MONITORING OF ANAEROBIC DIGESTION PROCESS TO OPTIMIZE PERFORMANCE AND PREVENT SYSTEM FAILURE

R. A. Labatut and C. A. Gooch
Department of Biological and Environmental Engineering
Cornell University, Ithaca, NY

ABSTRACT

Although anaerobic digestion (AD) is a rather mature technology, poor anaerobic digester performance and system failure are still frequent around the world. Most of these problems occur as a result of inadequate operational management and lack of process control. Digester upsets are usually temporary, and in most cases can be solved by taking simple measures, such as adjusting the influent co-digestion ratio and/or the frequency of influent pumping. If prompt and adequate measures are not taken, the digester operation will eventually fail. Recovery of a digester can take several months, during which, energy generation and waste treatment are not possible, resulting in increased operational costs for the farm. The importance of well-trained and qualified personnel to operate AD systems and properly control and monitor the process is essential, not only to prevent digester upsets and potential system failures, but also to ensure efficient organic waste stabilization and constant and stable biogas production. Analytical laboratories were installed on selected farm-based anaerobic digester systems in NYS to regularly monitor key process parameters and to evaluate performance and stability of the operations. Preliminary results of the monitoring confirmed that analytical labs are essential to detect process upsets more efficiently, and to identify and correct the source of the problem before system failure occurs.

INTRODUCTION

Anaerobic digestion (AD) systems are extremely sensitive to changes in environmental variables. Correct design and control of the system's parameters are essential to maximize process efficiency, increase stability, and prevent system failure[1]. Up to 1998, failure rates of on-farm anaerobic digesters in the U.S. were at a staggering 70% and 63% for complete-mixed and plug-flow reactors, respectively (Lusk, 1998). Today, with improved system design, better construction practices, and an increased number of qualified companies to develop AD projects, the probability of long-term system failure is likely to be somewhat lower. Nevertheless, underperformance[2] and short-term failure are still a common problem in on-farm AD systems across the U.S. Last year, three on-farm co-digestion operations in the Midwest (MI and OH) receiving thick stillage, a by-product of the ethanol distillation process, failed and presented

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[1] The performance of the anaerobic digester process decreases to a point where the entire operation, including combined heat and power (CHP) unit, needs to be shut down for an undetermined amount of time, which can last from a few days, or weeks (short-term), to several months (long-term)

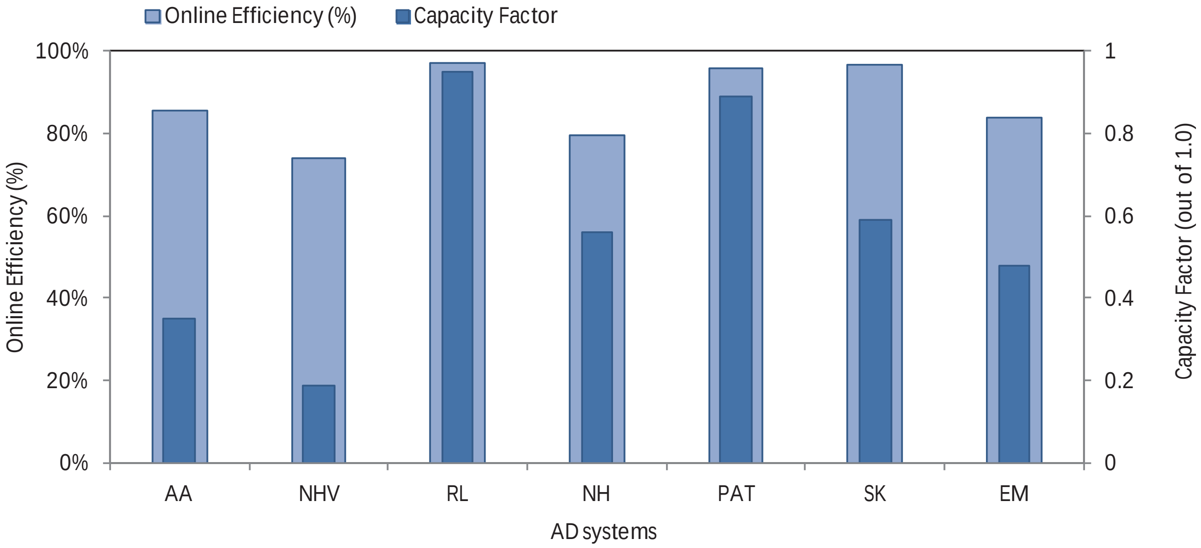
[2] The CHP unit operates below its nominal power capacity

depressed biogas production for a period of two to three weeks. Although many times not reported, in New York State the same problems are seen.

THE CASE OF NEW YORK STATE

In a year-long study conducted between 2008 and 2009, seven of the 22 on-farm AD systems currently in operation in New York State were monitored (Gooch et al., 2011). The average online efficiency[3], which represents the percent of time the CHP system was in operation during this same period, was found to be as high as 88% across the seven AD operations (Figure 1). However, the average capacity factor[3], which indicates the ratio of electrical energy produced by the combined heat and power (CHP) unit relative to its potential capacity, was found to be 0.57 across the same AD operations (Figure 1). This means that, even though the CHP units were running most of the time, the power output was only slightly higher than half of their potential capacity.

Figure 1. Average capacity factor and online efficiency of seven on-farm anaerobic digestion systems in New York State obtained from a 12- to 15-month operational period (Gooch et al., 2011)



Low CHP performance could be caused by several conditions:

1. Decreased/unstable biogas production
2. Decreased/unstable biomethane content in biogas
3. Downtime of CHP unit due to AD system failure
4. Decreased efficiency of CHP system
5. Over-dimensioning of CHP system
6. Downtime of both AD and CHP systems due to maintenance

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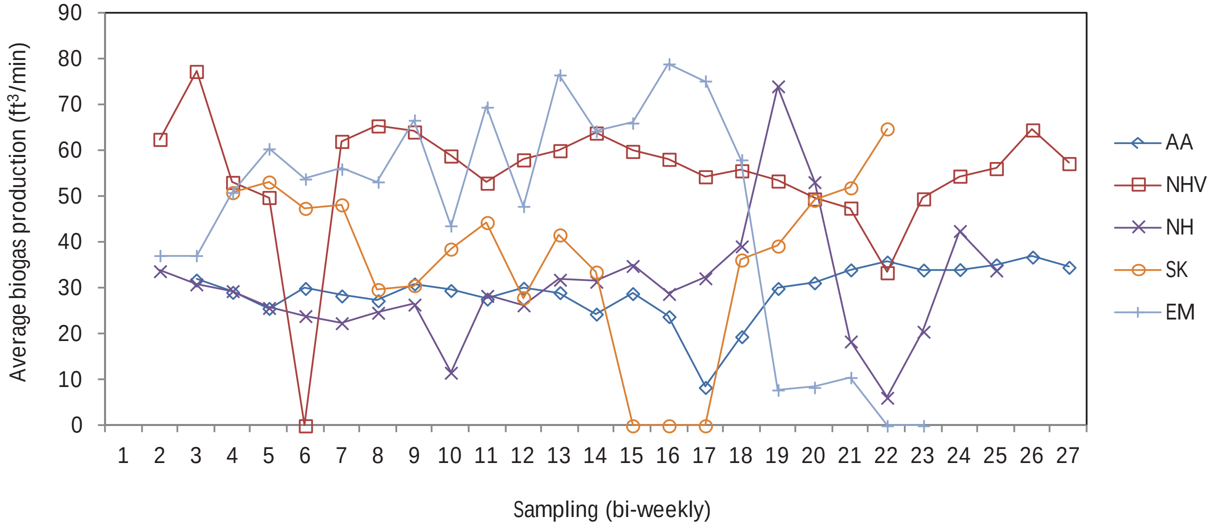
[3] See Appendix for definition and formulae

However, conditions related to the AD system performance (i.e., 1 – 3), rather than the CHP unit in itself (i.e., 4 and 5), are likely to be the main causes of low CHP performance. Indeed, episodes of AD system failure and fairly unstable biogas production were observed throughout the monitoring period in the AD operations with the lowest capacity factors (Figure 2). Such behavior is attributed to digestion process upsets, which are usually the result of inadequate operational management and poor process oversight. This is not surprising, considering that nearly all active on-farm AD systems in New York State are operated by a farm worker, who usually has no previous experience or training in anaerobic digestion. Furthermore, this person has to operate, maintain, and monitor both AD and CHP systems in addition to his/her daily farm-related activities.

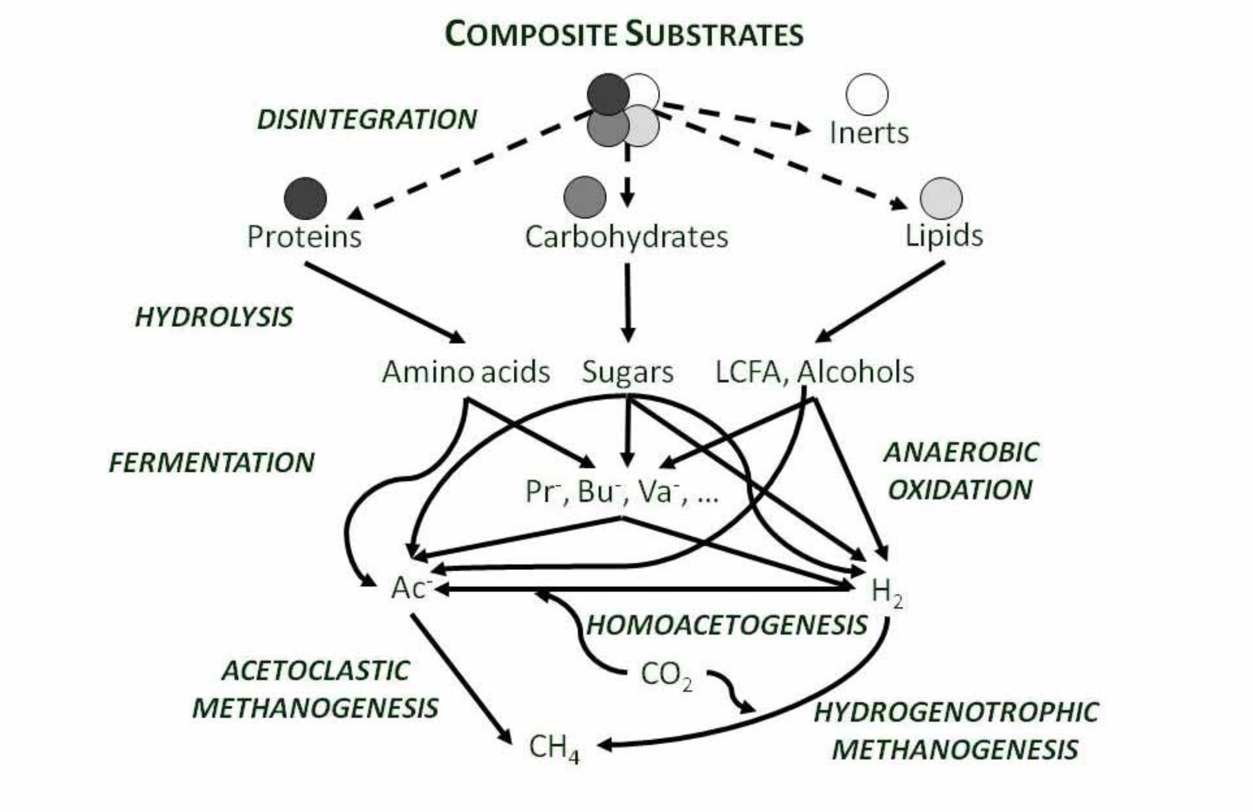
Figure 2. Biogas production (ft3/min) of five on-farm anaerobic digestion systems in New York State throughout a 12- to 15-month operational period (Gooch et al., 2011)



KEY PROCESS INDICATORS TO PREVENT DIGESTER UPSETS

The anaerobic digestion of complex organic matter is a highly dynamic, multi-step process, where physicochemical and biochemical reactions take place in sequential and parallel ways. The main biochemical conversion pathways of anaerobic digestion are depicted in Figure 3. The delicate balance between such reactants and products is what primarily determines how stable and efficient the anaerobic digestion process is. When the concentration of a particular intermediate reaches the homeostatic equilibrium of certain organism or group of organisms, such balance is disrupted. Intermediate products further accumulate and the digestion process becomes upset. Substrate stabilization and biogas production progressively decrease, and eventually the entire system fails.

Figure 3. Major pathways in the anaerobic digestion of complex substrates; Ac-: acetate, Pr-: propionate, Bu-: butyrate, Va-: valerate; adapted from McCarty & Smith (1986), Pavlostathis & Giraldo-Gomez (1991), and Batstone et al. (2002)



To prevent process upsets, proper system configuration and a rigorous control of the operational parameters are critical to maintain environmental variables steady and within the optimal ranges. Because of their central role in methanogenesis, propionate, acetate and hydrogen are probably the most important intermediate products of anaerobic digestion, and therefore the key process indicators to monitor in the system. About 64% of the methane produced during anaerobic digestion comes from acetate, while the remaining 36% comes from hydrogen (Batstone et al., 2002). Propionate is an important precursor of acetate and hydrogen – approximately 30% of the electron flow directly related to methane production goes through propionate (Jeris & McCarty, 1965; McCarty & Smith, 1986). In addition, propionate, acetate and hydrogen are more sensitive to process upsets than biogas production, methane content, or pH. The most important process parameters to monitor in AD systems are described below.

Volatile fatty acids (VFA) – As a process performance indicator, VFA concentration is probably the most sensitive parameter to monitor. They can be inhibitory of the digestion process which can lead to system failure. VFAs encompass a group of six compounds, i.e., acetic acid/acetate, propionic acid/propionate, butyric acid/butyrate, valeric acid/valerate, caproic acid/caproate, and enanthic acid/enanthate, from which acetate is predominant. In a correctly designed and well-operated digester, the concentration of total VFA is typically below 500 mg/L as acetic acid. However, if the digester is undersized for the organic load this concentration can be higher. At VFA concentrations over 1,500 – 2,000 mg/L, biogas production might be limited by inhibition. However, rather than a specific concentration, it is a sudden and steady increase of VFAs in the effluent what can be a sign of a digester upset. Thus, it is essential to monitor VFAs periodically (e.g. bi-weekly) in order to detect problems on time, and make the necessary operational changes before digester failure occurs.

Molecular hydrogen – Together with VFAs, molecular hydrogen is maybe the most sensitive parameter of process upsets. The energy available for the degradation of propionate is very small, and requires partial pressures of hydrogen below 10^{-4} atm at 25^{o}C (McCarty & Smith, 1986; Schmidt & Ahring, 1993). Such low hydrogen partial pressures in AD systems are only possible by the syntrophic relationships between hydrogen-producing bacteria to hydrogen-oxidizing methanogens (Bryant, 1979). The balance between these two groups of organisms is of foremost importance to prevent digester upsets (Demirel & Yenigün, 2002). As opposed to other parameters, molecular hydrogen is more difficult to measure due to the low levels found in AD systems, and requires specialized equipment to determine it.

pH – Maintenance of the system pH in the proper range is required for efficient anaerobic digestion. The generally accepted values are in the neutral range, between 6.5 and 7.6. The anaerobic digestion of complex organic substrates requires the joint work of several groups of microorganisms, from which methanogens are the most sensitive to low pH. Changes in digester operating conditions or introduction of toxic substances may result in process imbalance and accumulation of volatile fatty acids (VFA). Unless the system contains enough buffer capacity (alkalinity), the pH will drop below optimal levels and the digester will become “sour”. Depending on the pH magnitude and the duration of the drop, the biogas production will decrease to a point where it may completely cease. On the contrary, in a well-operated system, a slight increase of the digester’s effluent pH is expected, because organisms produce alkalinity as they consume (protein-rich) organic matter.

Alkalinity (Alk) – The buffering capacity of an anaerobic digester is determined by the amount of alkalinity present in the system. The bicarbonate ion (HCO_3^-) is the main source of buffering capacity to maintain the system’s pH in the range of 6.5 – 7.6. The concentration of HCO_3^- in solution is related to the percent of carbon dioxide in the gas phase. In a typical manure-only digester with a pH 7.4 and a percent CO_2 of 35%, the bicarbonate alkalinity is about 5,500 mg/L as $CaCO_3$. Such alkalinity usually provides enough buffering capacity to withstand moderate shock loads of volatile fatty acids. In fact, cow manure can play an important role in co-digestion operations by increasing the pH and buffering capacity of the influent mixture when high-strength, easily degradable industrial wastes are used as co-substrates.

Total ammonia-nitrogen (TAN) – Ammonia is produced during the digestion of protein-rich substrates, such as swine or cow manure. Likewise VFAs, ammonia can inhibit the digestion process and decrease its overall performance. Concentrations over 1,500 mg/L of ammonia-N have been reported to be inhibitory for the digestion process at high pH (i.e., > 7.4); however, acclimation to higher ammonia levels (>5,000 mg/L) has been also reported in manure systems.

Temperature – The optimal temperature for mesophilic anaerobic digestion is 37^oC (100^oF) (VanLier et al., 1997). Although some variation is considered normal, digester temperature should be always maintained between 35^oC (95^oF) and 40^oC (105^oF). Operating at temperatures outside the normal range will result in decreased biogas production and organic matter stabilization. In addition, long periods of time under these conditions may eventually stop biogas production and cause digester failure. Furthermore, the process will be generally more affected at higher temperatures than at lower ones.

Biogas production – The biogas production is probably the most important parameter to monitor in anaerobic digesters. Biogas is almost completely composed of methane gas and carbon dioxide gas, but it also includes traces of ammonia nitrogen, hydrogen sulfide, and other gases. Methane is the final product of anaerobic digestion, and its production is a measure of how well the digester is performing. The amount of methane produced during digestion is directly related to the amount of organic matter (VS) that has been stabilized (destroyed). More importantly, the more methane is produced, the more energy (electricity and heat) that can be generated. Biogas production should be fairly stable over time. If the biogas production drops below the average daily values, it is most likely that other indicators, as discussed above, have changed as well, and it is a strong indicator of a digester upset.

Methane content – Biogas is composed of two main gas components, methane (CH_4) and carbon dioxide (CO_2). The percent of methane in a well-operated/designed anaerobic digester treating dairy manure is in the range of 58 – 65%, with the remaining gas consisting mostly of carbon dioxide. When manure is co-digested with high-strength substrates, such as food wastes, this percent is usually higher. The methane content of biogas should be fairly stable over time unless there is a problem with the digester. A steady drop of methane below the digester's average daily values is usually an indicator of a digester problem. However, if substrate is fed intermittently, short-time drops may be observed at times of digester loading.

Volatile solids (VS) – Total volatile solids (VS) provide a measure of the organic matter content of the waste. The amount of digester influent being pumped and the percent VS of the waste are a measure of the digester's organic loading rate (influent mass per time). The difference between the VS concentration in the influent and that of the effluent indicates the percent of waste that has been stabilized (destroyed) through the digestion process. For an influent of constant characteristics, the higher the VS stabilized, the lower the solids found in the effluent and the greater the reduction of odors. The extent (percent) of organic matter stabilization primarily depends on the system configuration and the substrate's physicochemical characteristics. The percent VS stabilization in manure-only digesters is in the range of 30-42% (Gooch et al., 2011). In systems co-digesting manure and additional high-strength substrates, the percent stabilization of the waste is typically higher, but its magnitude varies according to the co-substrates employed.

THE IMPORTANCE OF PROCESS CONTROL AND MONITORING

Proper system operation and careful process control and monitoring are not only necessary to ensure efficient organic waste stabilization and constant and stable biogas production, but also to prevent digester upsets and potential system failure.

Digester upsets are the result of process perturbations caused by the digester operational parameters and/or the influent substrate characteristics (Figure 4). Preventing digester upsets will depend on the relative time taken to implement correcting actions to resolve the original cause of the perturbation (Figure 4).

Depending on the system configuration and the influent substrate, some operations are more or less susceptible to digester upsets. The two most common types of anaerobic digesters used in NYS are the continuously-stirred tank reactor (CSTR) and the plug-flow reactor (PFR)[4]. CSTRs are continuously (or periodically) mixed via impellers or sometimes pump mixed, so that the influent substrate material is theoretically diluted in the entire reactor's volume. In contrast, PFRs are not mixed – the influent material is pumped in one end of the reactor and advances as a plug-flow throughout its length until it exits at the other end. This fundamental difference makes CSTRs more suitable for high-strength substrates as shock loads can be minimized due to dilution. PFRs are better handling low-strength, stable-substrates, such as livestock manure. Indeed, anaerobic digestion of livestock manure usually presents a relatively low risk for upsets, regardless of the reactor. Its chemical properties (e.g., low-strength, optimal alkalinity, high nutrients) and particularly consistent nature over time, makes it a rather safe substrate for digestion. However, in farm-based co-digestion operations, livestock manure is usually co-digested with imported substrates coming from the food industry. The very same characteristics that make these type of substrates highly energy yielding, i.e., high chemical strength and increased biodegradability, make these operations especially susceptible to digester upsets.

In general, since changes in the system operational parameters and/or influent substrate characteristics are usually unintended, rather than scheduled, any type of operation is susceptible to process perturbations resulting in digester upset. Therefore, periodic monitoring of the process' key parameters is always recommended – it is essential for early detection of process perturbations, on-time resolution of digester upsets, and prevention of system failure.

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[4] See Appendix for description

IMPLEMENTATION OF ANALYTICAL LABORATORIES IN ANAEROBIC DIGESTERS IN NEW YORK STATE

The role of the AD operator not only requires exclusive dedication, but also formal training on the fundamentals of system operation and process control. Motivated by such need, the Manure Management Program at Cornell University, as a part of a NYSERDA-founded project, has created a program to educate and support a workforce of AD operators and technicians. This project involves the implementation of analytical laboratories on selected farm-based anaerobic digester systems across NYS. The purpose of these labs is to periodically monitor key process parameters to develop a baseline for each AD system and to evaluate performance and stability of the operations. This will help operators to detect process upsets more efficiently, and to identify and correct the source of the problem before system failure occurs.

Five on-farm AD systems were implemented with analytical labs, i.e., Sunnyside, Roach, Sheland, Noblehurst, and SUNY Morrisville. The labs were equipped with instrumentation to measure the parameters listed on Table 1.

Table 1. Parameters measured in the analytical laboratories and the methods used

Parameter	Determination method
pH	pH meter/single-junction electrode
Temperature	pH meter/thermocouple
Alkalinity (Alk)	Titration of sample with sulfuric acid 0.1 N to pH 4.0
Volatile fatty acids (VFA)	Distillation of sample and titration of distillate with sodium hydroxide 0.1 N to pH 8.3
Total solids (TS)	Drying sample in gravity convection oven at 105^{o}C overnight (> 8 h)
Total volatile solids (VS)	Ashing sample in muffle furnace at 550^{o}C for 1 h
Methane content	By difference of carbon dioxide content, measured using sensidyne tubes
Total ammonia-nitrogen (TAN)	Ion meter/ion selective electrode

pH, Alk, VFA, TS, VS and TAN are measured both in the influent and the effluent of the AD systems. Analyses should be conducted weekly; however, at least bi-weekly analyses of VFA in the effluent of the anaerobic digester are recommended due to the role of this parameter as an early indicator of digester upsets.

All the labs were equipped with the exact same equipment to facilitate the instruction and training, and to promote cooperation between the operators. Figure 5 shows the setup of two of such labs and part of the equipment used.

Figure 4. Main causes of process perturbation leading to AD system failure; the relative time assumes that no actions have been taken to correct the original cause of the perturbation

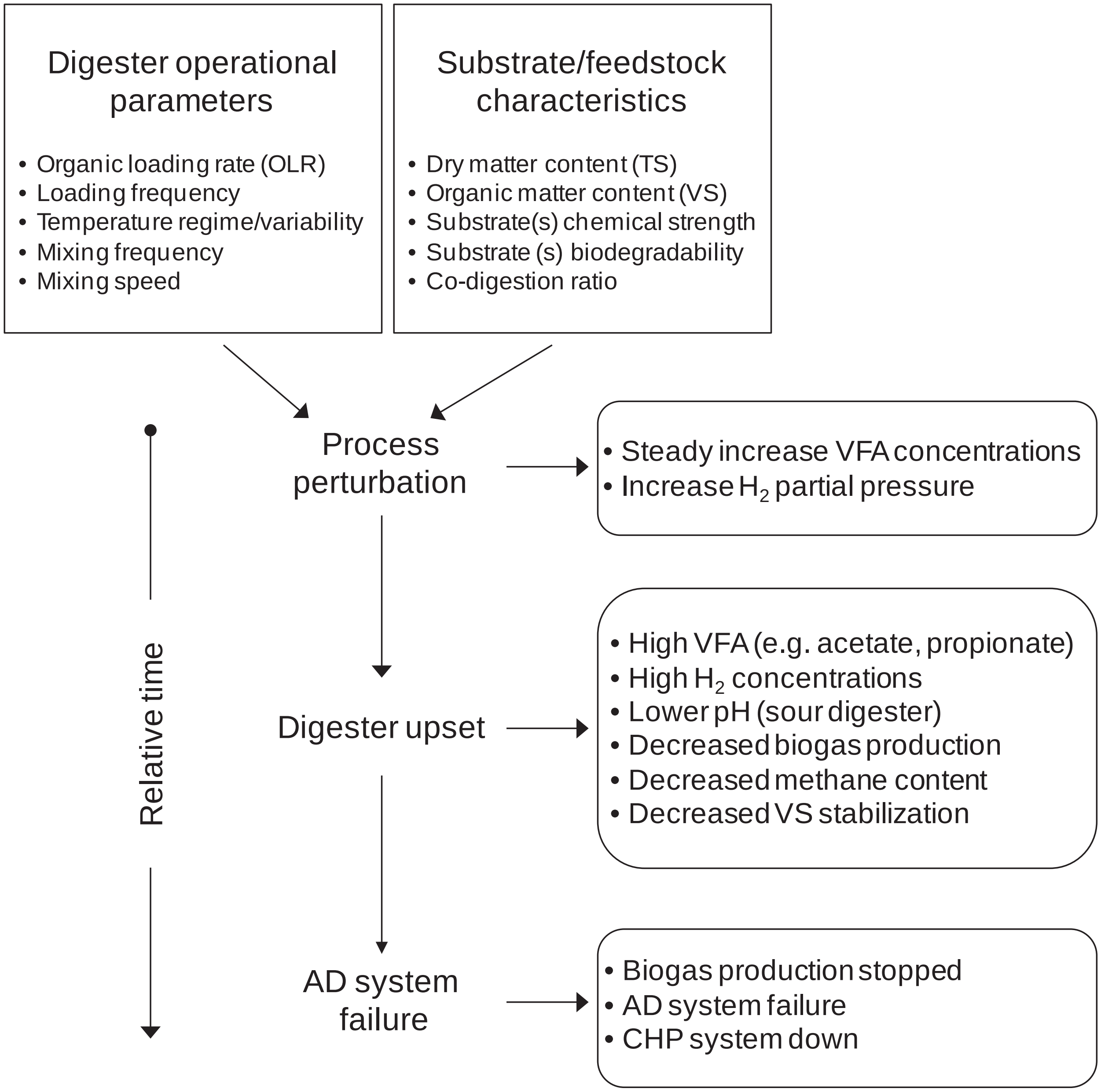


Figure 5. Setup of two analytical laboratories implemented in the AD system facilities (above) and the typical equipment used (below)

CASE STUDY: THE ALPHA ANAEROBIC DIGESTION SYSTEM

The capability of the AD analytical labs and the importance of monitoring are well demonstrated by the preliminary data obtained at one on-farm AD system in particular. The actual name of the AD system is not disclosed here to maintain the farm's privacy – it is referred here as the Alpha AD system. The Alpha AD system is a co-digestion operation treating the manure produced by approximately 3,000 cows and an average of 35,000 gallons of cheese whey every week. The anaerobic digester is a unique reactor design, a hybrid between a PFR and a CSTR. It consists of two separate U-shaped plug-flow reactors running in parallel, each one with an independent inlet and outlet. Mixing is conducted by recirculating biogas through defined sections along the reactor's length axis, one section at a time.

Figure 6 shows the power output of the CHP system and biogas production of the AD system observed from 2011 to date. As shown in the figure, although biogas production is somewhat irregular, its range of variability is fairly constant over time.

Furthermore, since the Alpha AD system produces twice as much biogas as the CHP needs to operate at full capacity, stability of electricity generation is not affected by such variability. There are three downtime periods of the CHP system. The first two were scheduled shutdowns of the system due to maintenance. However, the last downtime period (enclosed inside a box in the graph) was an unexpected shutdown due to AD system failure, as clearly evidenced by the coincidental decrease of biogas production.

Figure 7 shows the daily power output of the CHP system and daily biogas production of the AD system right before and after the system failed. These data are contrasted with the most relevant parameters obtained from the analyses performed at the AD analytical labs from samples at the effluent of the AD system, i.e., pH, volatile fatty acids (VFA), and volatile solids (VS). A seen in the graph, the AD system failure occurs shortly after the start of the monitoring (only one sample had been analyzed). A steady decrease in the biogas production (and methane content) forced the operator to shut down the CHP system – no electricity or heat was produced for two weeks. During the AD system failure, biogas production dropped 70% from its moving average, i.e. 320 to 100 ft^3/min, and methane content decreased from an average 65% to 52% (data not shown). Unfortunately, due to the additional responsibilities of the AD system operator, lab analyses could not be conducted as frequent as expected, and VFA levels were already at critical levels before any correcting actions could have been taken. From all the parameters measured in the lab, VFAs were certainly the only true early indicator of the digester upset. Indeed, before the biogas production showed any evidence of decreasing, VFAs show a two-fold increase in concentration, from 0.5 to 1.5 g/L (based on the projection of its first and second measurements, i.e. 10/13 and 11/01, respectively). Furthermore, by the third measurement, VFA concentrations are nine times higher than their baseline.

Interestingly, pH is many times taken as a sole indicator of a digester upset. Although this is true in certain cases, in farm-based co-digestion operations, pH does not always change during process perturbations, as shown in Figure 7. This is because cow manure provides increased buffering capacity to the digestate due to its high alkalinity. As opposed to VFAs, pH, biogas production, and methane content are a result of process perturbations, rather than a direct cause; therefore, it is not recommended to use them as early indicators (or predictors) of digester upsets.

Several (coincidental) operational problems in the Alpha AD system were the possible causes of the failure. One (of the two) pump located in the influent pit was out of service for two weeks during the same period, making the influent material highly inconsistent and stratified. Furthermore, almost twice as much volume of cheese whey (58,100 gal) was received by the farm for co-digestion the previous week to the upset than an average week (35,000 gal). In addition, the proportion of corn silage in the cow's feed was doubled during the same period. Considering that cheese whey and corn silage are highly biodegradable and acidic (pH = 3.3 and 3.5, respectively), and the fact that the influent material was not properly mixed during the same period, it is very possible that an increased in the rates of biodegradation had produced a shock load of VFAs and imbalanced the AD process resulting in the digester upset.

A simplistic, but conservative analysis of the costs resulting from not receiving cheese whey and not selling electricity to the utility company during the two-week downtime period of the Alpha AD system results in about $10,000 in tangible economic losses. This estimation does not consider the additional expenses incurred by the farm for extra fuel required to heat its facilities and the digester, or the losses in income from carbon credits.

CONCLUSIONS

Although anaerobic digestion is a rather mature technology, system failures are still frequent around the world. In New York State, a study revealed that some AD systems generate less than 60% of their electric energy potential due to poor anaerobic digester performance and system failure. Most of these problems occur as a result of inadequate operational management and lack of process control.

The importance of well-trained and qualified personnel to operate AD systems and properly control and monitor the process is essential, not only to prevent digester upsets and potential system failures, but also to ensure efficient organic waste stabilization and constant and stable biogas production.

Analytical laboratories were installed on selected farm-based anaerobic digester systems in NYS to periodically monitor key process parameters to develop a baseline for each AD system and to evaluate performance and stability of the operations. The preliminary results of the monitoring confirmed that these facilities are essential to detect process upsets more efficiently, and to identify and correct the source of the problem before system failure occurs.

LESSONS LEARNED

One essential aspect to consider when monitoring AD systems is the selection of the point where samples and/or measurements are taken. The influent pit is probably the most adequate location to obtain a representative sample of the influent material. On the other hand, the effluent of the AD system is the appropriate sampling point to evaluate efficiency of treatment (e.g., organic matter stabilization), or to perform an overall mass balance (e.g., COD, nutrients) around the anaerobic digester. However, to monitor process parameters, the effluent of the reactor is not always the optimal location. As newly added material undergoes mostly hydrolytic and fermentation reactions during the first days of digestion, in PFRs, for example, VFA and other key parameters observe their peak concentrations in the first segment of the vessel, rather than near the effluent. Thus, it seems apparent that in these types of reactors, process monitoring should be conducted within the first section of the vessel, in a specific point (or points) to be established through sampling trials. This would allow PFRs, such as the Alpha AD system, to identify upsets much more quickly, i.e., during the first days of digestion as opposed to after 20 (or more) days of retention time. Conversely, in an efficiently-mixed CSTR, process parameters can be monitored in its effluent, because the concentration of metabolites in the digestate should be (nearly) the same as that determined in the effluent.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the following farms for their willingness to participate in this project: Sunnyside, Roach, Sheland, Noblehurst, and SUNY Morrisville. Also, special thanks to the lab operators, Don Kulis, Gary Mutchler, Doug Shelmadine and Sons, Paul Tobias, and Ben Ballard and his students, for their motivation, and all the hard work they have done for this project, and will continue doing for their farms. Finally, the authors would like to thank the New York State Energy Research and Development Authority (NYSERDA) for funding in support of this work.

Figure 6. Power output and biogas production obtained daily from farm records at the Alpha AD system; box shows the downtime period of the CHP system due to the AD system upset

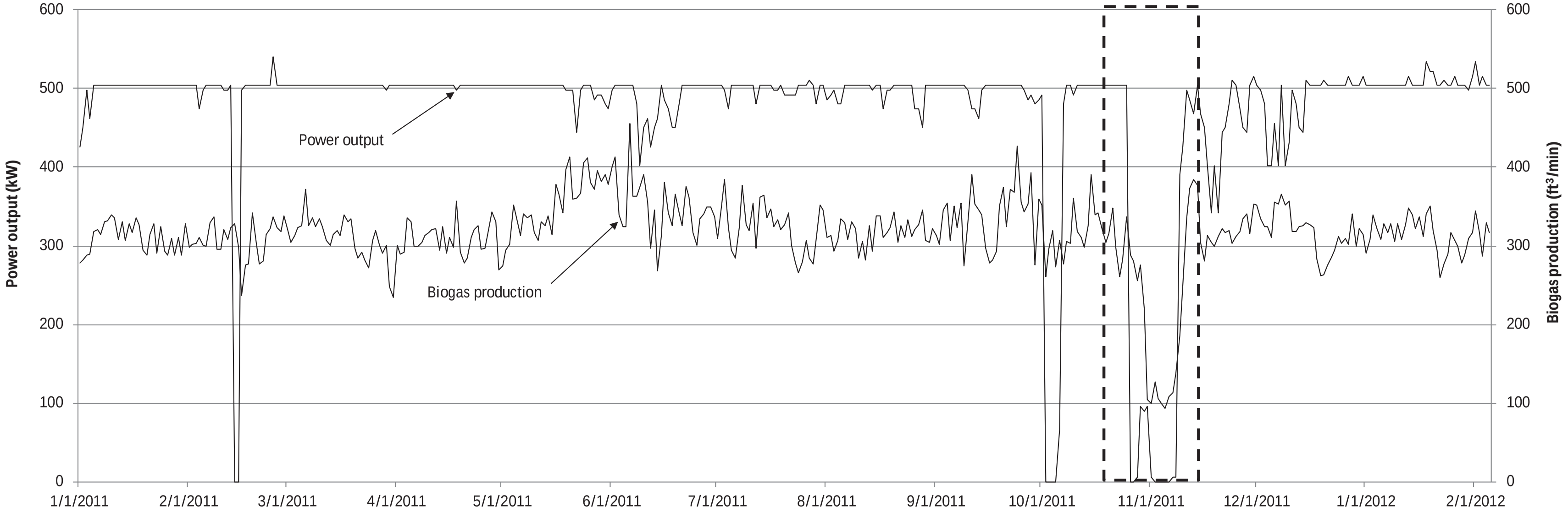
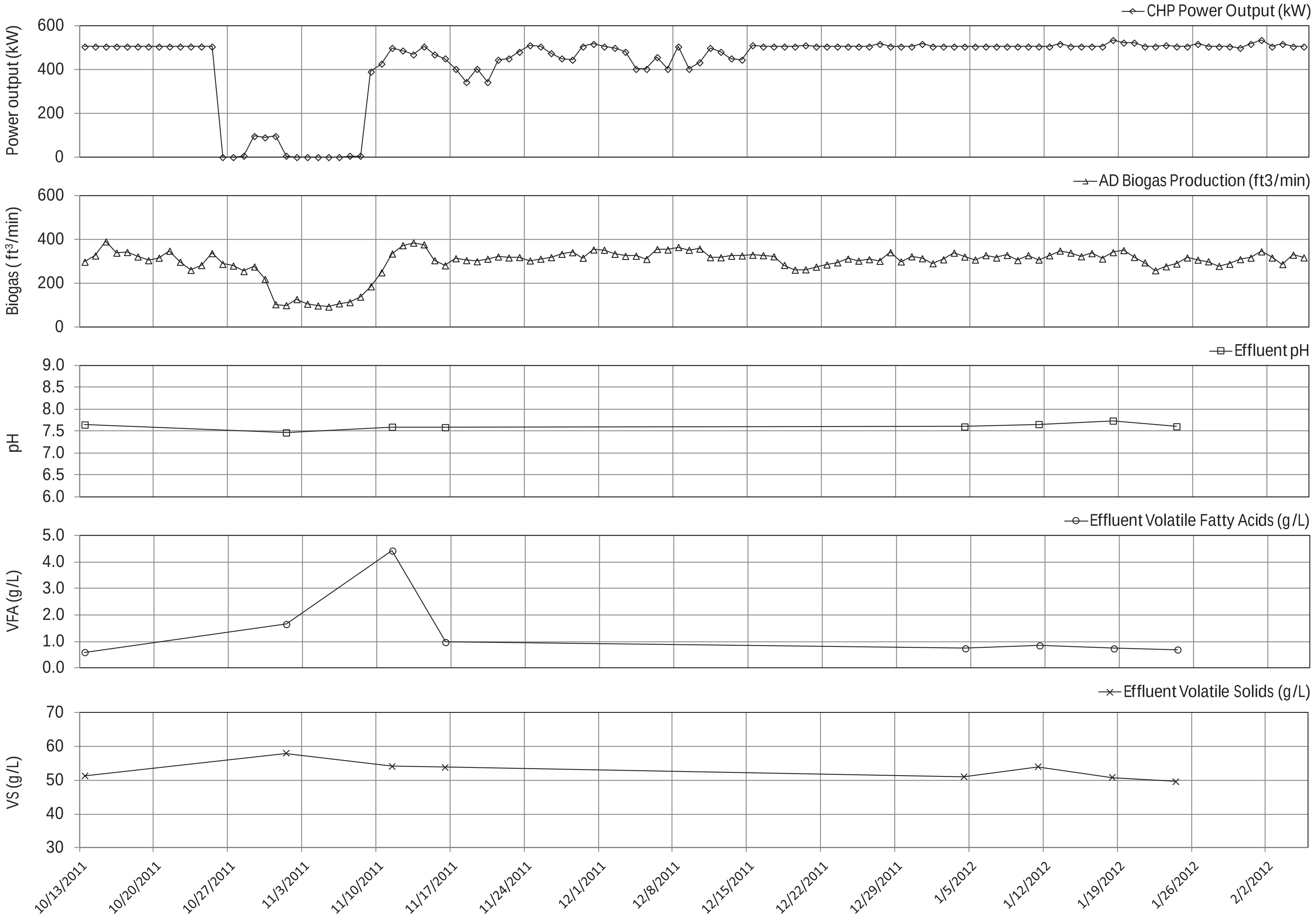


Figure 7. Preliminary results of the on-going monitoring at the Alpha AD system; power output and biogas production obtained daily from farm records; effluent pH, VFA, and VS obtained with the analytical laboratories



APPENDIX

Capacity factor

The capacity factor is the ratio of the actual electrical energy produced by the CHP system over a given period of time and the electrical energy that potentially could have been produced if the CHP had been running at nominal capacity over the same period of time.

$$Capacity\ factor\ (decimal) = \frac{Electricity\ generated\ over\ time\ period\ (kW \cdot h)}{Time\ period\ (d) \cdot 24\ \left(\frac{h}{d}\right) \cdot Nominal\ power\ capacity\ (kW)}$$

Online efficiency

The online efficiency indicates the percent of time the CHP system was operating over a given period of time.

$$Online\ efficiency\ (\%) = \frac{Electricity\ generation\ system\ run\ time\ during\ period\ (h)}{Time\ period\ (d) * 24\ \left(\frac{h}{d}\right)} * 100$$

Plug flow reactors (PFR)

Most PFRs are long, rectangular-vessels. The influent material is loaded in one end and exits the other end. Inside the vessel, the material advances as a plug and no mixing takes place.

Continuously-stirred tank reactors (CSTR)

The majority of CSTRs in Europe are upright circular tanks that are continuously mixed with one or two impellers fixed to an inclined shaft. Another type of CSTR, which is common in NYS, is a square tank. The tank includes several, but separate, mixers located on the sides of the vessel, which are turned on and off in shifts (i.e., one at a time).

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