Environmental Protection in Anaerobic Digestion: How implementation of a renewable technology can lead to greater risk of environmental harm.

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The Anaerobic Digestion (AD) industry has seen a rapid expansion in the last ten years, with over 600 plants now operating or in development in the UK. This technology is set to continue to grow due to subsidies available and development of biomethane plants, which inject upgraded biogas into the gas grid. AD plants offer an excellent way of harnessing energy from waste that would naturally decompose leading to greenhouse gas emissions, but poor implementation and operation can lead to damage in other areas of the environment, particularly ground, groundwater and surface water.

The technology has grown from what was initially agriculturally focused and has spread to commercial and municipal food waste, and industrial and domestic wastewater treatment. This has sometimes led to issues with the level of safeguards in place to deal with hazardous events - from both a safety and environmental perspective.

AD facilities must be designed and operated to manage a complex set of hazards; the explosive nature of the methane within biogas, the asphyxiation risk from the storage and handling of biogas, the toxic gases the biogas contains, as well as ensuring the risk of pollution associated with loss of containment is suitably managed.

This paper will discuss some of the incidents that have occurred in the AD sector in the UK, including a summary of the event and what lessons could be learned. The paper will also highlight some of the common issues seen in AD facilities that increase the risk of environmental damage such as; lack of secondary containment, poor odour control, lack of instrumentation, or flares – to reduce the impact of biogas release.

Further issues that will be discussed include how the often remote location of AD facilities can lead to them being close to small surface water bodies that can be sensitive to pollution event, and how the irregular presence of operators can mean that process deviation are not rectified promptly – or at all.

In spite of this, there are plenty of examples of good practice; from designers learning from their mistakes, developers implementing a rigorous Hazard Study plan, and the implementation of independent protection layers.

While AD may be a new area for some, the paper aims to highlight some of the issues being faced by a technology reaching maturity here in the UK. Furthermore, despite its relative infancy, many lessons can be learned across the spectrum of Process Safety.

Keywords: AD, Anaerobic digestion, biogas, biomethane, renewable energy, waste, environmental protection, environment, waste, process safety

Introduction

The use of Anaerobic Digestion (AD) to generate biogas is far from new technology, with records showing biogas in use for heating and lightning in the late 19th century (T. Abbasi, 2011). However, the use of this technology in the UK has rapidly expanded over the past ten years due to a regulatory emphasis on the treatment of segregated food and organic waste. In addition, the introduction of fiscal incentives to encourage the production of heat, electricity and substitute natural gas. There are now over 600 AD plants in the UK, either operating or in development (ADBA, AD Map, 2018), and while the growth of the industry has been rapid, it is predicted to slow as incentive degression continues, and the availability of organic feedstock reaches a peak.

The agricultural sector initially adopted the technology with cattle slurry and animal manures being the most common feedstocks. These wastes would traditionally be stored in slurry tanks or manure clamps before spreading on fields. While stored, the wastes would emit methane, a powerful greenhouse gas, 25 times more potent than carbon dioxide. The use of AD allows the methane to be captured and converted to renewable energy leading to a significant reduction in greenhouse gas emissions compared to traditional management techniques. In a similar manner diversion of food and other organic wastes from landfill to AD can also lead to reductions in greenhouse gas emissions most notably from the reduction of fugitive landfill gas emissions.

While the environmental benefits of reducing GHG emissions are clear, it is sometimes the case that the implementation and operational management of AD facilities poses a heightened risk to the environment. There is a range of examples, just from the UK AD sector – where lack of suitable controls, emergency procedures, safe working practices, and poor maintenance have led to catastrophic events.

This paper aims to raise awareness of the major accident hazards present at AD facilities, some of the general aspects that can affect environmental risks as well as highlight some of the common and more severe incidents in the sector.

Basics of the AD Process

At its simplest, anaerobic digestion is the biological breakdown of organic material - specifically carbohydrates, fats and proteins - within the digester contents (known as substrate) into carbon dioxide and methane, in the absence of oxygen. As with most biochemical processes, the individual steps of the reactions and the biology involved is complex. The AD reactions can be split into four sequential steps, with different types of bacteria or enzymes involved at each stage.

- Hydrolysis - The breakdown of long-chain carbohydrates, fats, and proteins into easier to digest compounds such as amino acids, fatty acids, and simple sugars.
- Acidogenesis - a range of acidifying bacteria convert the simpler organic compounds into Volatile Fatty Acids (VFAs) such as formic, lactic, acetic and propionic acids, as well as alcohols, carbon dioxide and hydrogen.
- Acetogenesis – acetic acid is generated from VFAs, lactic acid and alcohols by acetogenic bacteria
- Methanogenesis - methane is generated from acetic acid by methanogenic bacteria along with converting other compounds such as formic acid, methanol, methylamine and hydrogen with carbon dioxide into methane.

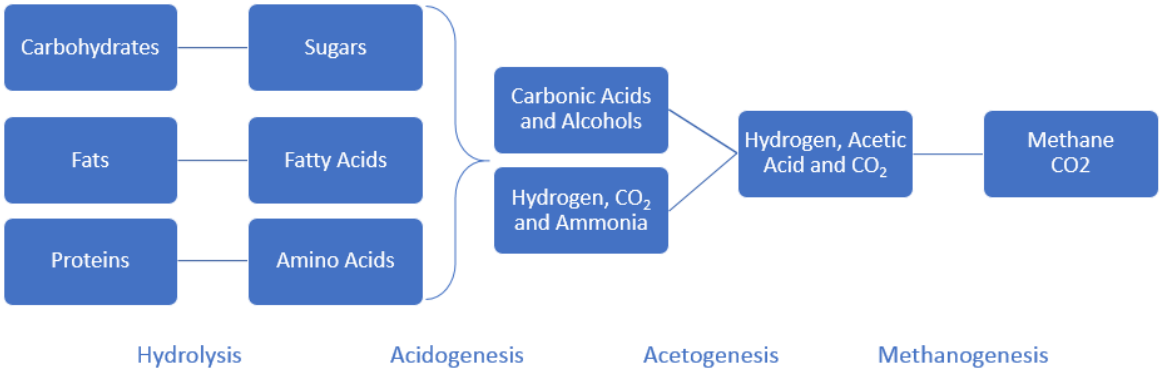

Figure 1: Reaction steps of Anaerobic Digestion

Once the volatile organic matter has been largely consumed – generally over 30-60 days residence time, the spent substrate, known as digestate, is removed from the vessel. Depending on the biological risk of the feedstocks, this digestate may need to be pasteurised to destroy any pathogens that could enter the food chain, especially if the digestate is spread on arable or grazing land. The digestate can either be applied in a whole form or separated into a liquid and solid fraction. Either way, the digestate is usually stored in tanks, lagoons or clamps over the winter months, then spread in summer when ground conditions allow. Typically, AD facilities will have up to six months storage for digestate - located either on-site or remotely depending on available space.

Some of the key process parameters that require control include pH, temperature, organic loading rate, dry matter content, and carbon:nitrogen ratio of the feedstock. As the digestion process is multi-stepped and involves different types of bacteria and enzymes, the setpoints for the various process parameters are a compromise between all these steps. The control of these setpoints is primarily to prevent overfeeding of organic matter – this can lead to acidification of the substrate and cause rapid decay of biological activity – and in extreme cases require the reseeding of digesters.

All of these parameters can have a significant impact on the amount of biogas generated. This detailed level of control is not only for the digestion – there are a number of significant process controls within the other unit operations such as feedstock handling, pasteurisation, biogas clean-up and biomethane upgrading.

The common operations of an AD plant start with feedstock reception, storage and processing. This stage can vary significantly depending on the type of feed, e.g. glycerol will be processed very differently from straw. The digester(s) are fed with organic material, sometimes incorporating a separate hydrolysis step. During digestion, volatile organic matter is converted to biogas as discussed above. Pasteurisation is typically carried out after digestion in small tanks where the digestate is heated to a set temperature and for a set time, prior to storage and onward utilisation. The set points for this step are regulated based on the category of the feedstock as specified under the Animal By-Product Regulations (2013) in the UK.

The biogas generated will require intermediary storage to allow for variations in generation and use of the gas. Following drying and clean-up the biogas can be converted, via an internal combustion engine, to electricity and heat. Excess electricity is typically exported and the heat is used to maintain digesters temperature, carry out pasteurisation as well as any peripheral uses such as digestate drying. The gas can also be purified to high-quality methane, and injected into the grid, once propane and odourant are added to meet mandatory quality requirements of the grid operator.

A typical process flow for an AD plant is shown in Figure 2. This diagram is for a biomethane injection plant, but depending on the specifics of the plant design there may further differences. An example is that some plants pasteurise before digestion and some plants have no pasteurisation at all, subject to the biological risk of the feedstock.

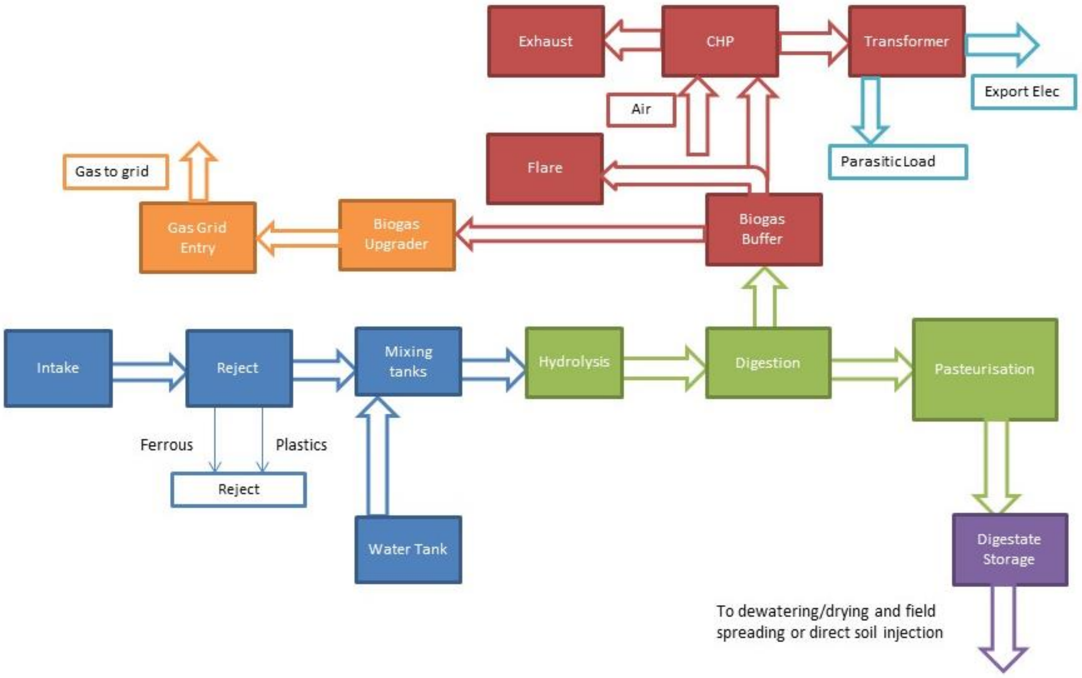

Figure 2: Simple Process Flow of Anaerobic Digestion plant, with Biomethane Injection

This section aism to demonstrate that AD is a complex process that needs detailed consideration throughout design, construction and operation, to be successful. This complexity, as well as the serious hazards inherent to the process, are not always treated with suitable scrutiny, which has led to some serious safety and environmental incidents. A selection of these incidents has been described in this paper so that lessons for developers, designers and operators can be learned.

Major Hazards

The AD process contains a range of inherent process hazards, including;

- Fire and explosion from methane
- Storage of compressed propane (at biomethane sites)
- Presence of toxic gases for example hydrogen sulphide and ammonia
- Asphyxiation from biogas
- Storage thousands of cubic meters of substrate and digestate – loss of containment
- High COD content of the substrate, in the tens of thousand milligrams per litre
- Biological pathogens – particularly in facilities processing food waste

Firstly, and most apparent of these hazards, is the explosive nature of methane. Also, newer plants that are upgrading their biogas for injection into the natural gas grid contain the hazard of the storage of compressed propane, used to increase the calorific value of biomethane to meet grid requirements. ATEX rated equipment is readily available and commonly used, but complacency around managing this hazard should not be allowed to creep in.

Of particular concern is transient operation periods where a plant is entering or re-entering operation following downtime. Under steady state conditions methane concentrations in the digester are well above the upper explosive limit, however, depending on the reason for downtime, it may have been necessary to expose the digester headspace to air. During these operations, methane concentration may pass through the explosive range and it is during these periods that special attention must be given to risks from any sources of ignition. All equipment, fixed and mobile, should be ATEX rated including mobile communication equipment and in these areas, safe practices are not always followed.

The specification of ATEX zones is not a simple process – especially considering that the biogas is a mixture of methane and CO_2. Some AD plant constructors have based their zoning on standards that exist in their native Germany (GAOHSA, 2008). However, it is not always clear that these correlate with the advice on zoning given for the UK by the Institute of Gas Engineer and Managers (IGEM/SR/25).

Secondly, and most importantly for environmental protection, is the risk of loss of containment, both of the substrate within the digesters and from digestate being stored on site. While the standard controls for this hazard should be followed, such as suitable materials of construction, level control, high-level switches and secondary containment, not all of these are commonplace, particularly for agricultural AD plants. Detailed guidance exists for developers from within the industry (ADBA, 2016) and beyond (Walton, 2014), but is not always adhered to in trying to reduce capital costs.

The materials of construction of process tanks also impact environmental risk; these can vary from stainless steel, glass reinforced plastic or concrete poured in-situ. Due to the corrosive nature of the hydrogen sulphide in the biogas, specialist coatings are required within the headspace of tanks to protect them. The continuing inspection of these is not always followed stringently – especially if a vessel is insulated.

Loss of containment can also arise due to foam formation within the digesters. As a biological process with gas generation, foaming cannot be eradicated, but a large amount of foam can lead to overflow of tank contents or the blocking of biogas pipes leading to overpressure within tank headspaces. Controlling foam requires the close management of feeding and feedstock selection, as well as the addition of defoaming additives when required. Some sites have installed specialist foam detectors to alert operators or automatically add defoamer, but this is not universal practice.

Fundamentally, not having the necessary controls commonly comes down to developers and designers pushing to reduce costs, although deficiencies in regulatory controls and lack of knowledge across the industry also plays its part. For example, if an agricultural AD plant is only feeding farmyard manure and energy crops (i.e. not defined wastes), there is no regulatory requirement to install secondary containment – hence it is rarely done. While this may be shocking to some, the reasoning behind this is that a farmer building a new slurry tank would not have to install a bund, and the potential extra cost can be a significant barrier to preventing development.

The biogas itself poses hazards other than its flammable nature; it can contain as much as 1000 ppm of hydrogen sulphide which is toxic at 10ppm. However, exposure to H_2S is not the only concern for operators as inherent lack of oxygen within biogas means that asphyxiation risk would also be present, particularly in vessels that require internal inspection or repairs, or at low points where carbon dioxide can pool due to its density.

In addition to the asphyxiation risk within the tanks of an AD plant, there is often the risk of moving parts within these confined spaces – typically agitators which could seriously injure or kill those working within those vessels. Also, there is an array of standalone mechanical equipment, such as hammer mills, used typically for feedstock processing that presents a risk of serious injury during operation and maintenance activities.

The storage of biogas and the pressure that can build up within the gas storage is a further hazard that requires serious consideration. The gas storage is typically within flexible membrane roofs, with a double skin – the bottom layer can move depending on gas volumes, with a secondary roof above that is inflated by air to ensure it stays in a fixed position. A similar set up is also used for gas storage systems that are separate from the process vessels themselves.

While gas storage pressures are low, normally less than 10 mBar(g), overpressure could still cause damage to the membrane roofs leading to significant biogas leaks and the generation of an explosive atmosphere, either within the top layer of the roof skin, or the area around the top of the vessel. In tanks with concrete roofs, overpressure at these levels can be sufficient to unseat and move concrete tank lids. As well as damage by overpressure, on rare occasions, high winds or snow can cause tears to the top membrane leading to exposure and risk of a release of biogas.

Almost all AD plants have overpressure devices fitted, and some also have underpressure protection to avoid vacuum pressures within the tanks causing damage to the membrane roofs, or in extreme cases, tank collapse. Some of these over/underpressure relief valves are water filled or filled with a mix of water and glycol to prevent freezing. If these water seal pots are not regularly refilled, or not filled with the right mix of glycol, the relief device can become unserviceable. That is not to say that the mechanical alternatives are infallible – due to the "dirty" nature of the biogas, lack of maintenance of these has been known to lead to overpressure events and subsequence membrane roof damage.

An important control measure to prevent overpressure within AD plants is the use of flaring, however not all plants, particularly those not subject to Environmental Permitting, are designed with a flare. While the use of flaring is not ideal from an environmental point of view, it is much preferred to venting biogas to the atmosphere.

Concerning environmental damage, feedstocks for Anaerobic Digestion needs to be of a reasonable high Chemical Oxygen Demand (COD) to make the process viable. This COD level means that leachate from solid feedstock storage, liquid feedstocks, and substrate within digesters all pose a significant risk to ground and surface water if there is a loss of containment.

Finally, a significant aspect from an environmental perspective is the control of odour. Feedstock, biogas, substrate and digestate all present an odour source that can cause a nuisance to those living or working within the immediate vicinity. The Environment Agency (EA) does require an Environmental Permit to operate AD plant which will include the requirement to manage the odour on and from a site. Typical controls include scrubbers, biofilters and ensuring that feedstock storage is covered with suitable extraction. Odour generation in AD plants is poorly understood and in many cases inadequately managed yet is probably the most prevalent cause of environmental complaint across the industry.

AD Sector Incidents

This section considers the safety and environmental performance of the AD industry from a top level and includes some specific incidents that can provide lessons to the sector as well as perhaps to a broader audience.

Safety Performance

Unfortunately, specific UK safety performance statistics could not be sourced from the HSE or trade bodies to interrogate. However, it is still worthwhile to briefly look at the broader performance of the industry areas that AD plants operate to get a general sense of overall performance. The vast majority of AD plants operate either in the HSE designated sectors of Waste and Recycling, or Agriculture, with a minimal number of plants operating within the Manufacturing sector.

As can be seen in Figure 3 below, the two sectors that AD plants operate in have, by far, the weakest performance regarding fatality rate. However, it is not appropriate to extrapolate those figures for broad industries of Agricultural and Waste & Recycling, to the AD industry specifically. It would, of course, be useful for those working in this sector to have specific safety statistics, say collated by trade body ADBA, to allow better analysis and targetting areas to improve.

From the author's knowledge, there has been one fatality reported at an AD plant within the UK. That was the case of two workers removing a biogas roof at an agricultural site in Dorset, both of whom were exposed to hydrogen sulphide, with one of the workers being fatally overcome by the gas (HSE, 2009-10 names and details of fatalities, 2012). In this case, it was reported that portable gas monitors or respiratory protective equipment were not in use. The lack of these basic controls highlights that the hazard of exposure to biogas was not being treated with the care it required.

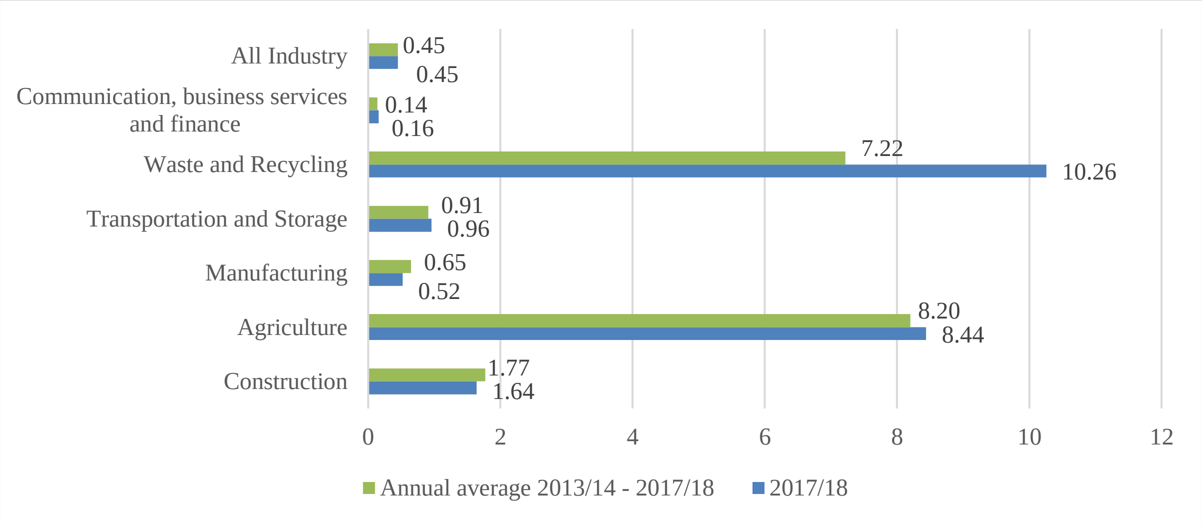

Figure 3: UK Fatality Statistics per 100,000 workers. Source: (HSE, Workplace fatal injuries in Great Britain in 2018, 2018)

There have, however, been further significant incidents in which fatalities could have occurred but were avoided. For example, in 2016, a commercial AD facility in Oxfordshire was struck by lightning causing loss of the biogas roof and a fire to start at the top of the digester. The plant did not have a lightning protection system installed, which may have prevented this. However, it did have a suitable secondary containment system that prevented loss of containment of the small amount of substrate entering the local water receptors.

Figure 4: Fire at Oxfordshire AD Plant. Source (Nierynck, 2016)

In 2017, an explosion occurred at a commercial AD plant in Nottingham, when two workers were carrying out welding work within the confined space of a pasteuriser. One of the worker's injuries required a leg amputation (Nottingham Post, 2017). The incident also required the EA to contain a slurry spill that was released due to the explosion. While the author does not have detailed information about this incident, it is clear that suitable controls for working in confined spaces and the hazards of flammable gases were not being followed.

All three of these incidents paint a poor picture of the design and maintenance procedures in the sector; in all these cases, the hazards associated with biogas (flammability and toxicity) were not properly controlled either with protection from ignition sources or through safe working practices.

On a brighter note, the EA requires HAZOP studies to be carried out as part of their Permit Requirement ensuring some basics of process safety review are being completed. This requirement is prescriptive however, and does not mean that other hazard studies are taking place.

A final note on general safety performance, while these are significant individual incidents, without sector specific fatality stats it is difficult to compare the sector against the UK average or even within the HSE sector that cover the different types of AD plant.

Environmental Performance

The potential for environmental damage is the main focus of this paper, and while there was the opportunity for environmental damage to occur during the incidents mentioned above, there have been a larger number of incidents within the AD sector where damage to the environment was the primary outcome.

To investigate this, there are some specific AD sector environmental performance statistics that can be presented to compare AD against - with the most up to date data available from the EA being from 2015. The data available was for Category 1 and 2 incidents that occurred in England, i.e. incidents that at “Major” or “Significant” respectively, but only covers “Biowaste” AD plants, i.e. agricultural and food waste plants rather than industrial or wastewater treatment plants.

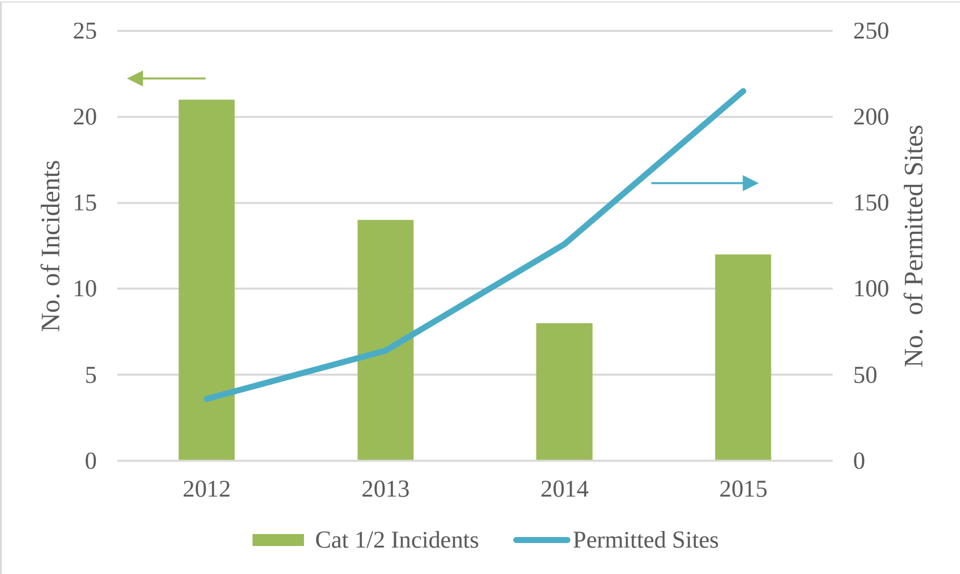

Figure 5: Category 1/2 Environmental Incidents from Biowaste AD plants in England. Sources: (Environment Agency, 2016), (Environment Agency, 2018)

Overall, this shows that the number of Category 1 or 2 pollution incidents at AD plants has decreased overall from 2012 to 2015, however, this is over a relatively short timescale, with the data also showing the number of incidents per permitted site reducing.

The EA also uses a measure of Category 1 or 2 incidents, per 100 permits, and has published values for the AD industry as well as the average for all UK industry. This comparison, shown in Figure 5 below, demonstrates a significant improvement for the AD industry – an order of magnitude reduction in the incident rate. However there remains work to do compared to the All Industry average.

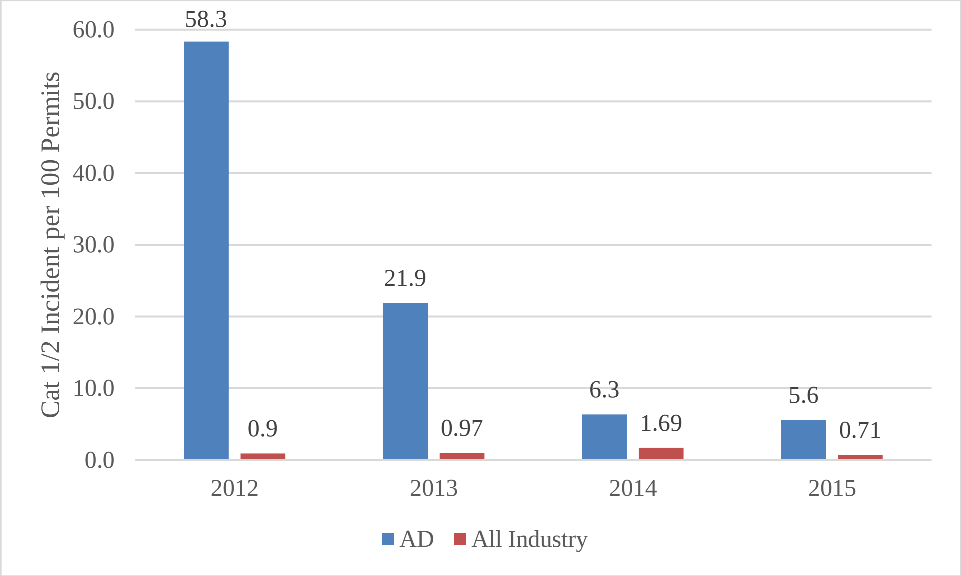

Figure 6: Category 1/.2 Incidents per 100 Permits. Source: (Environment Agency, 2016)

It is worth highlighting that the AD industry as a whole has made a significant improvement in a short period. There may be a variety of possible reasons for this, however, the common driving factor is probably greater awareness of the potential implications amongst designers, operators and regulators coupled with a more robust regulatory regime

Environmental Incidents

The following section provides details about a selection of environmental incidents and considers the lessons that could be learned.

Shropshire Tank Collapse

In 2014, a Food Waste Digester in Shropshire had a severe loss of containment caused by an explosion. This incident was, in fact, the second serious loss of containment that had occurred on the same site.

Figure 7: Tank Collapse and subsequent Loss of Containment. Source: (Environment Agency, 2018)

Specific details of this incident are not readily available as court proceedings are still understood to be ongoing. However, the explosion and subsequent tank collapsed occurred during the night. This suggests that the site did not have suitable pressure relief systems or that an ignition source was located close to the release point of an overpressure valve. Furthermore, the tank failed to withstand the impact of the gas explosion, suggesting that explosion risk had not been adequately considered during initial and detailed process and civil design, and the HAZOP study. Finally, there was no secondary containment to prevent the tank contents spreading to nearby land.

Bedfordshire Tank Overflow

Another loss of containment example is from an agricultural AD plant in Bedfordshire. The operating company was prosecuted and fined by the Environment Agency after a leak of over 300 m^3 of digestate occurred, with an estimated 10 m^3 escaping from the site. In this case, there was no damage to equipment, but simply an operator forgot to switch a pump off before leaving at the end of their shift. The tank had no high-level alarm or trip to stop filling. Hence it overflowed, and in fact, the Environment Agency had highlighted that this lack of instrumentation was a breach of their permit that required rectifying.

The simple installation of an automatic high-level switch would have prevented the environmental damage, process interruption, and the subsequent fine of £10,000 (Environment Agency, 2015). It is also worth highlighting that this incident, like the one in Shropshire, occurred at night when no operators were present – a common procedure across AD facilities.

Bund Collapse

Finally, it is worth highlighting an incident that did not directly harm the environment but illustrates that even when AD plants do have secondary containment, they are not always of the best construction. In Figure 8 below, heavy rainfall led to the collapse of an earth bund that was in place at a biomethane plant. This reduced the containment capacity, and also led to damage to the gabion walls used to protect the propane storage tanks. While a concrete bund wall would have been more expensive, it would not have been damaged by rainfall. The gabion walls had also been installed too close to the LPG tanks, contrary to industry guidance. The additional risk posed by the failing bund meant that the site owner had no choice but to temporarily halt operations until the LPG tanks could be relocated to a safer position.

Figure 8: Bund collapse towards Propane Storage.

Further Aspects

There are other aspects, often specific to the AD industry, that can increase the risk of environmental damage. For example, many of the plants, not just agricultural ones, are located in remote rural areas and have limited or no onsite personnel for up to 12 hours per day. Unless suitable control and instrumentation systems have been installed this can lead to the potential for pollution incidents to go unnoticed until the commencement of the next operational shift. This aspect will hopefully be a rare occurrence but, as seen in the incidents above, is not entirely out of the realms of possibility.

The remote or rural location can also mean that the sites are closed to small surface water bodies. These bodies will be far more susceptible to environmental damage from loss of containment events – even on a small scale.

Supplementary to operator presence is the technical capabilities of plant operators. Levels of training vary across the industry and normally rely on in-house training sessions provided by the plant manufacturer. In the author's experience quality of training sessions and operating manuals can vary immensely. Frequently, training sessions provide a broad overview of the plant but fail to provide detailed operating procedures, particularly for transient and safety related events.

The EA require AD plants that handle waste, to have a manager that holds suitable "technical competence" – which is normally achieved through a WAMITAB qualification. This requirement is not the case for all plants, and plant managers are often not permanently based on a single site.

The issue of foaming was noted earlier, and these incidents can lead to overflow of liquid, either by high-level devices not responding to foam, or damage to the devices due to the foam. The outcome of a foaming event, caused by a temporary loss of site power, is shown in Figure 9. In this instance, the secondary containment and concrete hardstanding of the plant prevented the substrate from being lost to ground or surface water.

Figure 9: Residue from foam overflow incident.

Before concluding this paper, it is worth highlighting the potential for poor design and safety culture to lead to dangerous conditions. For example, the site shown in Figure 10 below did not have a flare as part of the design, and when the gas engine suffered long-term downtime there was no permanent way to remove biogas other than venting. To prevent continual release of biogas – which would have had a higher greenhouse gas impact than flaring, the operator constructed this temporary flare, rather than hiring in a skid based system that is available.

Figure 10: Unconventional Flare used on Agricultural AD plant. Source: (Environment Agency, 2018)

Conclusions

The use of Anaerobic Digestion to generate biogas is a complex process and has a series of inherent hazards, including explosions, loss of containment, high COD liquids and gases that are both toxic and an asphyxiant. Despite these hazards, the environmental benefit can be significant, as AD plants generate electricity or biomethane from wastes and serve as a means of reducing fugitive greenhouse gas emissions from landfill and temporary waste storage.

Across the broader industries that AD plants operate in, agriculture and waste, have a poor safety record when compared to the UK average; however, there are no specific safety statistics for AD plants alone. Some particular incidents were investigated, including a fatality at an agricultural AD plant due to H_2S inhalation and severe injury due to an explosion during hot work activities.

As there are no specific statistics for the AD sector, and this technology covers multiple HSE industry categories, it may be useful for a voluntary system to be introduced where health and safety statistics can be analysed to allow for broader distribution of lessons learned from accidents and near misses, perhaps through the existing trade body, ADBA.

Statistics published by the EA on serious environmental incidents for biowaste AD plants indicate that significant progress has been made by the sector, since 2011, to reduce the number of environmental incidents. However, the incident rate per permitted site is still significantly higher than the all-industry average, and the sector must continue to reduce serious incidents and improve safety performance.

Over this period, there have still been some significant pollution incidents at AD plants, including an explosion leading to tank collapse, a lightning strike followed by biogas fire, and an overflow from a tank without high level protection. There are also some common aspects of AD plant incidents that should be considered more seriously, including remote operating and supervision, poor operator competence, lack of secondary containment, odour management and the rural location of many plants.

Lessons can and has been learned from these incidents, and collectively, the industry has become better at managing the major hazards and the real cost of incidents. AD technology does present an excellent method for reducing greenhouse emissions by using waste and producing an energy source that fits into our existing infrastructure, but continuing to damage the environment in other ways could easily lead to tariff reduction, greater regulatory scrutiny and increased fines all of which will impact detrimentally on financial viability of the industry.

References

ADBA. (2017). Market Report 2018. London: Anaerobic Digestion and Bioresources Association.

ADBA. (2018, 12 27). AD Map. Retrieved from http://adbioresources.org/map

Environment Agency. (2015, June 17). 2014 Enforcement actions against corporate entities - England. Retrieved from https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/463521/LIT_10163.xlsx

Environment Agency. (2016, September). Pollution Incidents: 2015 Evidence Summary. Retrieved from https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/651707/Pollution_incidents_2015_evidence_summary_LIT_10487.pdf

Environment Agency. (2018, September 15). Biowaste treatment sector environmental performance 2014.

Environment Agency. (2018). Review of biowaste permits to improve environmental outcomes. London: Renewable Energy Association.

GAOHSA. (2008, September). Safety Rules for Biogas Systems. Germany.

Greenhouse Gas Protocol. (2016, 12 16). Global Warming Potential Values. Retrieved from https://www.ghgprotocol.org/sites/default/files/ghgp/Global-Warming-Potential-Values%20%28Feb%2016%202016%29_1.pdf

HSE. (2012, 12 01). 2009-10 names and details of fatalities. Retrieved from http://www.hse.gov.uk/foi/fatalities/2009-10.htm

HSE. (2018, July 4th). Workplace fatal injuries in Great Britain in 2018. Retrieved from http://www.hse.gov.uk/statistics/pdf/fatalinjuries.pdf

Nierynck, R. (2016, June 21). Lightning strike at Agrivert AD plant. Retrieved from Let's Recycle: https://www.letsrecycle.com/news/latest-news/lightning-strike-at-agrivert-ad-plant/

Nottingham Post. (2017, September 21). Two seriously injured in explosion on Colwick Industrial Estate. Retrieved from https://www.nottinghampost.com/news/nottingham-news/live-explosion-colwick-industrial-park-504261

Ofgem. (2018, 12 28). Tariffs and payments: Non-Domestic RHI. Retrieved from https://www.ofgem.gov.uk/environmental-programmes/non-domestic-rhi/contacts-guidance-and-resources/tariffs-and-payments-non-domestic-rhi

Shropshire Star. (2014, May 30). Sludge power plant collapses in Shropshire. Retrieved from https://www.shropshirestar.com/news/2014/05/30/shropshire-sludge-power-plant-collapses/

T. Abbasi, S. M. (2011). A Brief History of Anaerobic Digestion and “Biogas”. Biogas Energy, 11-23.