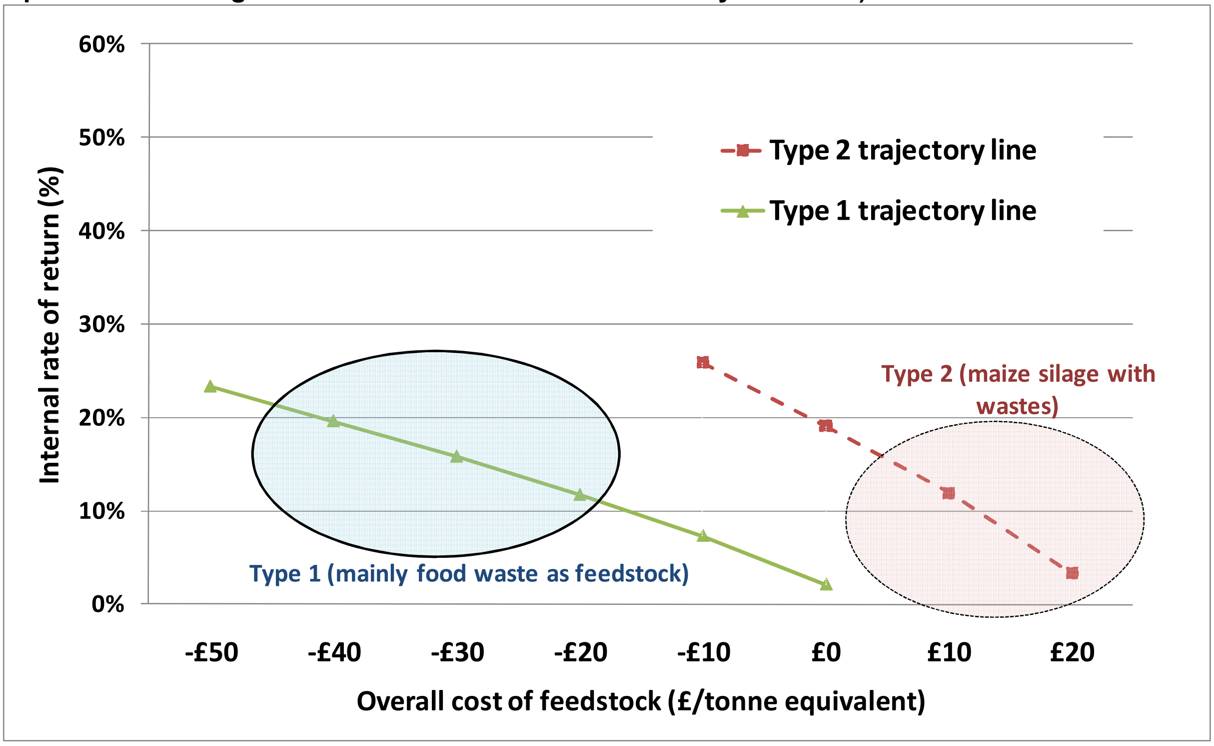
3.4 Commercial Assessment

The AD plants reviewed above will not be economic in their own right. They are in fact implemented because of the incentives currently being offered against AD plant performance (connected through energy recovery) but also because the technology helps to avoid a great deal of uncontrolled methane emission (e.g. from landfills and livestock slurry storage). As a result, AD technology has been gaining rapid and open favour with policy makers through such fiscal mechanisms as the Renewable Obligation Order, Feed in Tariff (FiT) and the Renewable Heat Incentive (RHI).

[9] Personal Communication, Kenny John MacLeod, 2010.

All of the above AD plants are classed as either Type 1 or Type 2. Relative economics of these two types of AD plants are commented on, based on a recent analysis (Mistry, 2010[10]). The analysis was based on both AD plant types producing around 3.5 million m3 of methane per year, supplying to a 1,500 kWe CHP engine and producing around 12 GWh of electricity per year. For the Type 1 AD plant the feedstock amounted to 40,000 t/a of source separated food waste. The analysis then considered a range of feedstock costs and the associated Internal Rate of Return (IRR). The same was done with Type 2 AD plants with the feedstock comprising varying proportion of livestock slurry and maize silage. The FiT rate of 9.0 p/kWh was used and the general picture that emerges is as illustrated in Figure 3.

Figure 3: Illustration of relative economics for Type 1 and Type 2 AD plants (shaded area represents the ranges of IRR and feedstock cost currently observed)



This graph is for illustrative purposes only.

It should be noted that the analysis was applied using a set of assumptions and economic numbers and is drawn for illustrative purposes only; but it does show the general trend that has emerged and the reactions of the industry. For instance, the Renewable Energy Association has publicly declared that the FIT rates are too low - where they cited mainly Type 2 AD plants. However, the WM industry that deals with food waste AD plants have not been as vocal despite their AD plants requiring a high degree of mechanical sorting and processing of waste and thereby more costly[11]. Most of these plants (Types 1 and 2) are designed to comply with the ABPR and the PAS110 specification requirements and therefore include on-site pasteurisation step and storage/holding for a minimum of 18 days.

In summary, Figure 3 illustrates that the returns on Type 1 AD plants tend to be between 5 and 25%, shown as shaded in green. The returns on Type 2 AD plants tend to be between 0% and 20%, as illustrated by the red shaded area. What is currently happening in the sector is that large plants tend to be based on readily available food waste feedstocks (Type 1) - often associated with major local authority contracts and/or commercial and industrial premises, while smaller plants (Type 2) tend to be based on a significant amount of livestock slurry and agricultural feedstocks. Both approaches provide a wide range of benefits including digestate sale, savings on the use of mineral fertiliser, environmental improvements, and income from the generation of renewable electricity.

[10] Bringing small scale AD to UK farmers – the challenge. Presented by Prab Mistry at the On-Farm Energy Generation Securing revenue streams from land based energy; 22nd-23rd June 2010, Stoneleigh Park Conference Centre, UK

[11] In a recent DECC consultation with industry, where AEA handled technical discussions and clarifications, the AD plants based on food waste were found to have around 25-40% higher capital cost than those based on livestock and agricultural feedstocks.

Clearly, the impetus is for the establishment of more AD plants. This is being driven by both waste management policies and targets and energy related policies and targets. The increasing use of economic incentives is helping to establish AD technologies across the UK and allow these technologies to demonstrate their favourable technical and financial performance.

While these AD plants (Types 1 and 2) are already happening, there is another category of plants (here called Type 3) which is likely to attract greater interest in the UK; these are much smaller scale on-farm AD systems that can be based on livestock waste and any agricultural residues that can be found within the confines of the farm. They are typically capable of generating around 100 kW of biogas or 35 kWe of electricity (see Table 4), and will address a number of objectives, including:

- improved livestock slurry management as well as reduced on-farm GHG emissions;
- generation of energy on-farm for use within the business and in local communities;
- opportunities for on-farm diversification activity as well as development of rural jobs; and
- reduced watercourse pollution risk due to enhanced nutrient release from digestate.

Currently, there are only a handful of digesters that meet the definition, and which have often been put up with farmer ingenuity making use of standard tanks to act as digester vessels. However, based on work undertaken by AEA and RASE recently , there is evidence that there would be a significant demand for smaller scale technologies adapted to the requirements of UK farms, if the overall cost of the plant could be brought down. Low-cost technologies are applied in other parts of the world, including India, Nepal and China, but these are unlikely to be suitable in the UK. The social and economic contexts within which these plants are operated are very different and because they are susceptible to biogas leaks and odour that may not stand the scrutiny of the regulators and the public in the UK.

Commercial or economic viability is closely linked to the capital cost of the installation, which we believe can be brought down by 20-40%. This is likely to come from innovative digester design, improved feedstock handling, ease of plant manufacture (e.g. pre-fabrication prior to installation) and process control. Other issues include effective use of biogas and effective integration of currently available technology into farm systems.

The above analysis was based on livestock farm holdings (~67,000 in England, from 2006 Farming Statistics) which were analysed to assess if individual farms could host an AD plant, based on their own livestock waste. It was found that the greatest impact from innovation would be on dairy farms, especially if a capital cost reduction of 40% could be achieved. Table 4 defines the likely ranges of dairy farm size alongside energy output and basic economics that could find well over 5000 applications in the UK alone. In fact, the technology innovation could provide modular, small footprint, easy to install and operate AD plants that should find thousands of applications in the UK. Such AD plants would also allow proliferation of small scale 'community digesters' (e.g. at schools, leisure centres, garden centres, work canteens etc). The key challenges are related to the capital cost of the AD plant equipment and effective cleaning and utilisation of biogas.

Table 4: Range of the on-farm AD plant characteristics

Key parameters	25 kWe (72 kW biogas)	35 kWe (100 kW biogas)
Installed capacity of CHP engine	28	40
Number of dairy cattle contributing 50% biogas generation (supplemented with waste silage)	135	190
Type of waste	Slurry	Slurry
Quantity of cattle slurry (kg/d)	14,000	20,000
Size of digester (m^3)	360	500
Total capital cost, current	£270,000	£300,000
Capital cost, with 40% reduction	£160,000	£180,000
Internal rate of return, with 40% reduction in capex	6%	11%

4. Future Developments

Although anaerobic digestion has long been commercial, further technology optimisation and cost reduction are still possible that could significantly improve the economic viability of smaller units. The main requirements are:

- to improve pre-treatment (to reduce digestion time);
- to reduce costs and to improve reliability of two-stage technologies;
- to improve biogas cleansing processes (mainly of corrosive H_2S); and
- to increase the robustness of the thermophilic process.

4.1 Operational Improvements

As already mentioned, mesophilic (~35°C) digestion is normally applied to low solids (high moisture) feedstock. Thermophilic digestion plants operate at higher temperature, around 55°C, and provide faster rates of digestion. They also provide higher conversion factors and thereby higher biogas yields, depending on the feedstock, but, on the other hand, are more prone to microbial failure.

Besides the process design and temperature of operation, it is important to understand sensitivity of various parameters that drive the economics of anaerobic digestion. Biogas yield is a key parameter in the economics of AD plants, and it can vary widely depending on several factors, including feedstock type, dry matter content, HRT, SRT and the overall mix of the feed (which can be influenced by mixing complimentary feedstocks). These parameters also influence biogas composition (i.e. its methane content) and hence its 'fuel' value for heat and power generation.

Owing to its complexity, key challenges with the AD technology revolve around how best to manage mixed waste streams and optimising the plant to maintain a consistent yield of biogas. Digesters for food waste tend to be more complex and expensive, as they need to recover bacteria in the effluent (e.g. using a down-flow filter bed or an up-flow sludge blanket), involve more operator training, and are also prone to acidification and failure. Increasingly, AD plants are having to handle more complex feedstock and varying volume streams. Although requirements in terms of reliability, stability and robustness are significant, such plants can produce a high yield of biogas of a high quality.

On the technical side, AD offers many applied research challenges and therefore scope for partnership between R&D orientated and commercial waste enterprises. Some of the challenges that need addressing relate to standard operations and tradeoffs of reactor performance (e.g. temperature, reactor size, flow rates, sensitivities, yields, costs), because these translate directly to business performance (of the waste management service provider) and investment performance.

4.2 Pre-Treatment Technologies

Pre-treatment and separation processes to remove any contaminants or to homogenise the organic feedstock generally prove more cost-effective than investing in capital intensive refining processes for digestate. The first pre-treatment operations are normally physical operations to reduce the size and increase the surface area of the feedstock, improving its accessibility to the reagents used. Washing may also be necessary for some feedstocks, and steaming followed by solvent washing has been proposed to remove resins that may inhibit the later biological processes.

Other physical methods have also been proposed for pre-treatment, usually in combination with dilute acid treatment (see below), the most common being steam explosion, where the slurry in the pre-treatment stage is flashed to low pressure to break open the cell structure. Acid will need to be recovered and sugars washed from the process and the liquor neutralised following pre-treatment. Lignin is also removed at this stage. Most developers propose to use this as a fuel for power and process heat generation.

4.2.1 Hydrolysis

Pre-treatment is followed by a second hydrolysis stage, where the cellulose is converted to six-carbon sugars. Historically, this has been achieved by acid hydrolysis using a higher temperature but lower concentration acid than in the pre-treatment step. An alternative route uses concentrated acids, which improves the yield of sugar but is critically dependent for its economics on effective recovery and reuse of the acid. This is technically possible but difficult and involves complex engineering.

Acid-based processes have been proven for many years, but only now are demonstrations being planned in the USA and the EU. This lack of progress has been historically due to the expensive equipment necessary and the low price of competing ethanol from sugar and grain. Only with the recent interest in ethanol as a biofuel has development restarted on this process. Following hydrolysis, the process will include separation stages, to wash out the sugars and remove fermentation inhibitors such as heavy metal contaminants and organic products of hydrolysis, followed by neutralisation with lime if acid has been used.

In the last decade, an alternative enzyme hydrolysis route has been proposed and developed to pilot stage. This technology has the potential to achieve high conversion rates with low production of inhibitors, due to the mild reaction conditions. The key development necessary for commercialisation is to reduce by an order of magnitude the cost of the enzyme cellulase. Enzyme-based processes are still in the development phase but offer the prospect of being economically more attractive than other options, if their further development is successful.

A substantial research programme has been underway for over a decade in the USA and EU to commercialise this technology.[12] This has resulted in several demonstration plants, but as yet no fully commercial installations.[13] In the UK, Aquegen has proposed to use MSW fractions at its installation to be built at South Milford in West Yorkshire. The chemical process appears to be acid hydrolysis of the cellulose and hemi cellulose, but the impact on the fermentation stage is unclear as such operating data is scarce.

4.3 Biofuels

Experience from the progress in second and third generation biofuels is also relevant to a discussion about AD development opportunities. Second generation biofuels are novel biofuels or biofuels based on novel feedstocks. They generally use biochemical and thermo-chemical routes that are at the demonstration stage, and convert ligno-cellulosic biomass (i.e. fibrous biomass such as straw, wood, and grass) to biofuels (e.g. ethanol, butanol, syndiesel). Most ethanol is produced industrially by the fermentation of sugars by yeasts or bacteria, although increasing consideration is being given to producing it from wood, ligno-cellulosic materials and the stem material of plants, by hydrolysing them.

In dealing with second generation biofuels, ligno-cellulosic materials are used to obtain two forms of sugars, cellulose and hemi-cellulose, both in polymer form. They are enclosed in a coating of lignin, a compound with no sugars that gives the plant its structural strength. To obtain fermentable sugars, it is first necessary to release the cellulose and hemi-cellulose from the lignin and then hydrolyse them to simple sugars. This step has proved technically to be the most difficult and is the subject of most of the research and development in this process. Once produced, the sugars can be fermented by yeasts or bacteria to produce bioethanol production. The same approach could in fact provide abundant feedstock for AD.

Third generation biofuels are generally defined as advanced biofuels from production routes that are at an early stage of research and development or are significantly further from commercialisation. These include biofuel production from algae and hydrogen from biomass. Algae are a large and diverse group of simple organisms that range in size from single cells (micro-algae) to complexes of multiple cells (macro-algae), including seaweed. Micro-algae is attracting attention as an alternative biomass feedstock, because it can be processed to produce high yields of oil that can be used as a feedstock for further refining into transport oil. For AD, seaweed holds out some promise as a large variety of seaweeds is available around the world. The key issues associated with seaweed AD are related to its moisture, salinity and toxicity. These can be overcome with appropriate design of the AD plant and operation regime. However, due to seasonality of the availability of seaweed, AD plants would have to be based on co-digestion with other complementary feedstocks.

In AEA's opinion, AD of seaweed is at least a decade away from becoming a serious commercial proposition. This is mainly owing to the fact that the quantity of seaweed washed up on beaches may be rather low, and seasonal. The obvious alternative of specifically cultivating seaweed has been fraught with uncertainties over volume, cost, regulatory impacts and environmental issues.

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[12] IEA (2008) From first to second generation biofuel technologies: An over view of current industry and R,D & D activities

[13] www.abc-energy.at/biotreibstoffe/demoplants.php.

4.4 Biogas Use Technologies

Biogas cleaning for use in heat or CHP generation is already well established, and more recent developments have focused on the production of biomethane for vehicles or gas grid injection. This is done by first removing the carbon dioxide and other impurities by scrubbing and ensuring that the calorific value (or energy content) closely matches that of the natural gas in the network. The resulting gas can then be compressed and, as processed biomethane, injected into the gas grid. Injecting biomethane is a way of making the gas in the grid more renewable, and has the advantage of using existing gas infrastructure. There are existing regulations governing the composition of biomethane and its injection into the UK gas grid (Ofgem, National Grid and the Health and Safety Executive have responsibility in this area).

Experience to date has been based on biogas from landfills and sewage sludge digesters. The technology is suitable at large scale, using in excess of 500 m^3/h of biogas (i.e. using biogas in excess of 3 MW). Although there are well established technologies for biogas cleanup, there is considerable ongoing development work to improve them and reduce their cost, especially at lower flows of gas.

There is a variety of technologies used to clean gas, and they are at differing stages of development. Three main biogas cleaning technologies in widespread use are described below:

+ **Water scrubbing:** This is generally the lowest cost technology for larger plants, where there are suitable economies of scale. It requires towers 14m high, which may require planning permission, and these towers can also recover some heat. The technology recovers 99% of methane, with 1% being vented to the atmosphere, and also removes H_2S and siloxanes.
+ **Chemical absorption:** This approach recovers 99.5% of the methane in the biogas, venting <0.5%. However, it does require significant process heat, making it ideal where waste heat is available, such as may be the case at a site that also has a CHP unit that is not fully utilised. If heat is not available, 15-20% of the biogas supply is required to produce it. Some stakeholders identified a possible risk of gas contamination when using this technology.
+ **Pressure Swing Adsorption (PSA):** This approach only concentrates 92% of the methane in the biogas, with the remaining 8% being siphoned off with the extracted CO_2. The 8% fraction can be burned but needs to be concentrated back up to around 30% methane to do so. However, the process does not vent any methane direct to the atmosphere. PSA technology also has the advantage of having a very small footprint.

Two more promising further technologies, cryogenic upgrading and membrane separation, are in development but are currently expensive and unproven in the field.

Some projects are seeking to bring in portable biogas clean-up kit based on chemical absorption. This arrives in an articulated trailer that contains a compressor, so biogas goes in one end and compressed biomethane (CBM) comes out of the other ready for use in vehicles. Such equipment is currently available on lease and therefore considered fully developed.

At present, a UK Government funded project (under ETF-AD Demonstration Programme managed by WRAP) is underway to demonstrate the biogas cleaning and upgrading at 250 m^3/h facility based at the Daveyhulme STWs operated by United Utilities. The equipment specified is Carbotech's biogas cleaning and upgrading technology based on PSA, which uses carbon molecular sieves for removing CO_2 and a catalytic activated carbon for removing H_2S from the raw biogas. The facility is designed to operate at around 7 bar pressure and 25°C temperature and is aimed at producing compressed biomethane that will be suitable for vehicle use and, after conditioning, for injection into the gas grid.

4.4.1 Other Improvements

Techniques to improve the biological digestion process (through ultrasonic treatment or enzymatic reactions) are currently at the R&D stage. These approaches could increase biogas output by several percentage points.

Microbial fuel cells could have interesting prospects in the longer term, but are still at an early stage of development. The concept is that micro-organisms are selected that digest the biomass to generate a hydrogen-rich 'biogas' that can in turn be used in fuel cells. Although feasibility has been proven, this technology will need to go through a great deal of R&D before it could reach demonstration stage. At present, this technique is being incorporated into the development of biomass measurement tools to assess energy content of feedstocks. This work is being carried out by teams at several universities in the UK, including by Ioannis Ieropoulos and Tim Cox in the Faculty of Environment and Technology at the University of the West of England.

Food waste separation from packaging has become an important area of development in the last few years. Several AD plants, especially those that collect food waste from commercial and industrial places, are implementing these. Two plants that are near completion are at FR Brooks site near Bristol and Langage Farm AD plant near Plymouth.

5. Conclusions and Recommendations

5.1 Principal Conclusions

This review has covered anaerobic digestion (AD) as part of a wider Energy from Waste (EfW) project, in order to examine the technology development and demonstration needs. The Consortium's requirement for this project was an up-to-date assessment of current development and demonstration activities in EfW technologies, with reference to NASA's Technology Readiness Levels.

A large number of technology providers have designed, built, commissioned and operated AD plants. There is a very large number of wet single stage, wet multi-stage but also some dry single stage operating plants. There are many configurations of the actual AD process itself. The wet multi-stage approach appears to be the most favoured amongst the AD plants for food waste processing. Additionally, there are examples of both mesophilic and thermophilic processes, but the number of mesophilic processes amongst the reference plants far exceeds the thermophilic processes. In some cases, these plants have been operational for a significant number of years, but gradual improvement in the technology and operations continues unabated.

From our search, we identified over 60 operational AD plants for consideration for this project (see Annex I), from which we selected some 15 to provide key technical information on their feedstock and performance. There are also some plants that are 'considered' unsuccessful but lessons from these are limited, partly because the reasons are often to do with inappropriate specification rather than being any fault of the technologies concerned. Among these was a 2-stage AD plant, based on BTA technology and installed in 1991 at Elsinore (Denmark) that was seen as State of the Art at the time and which focused on maximising biogas production. It was found to be expensive to run and so when odour problems developed, which would have required yet more expenditure, the owners decided to close the plant, some two years after it was commissioned.

There is a general difficulty with the TRL analysis in that nearly all the plants are operational and they merit the highest score. The examination demonstrates that AD technology is at an advanced stage of development and in many respects considered mature and operating well as long as the plants have been designed to specific needs.

Although anaerobic digestion has long been commercial, further technology optimisations and cost reductions are still possible that could significantly improve the economic viability of smaller units. The main requirements are:

+ to improve pre-treatment (to reduce digestion time);
+ to reduce costs and to improve reliability of two-stage technologies;
+ to improve biogas cleansing processes (mainly of corrosive H_2S); and
+ to increase the robustness of the thermophilic process.

Owing to its complexity, key challenges with the AD technology revolve around how best to manage mixed waste streams and how to optimise the plant to maintain a consistent yield of biogas. Digesters for food waste tend to be more complex and expensive, as they need to recover bacteria in the effluent (e.g. using a down-flow filter bed or an up-flow sludge blanket), involve more operator training, and are also prone to acidification and failure. Increasingly, AD plants are handling more complex feedstock and varying volume streams. Although requirements in terms of reliability, stability and robustness are significant, such plants can produce a high yield of biogas of a high quality.

There is, however, a category of AD plants that are likely to attract even greater interest in the UK. These are much smaller scale on-farm AD systems that can be based on livestock waste and any agricultural residues that can be found within the confines of the farm. There could be a significant demand for these if the overall cost of the plant could be brought down by around 40%. In fact, the technology innovation could provide modular, small footprint, easy to install and operate AD plants that should find thousands of applications in the UK. Such AD plants would also allow proliferation of small scale 'community digester' (e.g. at schools, leisure centres, garden centres, work canteens etc). The key challenges are related to capital cost of the equipment of the AD plant and effective cleaning and utilisation of biogas.

Various pre-treatment options can be applied to homogenise and solubilise the sugars for digestion. The most common is steam explosion, where the slurry in the pre-treatment stage is flashed to low pressure to break open the cell structure. Acid can then be recovered and sugars washed from the process and the liquor neutralised following pre-treatment. Techniques to improve the biological digestion process (through ultrasonic treatment or enzymatic reactions) are currently at the R&D stage. These approaches could increase biogas output by several percentage points.

Hydrolysis of feedstock to extract sugars is technically possible but difficult and involves complex engineering, making it rather expensive. However, with much interest in bioethanol from woody feedstock, this approach will be explored further. An alternative enzyme hydrolysis process is also possible, but any commercialisation in this area will require a significant reduction in cost of the enzyme, cellulase. Substantial research has been underway for over a decade in the USA and EU to develop this technology, resulting in several demonstration plants, but as yet no fully commercial installations exists.

Biogas cleaning for use in heat or CHP generation is already well established, and more recent developments have focused on the production of biomethane for vehicles or gas grid injection. Experience to date has been based on biogas from landfills and sewage sludge digesters. The technology is suitable at large scale, using in excess of 500 m^3/h of biogas (i.e. using biogas in excess of 3 MW) and there are well established technologies for biogas cleanup, including water scrubbing, chemical absorption and pressure swing adsorption (PSA). Two more promising technologies – cryogenic upgrading and membrane separation – are in development but are currently considered to be expensive.

From this work and our knowledge of the sector, we would draw the following conclusions:

+ Past experience shows that the cost of implementing new technology falls as the market size increases. Similarly, the capital cost of AD plants is expected to reduce as the number of applications continues to grow.
+ Single stage AD technology is relatively inefficient with respect to semi-solid waste, but will continue to be applied, with some modification, as it provides greater flexibility when feedstocks are prone to change from season to season or even daily.
+ Multi-phase AD provides greater energy yield, but is relatively more costly (tankage, quality of digestate, high level of control etc).
+ Pre-hydrolysis involving the use of chemicals or enzymes may prove too costly (the digestate will require different handling) to reach financial viability, but it will be important to keep abreast of the development with second and third generation biofuels, which look more promising.
+ Hydrolysis of the hemicellulose and cellulose fractions of ligno-cellulosic materials is still at the development stage, although there are plans for demonstrations in the EU and USA. It is not clear whether this should be a priority for the UK at present, since the same feedstock could potentially be used in more efficient thermal processes such as gasification and pyrolysis.

Going forward, AEA considers that incremental changes in the performance of AD technologies will occur in multi-stage AD plants for Type I applications, and around the effective use of biogas (50-100kW) at small scale (Type 3).

We see four potential opportunities for disruptive or step-change innovations in the market:

1. Biogas cleaning and compression (for gas grid or vehicle use) for Medium Scale AD plant applications generating around 300kW and 1500 kW of biogas (Type 2) applications
2. Multi-stage AD plant for Type 2 applications
3. Thermo-chemical pre-treatment of wastes to increase biodegradability of feedstock
4. Single stage AD plant for dairy farms (Type 3)

As might be expected, there are countless enterprises carrying out various development projects in AD of waste. Scottish Enterprise has recently funded work towards second and third generation biofuels to deal with AD engineering, micro-biological and implementation aspects. For instance:

+ Abertay University was examining co-digestion at high temperature (thermophilic) range
+ Newcastle University was using mixed beach-cast seaweed to examine methane yields
+ Glasgow Caledonian University was developing microbial cultures suitable for efficient conversion of seaweed

+ Zebec Systems was developing enzymes for use in seaweed AD plants
+ B9 Organic Energy in association with Questor (Queens University) was examining optimisation of seaweed and possible co-mixed waste AD process

If the Consortium decides it wishes to investigate further what is being done, AEA suggests these enterprises could be a good starting point.

5.2 TRL Assessment to Identify Future Improvements

In this review, AEA has looked at the current level of development of Anaerobic Digestion for the treatment of waste, and the possible directions of future developments. There is a general difficulty with the TRL analysis to be able to suggest future improvements, especially since the above analysis shows that AD technology is at an advanced stage of development and in many respects considered mature and operating well, as long as the plants have been designed to specific needs.

Figure 4 shows the TRL status of the technologies linked to **large scale AD plants**. Overall, AD plants are seen as a mature technology. However, some improvements in AD process applications, especially those dealing food wastes, will help to enhance the performance.

Figure 4: TRL status of the technologies linked to large scale AD applications

2010-30	Integration parts TRL:	1	2	3	4	5	6	7	8	9
AD - Type 1 Food wastes mainly	AD1 - Pretreatment PHYSICAL/MBT									
	AD1 - Pretreatment THERMO-CHEMICAL									
	AD1 - Pretreatment BIOLOGICAL									
	AD1 - Process technology									
	AD1 - Post treatment									
	AD1 - Biogas cleaning for CHP/heat									
	AD1 - Biogas to grid biomethane									

Figure 5 shows the TRL status of the technologies linked to **medium scale AD plants**. A great deal of the experience gained from European countries is being drawn into the UK. It will be important to focus on AD process technologies that are optimised for biogas yield and rate and on the applications that help to serve the biomethane markets (vehicle use or grid injection). In order to do this, smaller scale biogas to biomethane plants will be needed. Any improvements in pre-treatment of the feedstock, such as agricultural residues, will help to increase the biogas resource in the UK.

Figure 5: TRL status of the technologies linked to medium scale AD applications

2010-30	Integration parts TRL:	1	2	3	4	5	6	7	8	9
AD - Type 2 Co-digestion	AD2 - Pretreatment PHYSICAL									
	AD2 - Pretreatment THERMO-CHEMICAL									
	AD2 - Pretreatment BIOLOGICAL									
	AD2 - Process technology									
	AD2 - Post treatment									
	AD2 - Biogas cleaning for CHP/heat									
	AD2 - Biogas to grid biomethane									

Interest in **small scale AD technology** is gradually increasing and will require some innovation, not least to bring down the capital cost by considering modularisation and industrial manufacturing of standard units that can be installed in days rather than months. We estimate that such a focus would take between two and five years to reach TRL 9 status, if sufficient focus is brought to bear on this technology.

Figure 6: TRL status of the technologies linked to small scale AD applications

2010-30	Integration parts TRL:	1	2	3	4	5	6	7	8	9
AD - Type 3 On-farm (selective C&I by-products)	AD2 - Pretreatment PHYSICAL									
	AD2 - Pretreatment THERMO-CHEMICAL									
	AD2 - Pretreatment BIOLOGICAL					N/A				
	AD2 - Process technology									
	AD2 - Post treatment									
	AD2 - Biogas cleaning for CHP/heat									
	AD2 - Biogas to grid biomethane					N/A				

AEA Technology

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Annex I: Full List of AD Processes

	Site Name		Technology	System	[3]
1	Salzburg	AT	OWS	Dry: Single	
2	Biogas Plant, Merksplas	BE	Envitec	Wet: Single (CSTR)	
3	Biogas Plant, Viermaal	BE	Envitec	Wet: Single (CSTR)	
4	Brecht II	BE	OWS (Dranco)	Dry: Single (Plug)	Y2
5	Toronto	CA	BTA	Wet: Single	
6	Biogas Plant, Julcin	CZ	Envitec	Wet: Single (CSTR)	
7	BGA Hinske	DE	NES GmbH [1]		
8	BGA Luneburg	DE	NES GmbH [1]	Wet: Multi (2 stage)	~~Y1~~
9	BGA Stellinger Moor	DE	NES GmbH [1]	Wet: Multi (2 stage)	
10	Engelskirchen	DE	Valorga	Dry: Single (Plug)	
11	Freiburg	DE	Valorga	Dry: Single (Plug)	~~Y2~~
12	Greimel Biogas Plant I	DE	UTS	Wet: Multi (2 Stage)	~~Y1~~
13	Greimel Biogas Plant II	DE	UTS	Multi (2 Stage)	
14	Jessen	DE	Strabag	Dry: single	Y2
15	Kirchstockach	DE	BTA	Wet: Multi (2 stage)	
16	Kogel	DE	Entec Biogas	Wet: Single(CSTR)	~~Y1~~
17	Lechfeld	DE	Strabag	Dry: single	
18	Malchin	DE	Entec Biogas	Wet: Multi (acidification, CSTR Digester, Post Digester)	~~Y1~~
19	Mulheim a.d. Ruhr	DE	BTA	Wet: single	~~Y2~~
20	Pellmeyer Biogas Plant I	DE	UTS	Multi (2 Stage)	
21	Pellmeyer Biogas Plant II	DE	UTS	Multi (2 Stage)	Y1
22	Senftenberg	DE	Entec Biogas	Wet: Multi (acidification, CSTR Digester, Post Digester)	
23	Gustrow Bioenergy Park	DE	Envitec	Wet: Single	~~Y2~~
24	Biogas Benet	FR	Entec Biogas	Wet: Multi (acidification, CSTR Digester, Post Digester)	Y1
25	Nakasorachi	JP	Entec Biogas	Wet: Multi (2 stage)	Y1
26	Tilburg	NL	Valorga	Dry: Single (Plug)	Y2
27	Waterschap Veluwe	NL	HoSt Bioenergy Installations	Multi (2 Stage)	Y2
28	Adnams Brewery	UK		Wet:	
29	Barfoots of Botley	UK	MT-Energie	Wet:	
30	Barkip	UK	Xergi	Multi (2 stage)	Y2
31	Bedford	UK	WELtec		
32	Biocycle	UK	WELtec	Wet: Single	
33	Bourne park Estate	UK		Wet:	

	Site Name		Technology	System	[3]
34	Bulcote Farm	UK	Schmack Biogas		~~Y1~~
35	Carr Farm	UK	Monsal		
36	Cassington, Oxford	UK	Agrivert	Multi stage	Y1
37	Davyhulme WwTW	UK		(Conventional sludge digester, CSTR)	
38	Deerdykes	UK	Monsal	Wet:	
39	Didcot Sewage Works	UK	Chesterfield Biogas	(Conventional sludge digester, CSTR)	
40	Doncaster	UK			
41	Glenfarg	UK	UTS		
42	Holsworthy	UK	Farmatic	Wet: Single(CSTR)	Y3
43	Langage	UK	FITEC		~~Y2~~
44	Lower Reule Bioenergy	UK	WELtec		
45	Melbury Dairy	UK	Biogas Nord	Multi (2 Stage)	
46	Nigg Bay WwTW	UK	CAMBI		
47	Northwick Estate	UK	MT-Energie		
48	Organic Power	UK	Organic Power		
49	Poplars Landfill Site	UK	Ros Roca Envirotec		~~Y1~~
50	Rogerstone	UK	InSource Energy		
51	Rothwell Lodge	UK	WELtec	Single	
52	Sandhill, Driffield	UK	NES GmbH [1]	Wet: Multi (Hydrolysis + primary and secondary stage)	
53	Selby Renewable Energy Park	UK	Entec Biogas	Wet: Multi (acidification, CSTR Digester, Post Digester)	Y1
54	Staples Vegetables	UK	Xergi		
55	Stornoway	UK	Strabag [2]	Dry	Y3
56	Twinwoods, Beds	UK	WELtec, BiogenGreenfinch	Single	Y2
57	Wanlip	UK		Wet: Multi (2 stage)	
58	Westwoods Plant	UK	WELtec		
59	March, Cambs.	UK	Local Generation		
60	RF Brookes, Newport	UK	InSource Energy		~~Y2~~
61	Tel Aviv	IL	ArrowBio		Y2

Notes:
1 NES GmbH was formerly Hese Umwelt GmbH
2 Strabag was formerly Linde
3 The last column shows the reason for selecting the chosen plants. Those with struck-through text were originally shortlisted but then removed from the review, on the basis of a lack of relevant and noteworthy data.

Annex II: Pellmeyer II AD Plant

This plant uses energy crops as feedstock for AD plant and is among the highest performers. The description given below shows that while individual unit operations are fairly standard, their integration is the key to ensure that the plants deliver the economic returns. This plant was commissioned in 2006 at the Pellmeyer farm and the description below is taken from the supplier's web site[14].

This plant is owned and operated by Biomasse Kraftwerk Eggertshofen GmbH and it was designed by UTS to take advantage of the high tariffs offered by the German government for the generation of renewable energy using energy crops grown on 150 ha Pellmeyer farm along with other biomass sourced locally.

Pre-treatment

The feedstock comprises 9,000 t/a of maize silage, which is grown on site at the Pellmeyer farm; a further 3,600 t/a of grass is imported from the adjacent farms – both of which are silaged in order to provide a year round supply. No other significant pre-treatment is required. Maize and grass silage is stored in the open hardstanding areas. A front loader is used to transport the silage from the clamp to an automated solids feeder, which transfers feedstock to the two primary digesters via a conveyer belt system. Feedstocks are added to the primary digesters at a rate of approximately 25 t maize silage per day and 10 t grass silage per day.

AD stage

This stage comprises two primary digesters each with a volume of 1,527 m3 (i.e. 3054 m3 total volume). These are above ground tanks of concrete construction, insulated with 80 mm of extruded polystyrene and externally clad with plastic coated box section cladding. Primary fermenters are internally heated using stainless steel heating rings. The plant also includes a secondary digester with a volume of 2,281 m3. Construction is as per the primary digesters described above.

Digester temperatures are maintained at 39-40°C using heat from the CHP engines. Feedstocks entering the digesters would be anticipated to contain approximately 33% TS of which 95% would be volatile solids. The designed loading rate for the plant is 3 kg VS/m3.d. Fermenters are mixed using hydraulically powered mixers supplied by UTS (3 No. per fermenter). Retention time in the primary and secondary digesters totals 70-80 days.

Biogas is desulphurised through the addition of a controlled amount of air into primary and secondary digesters to encourage the growth of sulphide oxidising bacteria at the gas / substrate interface. Air is added subject to the measured H2S concentration with the aim of reducing concentrations to <100 ppm. Nutrients are added at a rate of 400 ml / d (a mix of trace elements, some salts and iron). Parameters monitored include temperature, liquid level, gas pressure, gas quality values and CHP performance.

Energy production and integration

Biogas is produced at the plant at a rate of approximately 220 m3 biogas per tonne of substrate treated. This corresponds to an annual biogas production of approximately 2,810,949 m3/yr. Biogas quality is monitored continuously, which is found to average 53% methane. Biogas is collected from the primary, secondary and digestate storage tanks and passed via gas cooling pipework to reduce moisture content. Gas condensate is collected within a sump.

Electricity is generated using two 370 kW CHP plants driven by gas powered engines, giving a total generation capacity of 840 kW. Electrical energy production for the plant is 5,800 MWh/yr with an internal parasitic demand of approximately 10% (incl. CHP usage). Thermal energy production for the plant is 5,000 MWh/yr with an internal parasitic demand of approximately 25%. Any excess thermal energy is either used to dry wood chips or vented to atmosphere via heat exchangers located at the CHP building.

Digestate

Digestate is stored within an above ground concrete tank with a volume of 5,609 m^3, which is also insulated and could be heated, if required. The digestate storage tank also includes a flexible membrane roof that acts as a form of biogas storage for the plant. Contents of the digestate storage tank are mixed.

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[14] http://www.walesadcentre.org.uk/Controls/Document/Docs/Pellmeyer%20Case%20Study%20(FINAL).pdf

As per the waste treatment AD plant the digestate produced is utilised on adjacent farms to grow more energy crops, put onto land is with the dribble bar hose applicator. The digestate is stored for 180 days. As with the digestate from the waste plant, crop yields have remained unchanged since applying digestate to land, although improvements in the soil condition have been noted. Typical analysis of the digestate is as follows:

	% (Dry Matter)	% (Fresh Matter)
Dry Matter	5.8	
N		0.30
NH_4		0.19
P_2O_5		0.15
K_2O		0.40

Water and wastewater treatment

The plant does not utilise any fresh water within the digestion process. Site surface waters and runoff, particularly from the silage storage areas, are collected within a central sump and then stored within an above ground concrete tank with a storage volume of 923 m3. This is spread directly onto the adjacent fields, and not used in the digestion process.

Costs and Economics

Capital costs for the plant are understood to have been approximately 3.0 million Euros. Tariffs for the energy generated at the plant are per the EEG2004. The tariffs generated at the plant are therefore summarised in the table below:

EEG 2004 Tariff Element	Cent / kWh_e (or kWh_{th} if stated)
Basic Compensation (up to 150 kW)	11.5
Basic Compensation (150-500 kW)	9.9
Basic Compensation (over 500 kW)	8.9
Energy Crop Bonus	6.0
Technology Bonus	2.0
Heat Utilisation Bonus	2.0 kWh_{th}
Degression	1.5%

Each kWh of electricity generated at the site would therefore attract a total tariff of 16.9 Euro Cents giving a gross income of approximately 980,200 Euros per year, and each kWh of heat would attract a further 2 Euro Cents (multiplied with the CHP coefficient) giving a gross income of 120,000 Euros per year.

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