Thermochemical processing of digested sludge and its implications in the United States

Jennifer Lawrence, Ruth Reed, Sara Tischhauser, Casey Zak

ABSTRACT

Currently, the majority of wastewater treatment plants utilize anaerobic digestion processes to treat sludge and reduce overall volume. Digester gas, or biomethane, is produced as a result of this process and can either be flared off to reduce greenhouse gas emission, or can be used for onsite heat and power needs. The high quality digested sludge is then used as fertilizer, and the low quality sludge is placed in landfills. Unfortunately, if sludge is used as fertilizer, heavy metals and harmful organics are able to contaminate crops and groundwater. In addition, methane emissions from anaerobically digested sludge in landfills is a potential threat to climate change, as methane is a highly potent greenhouse gas. Although land is not currently constrained overall in the United States, use of landfills may not always be a viable option in the future. In this paper, we analyze the use of thermochemical processing as an addendum to current wastewater treatment plants using anaerobic digestion to mitigate many of these issues. The addition of thermochemical processing, specifically gasification and pyrolysis, allows for a reduction in the volume of sludge to be disposed of, decreasing the demand for landfill space. Furthermore, the addition of thermochemical processing enables sequestration of many harmful chemicals found in the digested sludge that have the potential to contaminate crops and the environment, and allows for decreased greenhouse gas emissions. Despite these potential benefits, there are still hurdles to overcome. Infrastructure changes, funding, policy change to motivate adoption of this technology, and public perception are all issues yet to be resolved. This paper will address the key environmental, political, and business implications of using combined heat and power from anaerobic digestion and thermochemical processing to convert sewage sludge to useful energy, and will examine its potential within the United States.

INTRODUCTION

Wastewater treatment sits at the nexus of water, energy and land use. Clean water is essential to all sectors of the economy, and the treatment of that water accounts for approximately 4% of the United States' electricity load (Menendez 2009). Additionally, the disposal of sewage sludge (also known as biosolids) requires land, either in the form of landfills or agricultural land where sludge can be used as fertilizer. Landfill space is becoming scarcer, particularly along the eastern seaboard, and 'persistent uncertainty' remains about the safety of sludge as a soil amendment (Van Buren 2003, Committee 2002). Thus, making sustainable choices in wastewater treatment means addressing all three of these limited resources. An example of such a choice is the use of anaerobic digestion (AD) to reduce sludge volumes as well as produce digester gas (also known as biogas, or biomethane) for meeting onsite heat and power needs. Biogas is a methane-rich byproduct of this process that can be combusted to offset some of a plant's heat and electricity needs. AD is currently being used in most large wastewater treatment facilities in the United States, and this technology is well suited for widespread adoption (Opportunities 2011, Emerging 2006, Evaluation 2012). However, the sludge that remains after anaerobic digestion processes still contains within it large quantities of energy, and is most often simply being disposed of. One proposed improvement to wastewater treatment processes is the addition of thermochemical processing (TCP) of the digested sludge (Yong-Qiang 2012), for increased energy output and decreased sludge volumes. TCP refers specifically to using one of two processes: pyrolysis and gasification. These reforming methods involve heating organic matter to high temperatures in the presence of little or no oxygen to produce either liquid bio-oil (pyrolysis) or bio-syngas (gasification). The addition of one of these processes to a system already utilizing anaerobic digestion has the potential to greatly reduce the sludge volume even further, while simultaneously producing valuable intermediate feedstocks. These intermediate feedstocks can be used for heat and power generation onsite or upgraded to transportation fuels and sold for profit.

Thermochemical processing has been studied extensively in academic settings, and all the peripheral technologies required to build a fully operational system exist (bio-sludge minimization). Even so, TCP has not been successfully implemented with sewage sludge as a feedstock in the United States, even at the pilot scale. These systems suffer from high capital and operational costs and there is also much disagreement in the literature over whether pyrolysis and gasification can be net energy positive. This is due to the large energy cost of drying sludge prior to processing and the endothermic nature of pyrolysis (Yong-Qiang 2012, Xu 2009). In the face of this technological and economic uncertainty, it is important to assess the viability of TCP from other viewpoints to determine if its success is worth further time and effort. Thus, this paper will address the key environmental and political implications of thermochemically processing digested sewage sludge into useful energy, and will examine the technology's potential within the United States. Policy makers, business leaders, and those in charge of public utilities can use the information collected here to guide them in their decision-making process concerning this new technology.

There are in fact many different technologies available for reducing sludge volume and deriving useful products, and several reviews can be found in the literature of their relative merits (Yong-Qiang 2012, Xu 2009). However, in this work we restrict our focus to pyrolysis and gasification and do not discuss other volume reduction technologies like incineration, wet oxidation and plasma processing. While it is possible to thermochemically reform sewage sludge without anaerobic digestion, it has been shown that TCP offers the most benefit when used in conjunction with digestion and biogas utilization (Cao 2012). As a result, this work focuses on the addition of TCP systems to wastewater treatment plants (WWTP) that currently have or are considering installing AD/biogas capacity (typically those that process 5 million gallons per day or more) because these larger facilities have the sludge flow rates and economies of scale to maximize the technical feasibility of a AD/TCP system. It is also assumed that they service large urban centers and are the most burdened by the land constraints mentioned previously. These facilities treat more than 50% of the country's wastewater, such that any improvement to these facilities would represent a significant step towards more sustainable practices (Opportunities 2011). For the sake of brevity, we do not address the countless improvements that could be made in related areas, including: the wastewater treatment process, the anaerobic digestion process, and the drying process.

The following sections are organized in an attempt to give a clear picture of the non-technical aspects of thermochemical processing. This, of course, requires some degree of technical knowledge. Along those lines, we begin with an overview of the technologies being discussed. The next section focuses on the positive and negative environmental impacts of this technology, and attempts to assess their relative importance. This is followed by a discussion of the political environment surrounding sludge-to-energy systems, including current (and anticipated) policy drivers and barriers and the regulatory requirements for implementation. Finally, we survey the current companies and funding sources in this area and identify some of the important economic and social changes that must occur to make this technology viable.

TECHNOLOGY OVERVIEW

Wastewater and sludge treatment

Due to a number of factors, including plant size, effluent load, local regulations, and resource availability, wastewater treatment practices and the resulting sludge vary widely across the United States (Quinn 2013). Figure 1 shows a flowchart of the general wastewater treatment process, including the anaerobic digestion/TCP combination under study. Most facilities carry out at least two stages of treatment: primary and secondary. Primary treatment involves holding effluent in large tanks and allowing solids to settle to the bottom. These solids are then scraped away and secondary treatment occurs. In this stage, suspended solids still present in the effluent are removed through microbial activity. These formerly suspended solids (sometimes called activated sludge) are combined with the solids from primary treatment and sent to landfills, or fed into anaerobic digesters if they are present.

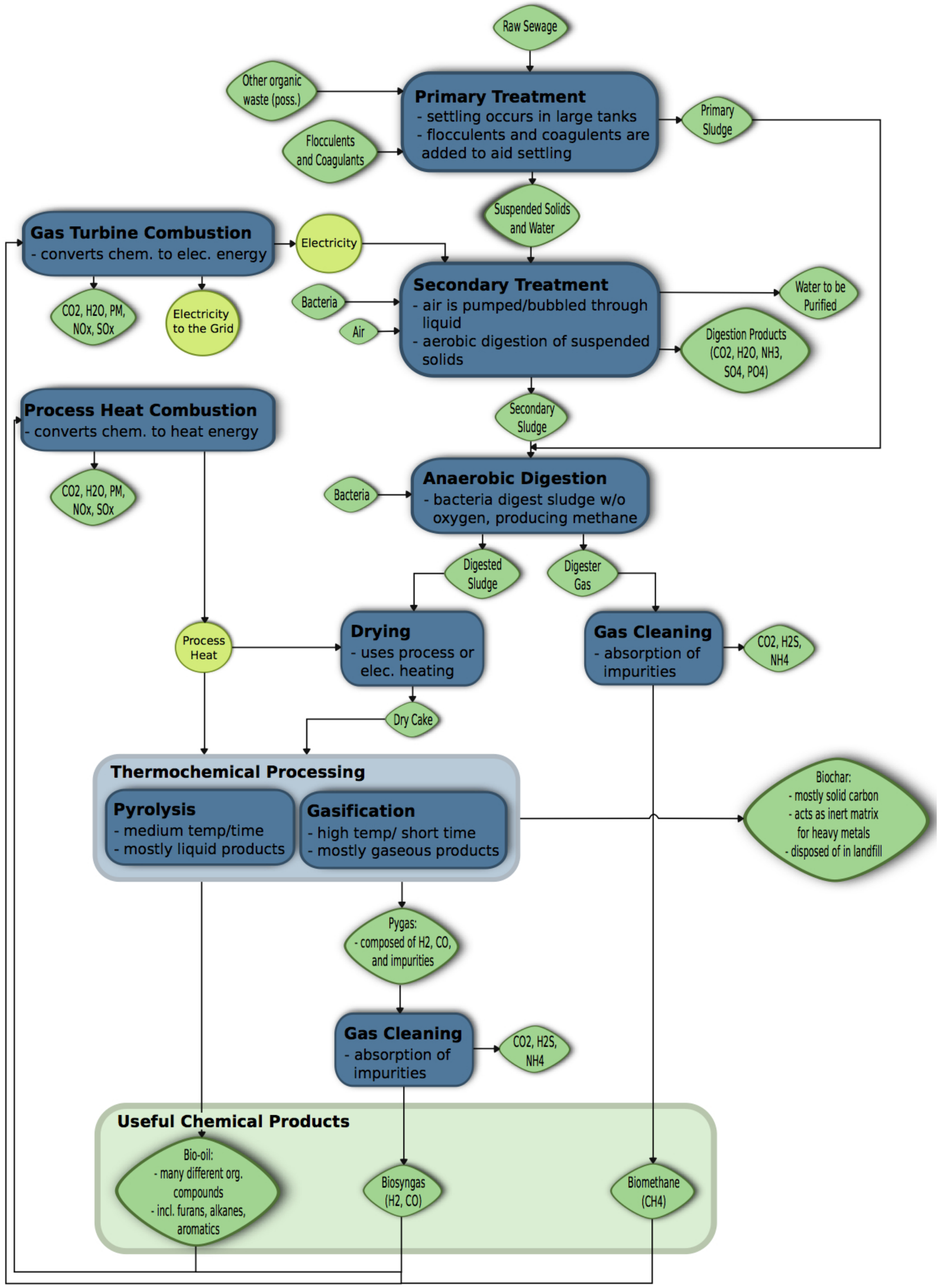

Figure 1 - Process Diagram of Wastewater Treatment

Anaerobic Digestion and Combined Heat and Power Systems

During anaerobic digestions, microbes break down the organic material present in the sludge in the absence of oxygen, releasing biogas as a byproduct of their metabolic processes. This gas is comprised mainly of methane, but also contains within it other trace gasses (Molino 2013). This process can occur at temperatures around 37 degrees C (mesophilic) or around 55 degrees C (thermophilic), depending on the type of microbial activity required for the specific sludge composition. The latter is generally more efficient but requires greater attention and energy input to maintain the high temperature requirement (Xu 2009). To help offset the power needs of a wastewater treatment facility, biogas, bio-oil and syngas can be used in some sort of a combined heat and power (CHP) system. CHP is a complex field itself, and the reader is invited to consult the literature for several helpful reviews (Evaluation 2012). Wastewater treatment plants' heating requirements can be met by directly combusting any of the three aforementioned fuels. For electricity generation, gases like biogas and syngas are combusted directly in turbines or piston engines that drive a generator. Direct chemical-to electrical conversion within a fuel cell is also an option (Yong-Qiang 2012). Bio-oil is burned to produce steam; this steam then drives a turbine-generator system.

Drying, Pyrolysis and Gasification

Digested sludge has a water content of more than 95%, the majority of which is 'interstitial water' and difficult to separate from the solid fraction. Mechanical and chemical thickening and dewatering must be used before disposal, but these can only reduce the water content by at most 70% (Manara 2012). Thermochemical processing requires a moisture content of 5% or less and this must be achieved with thermal drying, either using process heat or electricity.

Pyrolysis is the non-oxidative thermal decomposition of organic matter and it can produce varying amounts of solid, liquid and gaseous fractions. These first two products are often referred to as char and bio-oil, respectively. Using short residence times and temperatures around 500 degrees Celsius (so-called fast pyrolysis) maximizes the production of bio-oil. This intermediate feedstock is desirable because of its relatively high energy density and ease of transport. The composition of this bio-oil varies greatly depending on system design parameters and sludge composition, but will most often contain both aqueous and non-aqueous fractions. Its liquid state makes it more amenable to storage and transport, but its aqueous components and high acidity present additional challenges in this regard (Xu 2009). The non-aqueous fraction of bio-oil can be combusted onsite or upgraded into more useful fuels and chemicals.

Gasification is similar to pyrolysis in theory and operation, but occurs at higher temperatures (~1000 deg. C) and in the presence of small amounts of air, oxygen, or steam. These higher temperatures and additional reactants preferentially produce a combustible gas mixture known as syngas. Its main components are CO and H_2, but it also contains CH_4 and other non-condensable hydrocarbons. Gasification systems can achieve high thermal efficiencies and, after cleaning, syngas can be upgraded to more useful chemicals or used for onsite power generation. A major technical obstacle for gasification is the removal of tar from system components (Yong-Qiang 2012, Xu 2009). Tar is a mixture of condensable hydrocarbons similar to bio-oil, but at very high temperatures these compounds adhere to surfaces and are difficult to remove. Thus, additional technology must be used to make sure system components remain tar-free.

ENVIRONMENTAL IMPLICATIONS

From the perspective of environmental sustainability, there are several drivers for the incorporation of thermochemical processing into municipal wastewater treatment plants. Not only will the incorporation of this technology decrease the energy footprint of WWTPs, but it will also decrease the amount of waste product and greenhouse gases released to the environment through the life cycle of the treatment process. These latter points are especially important because sewage sludge effluent has been proven to be very toxic to the environment, and climate change mitigation is necessary for sustainable operation. Of course, new concerns will arise with the adoption of this technology; bio-oil, the product of thermochemical processing, may be more toxic than its traditional fossil-oil counterpart. In the next few paragraphs, we will discuss in greater detail the environmental drivers both encouraging and discouraging the adoption of thermochemical processing.

Environmental Drivers

As resource scarcity and adverse climate conditions become increasingly apparent, the adoption of technologies that decrease the United States's energy demands are very important. The United States currently produces seven million dry tons of waste sludge per year (Kaufman 2011), and each ton contains within it 12 - 20 million kiloJoules of energy (in reference to coal, there are 15 - 27 million kiloJoules per ton) (Manara 2012). Despite the vast amounts of potential energy streaming through municipal treatment plants each day, the majority of the treatment plants in the United States are currently powered by electricity through fossil fuel combustion. In fact, approximately 4% of the nation's total electricity consumption of 100 billion kiloWatt hours is used for wastewater treatment (Menendez 2009). The combination of anaerobic digestion and thermochemical processing of municipal sewage sludge would maximize the amount of useable energy that can be extracted from the sewage sludge, and would allow WWTPs to meet some if not all of their energy needs, and potentially even produce a surplus of energy that could be sold as electricity or as a liquid fuel for profit.

Another driver for the adoption of thermochemical processing is its capacity to reduce greenhouse gas emissions. Municipal sewage sludge contains within it many nutrients useful to microbes; thus, its composition will eventually break down to gaseous compounds including methane (CH_4), hydrogen sulfide (H_2S), ammonia (NH_3), and hydrogen chloride gas (HCl) (Manara 2012). (It is important to remember that methane, as a greenhouse gas, is 25 times more potent than CO_2 (Chiemchaisri 2011). The AD process significantly mitigates the emission of these gases to the atmosphere, but wastewater sludge that is not thermochemically treated will still emit trace amounts of these gases to the atmosphere when dumped in a landfill. Overall, landfills account for 10% of all methane emissions in the United States (EPA 2012). The combined process of anaerobic digestion and thermochemical processing would help to further reduce this percentage through its capture and advantageous use of greenhouse gases before they are emitted into the atmosphere.

A third driver for the adoption of thermochemical processing is its capacity to concentrate and immobilize trace contaminants within sewage sludge (Rulkens 2008). The quality of digested sludge is highly variable, and despite efforts on the behalf of wastewater scientists and engineers the sewage sludge often contains contaminants toxic to both the environment and human health. The contaminants within sewage sludge streams may end up partitioning into and contaminating the atmosphere, soil, and water resources (Rulkens 2008). The contaminants most commonly found in digested sludge are heavy metals and pharmaceuticals (Wu 2012). The heavy metals especially of concern are arsenic, cadmium, chromium, copper, lead, nickel, and zinc. All of the heavy metals' concentrations can vary from less than one part per million to more than 1000 parts per million (Tyagi 1993), and often it is very difficult to predict which end of the spectrum the contaminants' concentrations will fall on (concentrations vary so dramatically due to differences in geography and the corresponding anthropogenic activities (Zhao 2010)). Based on toxicity per concentration however, cadmium is regarded as the most hazardous metal element in biosolids (Keefer 1986, Manara 2012). When ingested over a prolonged period of time, it can cause kidney damage and bone fragility (Alloway 1990).

Once mobilized, pollutants can potentially accumulate in smaller organisms and plants, and subsequently work their way up the food chain and cause damage in all levels of the food web (Du 2012). Most of sewage sludge's impacts as a soil amendment have not yet been quantified (Richardson 2010), but it has been proven that crops grown in biosolid-amended soils have higher concentrations of heavy metals, chemicals, and pharmaceuticals than similar control crops (Keefer 1986). In 2012, researchers found 24 chemicals in vegetables grown in biosolids-based fertilizers, including DEET (a mosquito repellent), various antibiotics, and cocaine (Sabourin 2012). The unpredictable nature of biosolids fertilizer has raised alarm in many counties across the country, and its use is slowly being limited under various laws and ordinances. The inclusion of thermochemical processing at WWTPs would more successfully capture and immobilize these aforementioned trace contaminants in a char residue (Rulkens 2008), limiting their toxicity not only in biosolid fertilizers, but also in the ecosystems surrounding landfills. (The following section of this paper will discuss in more detail the regulations surrounding heavy metal disposal.)

High volumes of digested sewage sludge are also undesirable, as landfill space--its only viable dumping location for the reasons discussed above--becomes more constrained and more geographically isolated. With the progression of time, landfills nearest to human populations will fill, and sludge will be shipped further and further away from its source of creation. Additional greenhouse gases will be emitted in the transportation of sewage sludge from the treatment facility to the landfill site. Under landfill regulations currently in place in the United States, it is not uncommon for waste to travel over 500 miles between these two points. In travelling this distance, one ton of sludge generates 115 pounds of carbon dioxide. If all seven million `tons of sludge produced in a year were shipped this distance, an additional 800 million pounds of carbon dioxide would be released to the atmosphere (Palmer 2011). As time progresses, the cumulative distance for sewage sludge to travel will increase. States on the eastern seaboard, such as Massachusetts and Rhode Island, will reach their maximum landfill capacity in the next 12 years (Palmer 2011). A reduction in sewage sludge volume would be highly beneficial in overall energy balances, as less miles would be covered in sending sewage sludge to its final resting place with decreased sludge volumes. The inclusion of thermochemical processing at wastewater treatment plants would reduce biosolid volume by over 50% (McCarty 2011), similarly reducing greenhouse emissions for shipping sewage sludge by over 50%.

Environmental Concerns

In addition to gaseous products from sewage sludge digestion, thermochemical processing of sewage sludge produces bio-oil, a fuel with purposes similar to that of traditional, fossil-based oil. The yield, quality, and stability of bio-oil produced from this process is closely related to characteristics of the sewage sludge, as well as reactor type and configuration, heating rate, and pyrolysis temperature (Hyun 2012), and again its quality can be highly variable and difficult to regulate.

Components of bio-oil include oxygen, water, sugar, phenolics, organic acids, aromatics, furans, organic nitrogen compounds, and other non-volatile organic components (Czernik 2004, Cao 2010). Many of the aforementioned harmful compounds are similar to what we see in petroleum based fuel, however two major differences exist: In bio-oil, one finds higher concentrations of nitrogen compounds and furans. The increased presence of nitrogenated compounds may lead to increased NOx emissions when the bio-oil is combusted (Williams 2012), which is a criteria air pollutant according to the EPA (because it scavenges ozone molecules in the atmosphere). Fortunately, low temperature pyrolysis can help to eliminate the formation of SO2 and NOx entirely (Liu 2012). More about NOx emissions, including its political implications, will be discussed in the following section. Also, combustion products of the furan compounds produced in the pyrolysis process are a possible concern (Peterson 2013), as they have demonstrated carcinogenicity in several studies. However, other studies have demonstrated that these potentially carcinogenic compounds can be destroyed completely at temperatures above 800 degrees Celsius. With the proper technological developments, both of these concerns could be eliminated.

It is important to note that many of the organic alkanes, nitrogen compounds, and aromatics that are found in bio-oil originate in the sewage sludge. If pyrolysis were not used to convert the sludge to bio-oil, these contaminants would be put into a landfill where they would run the risk of contaminating water sources, soil, and organisms. Instead, when the sewage sludge is made into bio-oil, many of these harmful organics can be burned as fuel, both lessening their harmful effects through the combustion process as well as producing energy from a non-fossil fuel source. In conclusion, the conversion of municipal sewage sludge to biofuels taps into an energy source that is otherwise regarded as waste, and from an environmental standpoint should be considered a viable option for biofuel production as the United States progresses towards a more sustainable future.

POLITICAL IMPLICATIONS

In addition to environmental sustainability, the policy and law environment surrounding a particular biofuel technology greatly affects that technology's ultimate viability. This is especially true in the case of sludge-to-energy systems, where the main players are risk-adverse public utilities or municipalities with little economic motivation to move beyond the status quo. In the following section, we will discuss environmental and land use regulations, toxicity regulations, as well as climate change policies that might affect the adoption of thermochemical processing systems. We will also make an assessment of scalability issues surrounding the technology. Recommendations for favorable policies that would help the industry grow will follow.

Land Use and Emission Regulations

We will begin with a brief overview of the infrastructure required for a thermochemical processing unit to be amended to an existing WWTP with anaerobic digestion capacities. The first issue that we will discuss surrounds land usage. Because thermochemical processing units require additional machinery on top of the existing anaerobic digestion components, adoption of this technology will likely require that the existing WWTP be capable of obtaining additional land space for this machinery (however, the precise amount of land space required is currently unclear as this technology has not been adopted elsewhere). Furthermore, if the useful products (i.e., biogas, pygas, and bio-oil) are to be used for onsite power generation, then space for turbines and boilers will also be required. There should be little infrastructure change required if the plant decides to export excess electricity back to the grid, but excess useful products would need to be moved offsite. In the case of biogas, this may mean simply interfacing with the existing natural gas pipeline network once the gas is cleaned, but most likely all products will require trucking or new pipeline installation to transport them to a refinery or power plant. With respect to environmental and land use, the expansion of an existing WWTP will require the acquisition of zoning permits, and these may be difficult to come by depending on the nature of the land use already surrounding the plant. For example, residential areas may be especially resistant to the installation of gas turbines near their homes. Pipelines and trucking operations would also be subject to local and state regulation, and restrictions could result in a ‘stranded’ facility with no way of moving its products.

Additionally, if the facility chooses to generate power onsite, combustion emissions and their effects on the area surrounding the plant must be considered. The utility must comply with both Clean Air and Clean Water Act regulations, as well as the concerns of local communities. For example, California’s East Bay Municipal Utility District (EBMUD) (currently employing only anaerobic digestion) can operate only two of its three generators at any given time, because the use of all three in conjunction exceeds air quality standards in the area (Wastewater and Energy 2013). This consideration favors installation of systems in more rural areas where emissions concerns may be outweighed by the desire to promote industry and create jobs. The obvious danger in such a scenario is that the sludge-to-energy system may place a high emissions burden on uninformed people living close to rural WWTPs. Additionally, it is ideal for the sludge-to-energy plant to be located near the energy market, to reduce transportation infrastructure demands. If the system is based in a rural area, the raw sludge will need to be transported long distances to reach the plant, emitting carbon dioxide in the process (Palmer 2011).

Another possible emissions issue that may arise with the adoption of TCP concerns the amount of nitrogen compounds found in bio-oil. The amount of fuel-bound nitrogen in sewage bio-oil varies greatly depending on the sludge composition, but research has found that the amount of nitrogen in bio-oil ranges from 6.1-11.1% by weight depending on the type of feedstock (Wastewater and Energy 2013). In comparison, coal contains only around 2% nitrogen by weight (Pokorna 2009). It can be inferred that any transportation fuel derived from bio-oil would have similar nitrogen concentrations as its parent sludge. However, Manera and Zabaniotou (2012) reported that, under pyrolysis conditions, about 60% of the fuel bound nitrogen compounds are instead converted to NH_3 in the pyrolysis process, reducing combustion-bound nitrogen compounds in bio-oil to the same concentrations found in coal. As discussed previously, NOx emissions from nitrogen compounds in fuel are regulated under the Clean Air Act and similar state regulations, and it may be difficult to find a market for a particular bio-oil if its nitrogen content is too high. Further scientific investigation needs to be conducted on this topic.

Bio-oil, the product of thermochemical processing, will also be subject to regulations determined by The Toxic Substances Control Act (TSCA). An analysis of the representative compounds found in biomethane and bio-oil (these compounds include but are not limited to: methane, benzene, toluene, acetamide, 4-methyl phenol, phenol, pyrimidine, and 1-(-2-furanyl) ethanone) showed that all of these chemicals were listed in the TSCA chemical inventory. Therefore, no additional premanufacture notices (PMNs) must be written for these chemicals. The microorganisms needed for the anaerobic digestion of our sludge were also considered and, because these microorganisms are not genetically modified, no further PMNs must be written for these microorganisms in accordance with TSCA rules. The major difference in chemical composition of bio-oil, as compared to petroleum crude, is the presence of furans. United States EPA regulations are already in existence for furan emissions as part of an amendment to the Clean Air Act of 1990, so no further policies would need to be put into place; however, these regulations could make it difficult to market high-furan fuels (Dow Chemical, Caponi 1998).

Although the products of this technology are listed under the TSCA inventory, and regulations exist to limit the amount of furan emissions, the corresponding toxicity of these compounds must be considered in order to determine potential impacts on those populations located in close proximity to the implementation of this technology, as well as those employees working within the process. Compounds found in the bio-oil product, such as methylbenzene, 4-methyl phenol, phenol, and 1-(-2-furanyl) ethanone, must be handled with care as inhalation poses a risk for both human health and emission of these compounds threatens air quality, not dissimilar to typical petroleum based fuels (ChemSpider, Pharos). In the future, this technology must also be treated under REACH guidelines in addition to TSCA to allow expansion of this technology to the European Union.

Climate Change Regulations

The next portion of this analysis will address climate change policy, which seems to be one of the areas in which sludge-to-energy systems can really shine. Most of these incentives, guidelines and standards are concerned with a technology's greenhouse gas emissions performance relative to fossil fuels; thus, it is important to accurately assess this performance. Cao et al. (2013) recently performed this analysis for two emerging sewage sludge-to-energy systems and compared their GHG emissions to fossil fuels technologies: one system uses fast pyrolysis combined with anaerobic digestion (known as Combined Pyrolysis (CP) in the study), and the second system uses only fast pyrolysis (also known as Simplified Pyrolysis (SP) in the study) (Cao 2013, Kharecha Mazria 2010). Due to the anaerobic digestion step, CP has an extra bioenergy product (biogas), and produces less char but produces less bio-oil due to the lower mass of its feedstock (digested sludge) used during pyrolysis/gasification. This reduction in yield leads to a decrease in GHG emissions. The pertinent results of the analysis are shown in Table 1 below.

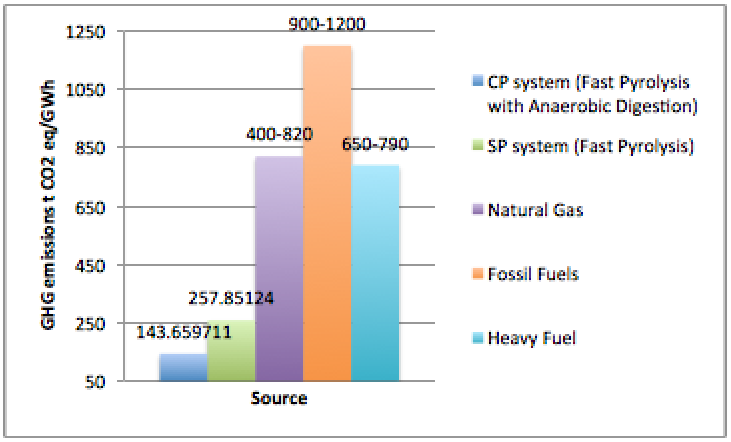

Table 1 – Comparison of GHG emission for sewage sludge-to-energy conversion to different technologies (Cao 2013)

It should be noted that the values in Table 1 are not broadly applicable due to some of the benefits assumed from using biochar as a soil amendment. Depending on the concentration of heavy metals in the char it may be safest to simply dispose of the char in a landfill rather than risk contamination of soils and groundwater. Even so, they can be taken as a rough estimate and it is clear that use of sludge-to-energy systems result in a net reduction in GHG emissions, specifically in the case of the CP system.

With the Supreme Court's 2012 decision to uphold the EPA's ability to regulate greenhouse gas emissions (Center for Climate and Energy Solutions "Clean Air Act Cases"), it seems likely that more restrictive carbon policies are on the way, making sludge-to-energy systems attractive in the near future. Already, the EPA has created numerous mechanisms, partnerships and voluntary reduction programs like the Landfill Methane Outreach Program and the Waste Energy Recovery Registry, all of which create a favorable environment for technologies that reduce the amount of GHGs produced (What the EPA is Doing About Climate Change 2013). In the event that a cap-and-trade system is established to regulate carbon emissions, sludge-to-energy systems may be a feasible way for public utility partnerships to earn valuable carbon credits.

Forecasting how this policy climate will help or hinder this technology is a daunting task given that no wastewater treatment plant in the United States is currently using both anaerobic digestion and thermochemical processing (pyrolysis/gasification) to treat their wastewater streams. Even so, a clearer picture can be gained by looking at only anaerobic digestion, a technology that is currently in some degree of use. According to the American Biogas Council, there are currently 1,500 anaerobic digesters at the 21,000+ public wastewater treatment plants across the country (Business Analysis of Anaerobic Digestion in the United States 2013). Of these, only 250 are taking advantage of the biogas that they produce (while the remainder that use AD are simply flaring their biogas into the atmosphere). California Assembly Bill 1900 defines biomethane as a renewable fuel (AB 768 Bill Analysis 2011). This bill empowers the California Energy Commission to regulate a certification process for biogas energy content and purity, enabling biogas producers to sell their fuel rather than releasing it into the atmosphere or burning it in flares. Even more recently, in 2013, the Biogas Investment Tax Act has been introduced (Kind 2013) as a possible future policy. This bill would provide a 30% investment tax credit for systems that use anaerobic digesters to convert biomass into a gas that consists of at least 52% methane. This act would add biogas to a list of renewables already receiving an equivalent tax credit, encouraging biogas's injection into pipelines and use in vehicles. In California, EBMUD has gone so far as to produce more energy from their anaerobic digesters than they need to run their facility, and they can actually sell power back to the grid (Cao 2013, Business Analysis of Anaerobic Digestion in the USA). This indicates that the policy environment around a particular industry can greatly affect its adoption and foster further technical advancements

The Role of Public Opinion and the Government in TCP Policy

Despite the benefits regarding climate change policy, the ability to sequester heavy metals from the sludge, and the elimination of toxic chemicals released into our land, the adoption of thermochemical processing onto existing WWTPs will still prove to be difficult unless certain barriers can be overcome. One such barrier is public education. Pyrolysis is not currently a word embraced by the general public. When the general public hears the word "pyrolysis", they assume that it is interchangeable with "incineration", and that this "incineration" will emit countless harmful particulates into the air as well as significant amounts of greenhouse gases. A combined anaerobic digestion and pyrolysis pilot project located in San Jose, California was shut down before construction even began because of public outcry stemming from this fear (Interview, Chakrabarti 2013). It is vital that the public understand the difference between pyrolysis and incineration, and that thermochemical processing has the potential to lower the amount of greenhouse gases released into our environment, prevent toxic chemical exposure, and emit much cleaner byproducts than an incineration process would emit. This becomes especially important in a voting environment, where citizens are able to voice their opinions regarding adoption or rejection of these technologies.

In addition to mere public acceptance, widespread adoption of thermochemical processing units onto existing WWTPs relies heavily on policy and government regulations. Initial infrastructure costs for anaerobic digestion alone hover around $600 per ton of capacity, and operating costs range from $40 to $150 per ton of waste delivered depending on waste composition (Business Analysis of Anaerobic Digestion in the USA 2013). As mentioned before, municipalities are inherently risk averse and they have little motivation to adopt these new technologies under such a large startup cost. Incentives from the government could help to overcome this hurdle, since biogas satisfies clean energy regulations under the Renewable Fuel Standard and also under the Low Carbon Fuel Standard. We will now discuss the role of these two regulations in the adoption of thermochemical processing.

The Renewable Fuel Standard program began under the Energy Policy Act of 2005, and was expanded under the Energy Independence and Security Act of 2007 (United States Environmental Protection Agency). The program works to reduce the amount of greenhouse gas emissions by increasing the use of renewable fuels through a renewable fuel volume mandate. Under the original program, 25 billion gallons of renewable fuel had to be blended with gasoline between 2005-2011. The current program requires 36 billion gallons to be blended with transportation fuels by 2022. The type of transportation fuel expanded from gasoline in 2005 to gasoline and diesel by 2007. The EPA is also required to construct lifecycle analyses of the renewable fuels in use under this program to ensure they emit fewer greenhouse gases than the fuel it replaces (United States Environmental Protection Agency). The need to incorporate renewable fuels into gasoline and diesel is a possible incentive to move toward production of bio-oil through combined thermochemical processes.

Another policy that may prove to be helpful in the adoption of our technology is the Low Carbon Fuel Standard. Established in 2007 in the state of California, this policy has triggered research interest in alternative fuels in order to attempt to lower greenhouse gas emissions (California Energy Commission). Because anaerobic digestion with combined thermochemical processing applications does significantly reduce carbon emissions, it would be an attractive technology to invest in under this policy.

With the broad adoption of policies like these (i.e., supporting investment in the adoption of biomethane as a renewable fuel), it is feasible to forecast the inclusion of anaerobic digestion and thermochemical processing at every wastewater treatment facility in the United States. Wastewater treatment plants will continually be receiving influent waste streams, and it only makes sense for them to capture as many benefits from the waste stream as they can.

Implications of Scale-Up

The scale-up of thermochemical processing technologies could expose wastewater treatment facilities to different sets of laws and policies. Most notably, wastewater treatment plants may have to consider air quality regulations. As mentioned earlier, East Bay Municipal Utility District, for example, can only operate two of its three generators at any given time, because the use of all three in conjunction exceeds air quality standards in the area. Air quality will be especially of concern in urban areas, because air pollution rates are already elevated. Zoning regulations, also in urban areas, may hinder the adoption of this technology.

Ultimately, if this technology catches on, and the majority of wastewater treatment plants in the United

States incorporate anaerobic digestion and pyrolysis into their treatment processes, policy and lawmakers could mandate that natural gas must be captured from wastewater streams (to prevent its release to the atmosphere). They could also mandate that heavy metals be sequestered through the pyrolysis process.

Adoption of thermochemical processing relies on fundamental need which, as of yet, does not exist in the United States. The status quo works. And, as was previously stated, we are not running out of space for landfills in the immediate future. Therefore, investment in the adoption of these new technologies, although benefits may exist, is unlikely. If there were a way for policy to increase need, it is possible that likelihood might increase. Similar to a carbon tax, if a landfill tax were to be implemented, the push for adoption of thermochemical processes may be more of a concern. Until we can make clear that adoption of this technology is necessary, change will remain difficult.

As is the case with many biofuels technologies, it appears that the current policy and law landscape is amenable to, but not promoting of, sludge-to-energy technology. The largest hurdles appear to be potential zoning and emissions issues, potential nitrogen contamination of wastewater plant effluent, and the large upfront capital cost required of conservative public utilities. Stricter regulation of carbon emissions and landfill pollutants, along with incentives and mandates to use this 'something for nothing' technology will ensure that this technology becomes a standard in the waste water treatment industry.

INDUSTRY STATUS OF THERMOCHEMICAL PROCESSING

The business environment surrounding a new biofuel technology substantially impacts the technology's endurance and success. This statement is especially true for the 'sewage sludge to energy' biofuel technology market in the United States. As an introduction to this section, we will describe the business environment surrounding anaerobic digestion and thermochemical processing of sewage sludge technologies. First, we will look at the technology's development towards commercialization, and second we will look at funding availabilities for this technology. In conclusion, we will identify some of the economic obstacles preventing the widespread adoption of this technology and suggest strategies to overcome them.

Current Economic Status

Currently, a system utilizing combined anaerobic digestion and thermochemical processing to turn sewage sludge into useful energy does not exist on any scale within the United States. As a result, the businesses that do work in this field tend to be focused on developing thermal processing systems independently of anaerobic digestion. We expect that these technologies can later be purchased by public utilities and appended onto their current infrastructure. Of the several companies that have developed technologies for TCP, all are at the pilot or demonstration stage and are utilizing non-sewage feedstock (agricultural, forestry, logging, and mill residues, or municipal solid waste). One of the biggest reasons why digested sewage has not yet been utilized as a feed stock is due to the lack of funding. As mentioned earlier, municipalities are inherently-risk averse, and have little incentive to invest large sums of money into such a risky idea. We will now describe a handful of companies, what they are doing to further thermochemical processing technologies, and where their funding is coming from.

One company that has made substantial progress for thermochemical processing technologies is Avello Bioenergy, which has secured funding at the federal and state level (Iowa) for a 2.5 dry ton per day (TPD) thermochemical processing plant. They are using corn stover as a feedstock, and are converting it to bio-oil (Avello 2013). While there are no apparent obstacles facing Avello at this level of operation, it remains to be seen whether their project will be successful. If Avello succeeds, then its TCP technology could potentially be applied to digested sludge as well.

Envergent Technologies, a joint venture by UOP and Ensyn, is another company in the field, and they claim to have the "only commercially proven TCP technology." Exact examples were scarce in the company's own media, but it can be inferred that these commercial scale systems were processing industrial byproducts (and thus not overly advertised) (Envergent 2011). A project involving forestry waste in Massachusetts is mentioned as a case study on their website, but no scale or time to completion is given.

Perhaps most interesting is the startup Intellergy, based in Richmond, CA. The company focuses on the gasification of organic waste streams, and has an operational pilot scale system capable of processing 0.1 tons per day (TPD). They claim to have processed medical waste, chicken litter (bedding), biomass, and special wastes of all kinds (Walsdi 2011). They plan to have a demonstration scale plant operational by 2013 that will process digested sludge from the city of Richmond. To fund the project, they have partnered with the Bay Area Biosolids to Energy Coalition (BAB2EC 2009), a coalition of city governments and wastewater utilities that is seeking a way to utilize the remaining energy in sewage sludge (Bay Area BioSolids 2009), in a fund-matching program. At the time of writing, Intellery was having difficulty bringing its own funds to the table, and it is uncertain if the demonstration plant project will indeed come into fruition.

Funding Opportunities

A surprising number of companies that use TCP as their main technology but not digested sewage sludge as their feedstock have already received funding to move forward with their waste-to-energy technologies. Avello Bioenergy, mentioned earlier, has received a grant of $2.5 million from the Iowa Power Fund to design, build, and operate their 2.5 TPD thermochemical processing demonstration plant. They have also been awarded $2.5 million by the U.S. Department of Energy to further support their current project. Additionally, they were granted another $2.8 million from Partner In-Kind Contributions to obtain engineering support, equipment and facilities usage, and market testing of their products. Another company, Honeywell UOP, a joint venture of Envergent Technologies LLC and Ensys Corp, received $25 million from the U.S. Department of Energy to build an integrated biorefinery in Hawaii that turns biomass (forest residuals and other cellulosic biomass) into bio-oil (Gross 2010). Additional funding grants can be read about in the 2012 Advanced Biofuel Market Report (Soleoki 2012). Thus, we have determined that the types of funding mainly available for this biofuel technology are federal and state public funds (from the U.S. Department of Energy and U.S. Department of Agriculture on the federal level, and from the California Energy Commission, Iowa Power Fund, etc. on the state level). Right now, this first round of pilot and demonstration plants must prove themselves to be viable. Once this happens, new additional funding sources may become available in the near future.

Economic Obstacles

There are several economic obstacles that are preventing the widespread implementation of thermochemical processing of sewage sludge. First, the overall economic feasibility of the process is not yet clear. According to Alicia Chakrabarti at East Bay Municipal Utility District (EBMUD), the utility considered thermochemical processing about ten years ago, but deemed it technically unfeasible due to the large amounts of energy required to dry the digested sludge. The literature is still in disagreement to this point; some argue that the process is indeed energy positive, while others agree with EBMUD in that the drying process it too energy intensive to make a profit from the resulting bio-oil. Solar drying has been suggested as an alternative drying mechanism to reduce energy requirements, but research is still needed for this process.

This brings us to our second hurdle. Because there is such a great deal of uncertainty regarding the process's energetic feasibility, companies are having a hard time coming up with funding for wastewater sludge-specific pilot-scale thermochemical processing projects. Intellergy, discussed earlier, is the perfect example of this. They were offered $1 million in grants, if they could raise $4 million of their own funds (Bay Area Biosolids). Unfortunately, they were not able to come up with their own funding, and Intellergy was passed over as a grant recipient.

Another economic disincentive is the diminishing worth of thermochemical processing's end products. Large volumes of undigested sewage sludge can easily be sent to landfills to be used as a daily cover, and there is little cost associated with its dumping. Thus, there is little demand to decrease the volumes produced at WWTPs. Similarly, bio-oil and bio-methane are not in high demand, as it is difficult to compete with the price of fossil fuels. Additionally, bio-oil and biomethane have not yet established themselves in the market, and many potential buyers are weary of its sub-par quality (Chakrabarti

2013).

The Role of NGOs

Many NGOs, as well as other organizations, might be in a position to help businesses in the sludge-to-energy sector move forward with their pilot scale projects. In the next few paragraphs, we will recount some of the steps that these organizations have taken to promote thermochemical processing technologies. First, we will discuss the Biomass to Power Organization. This organization is interested in increasing the amount of power from biomass, thereby decreasing the dependence on foreign sources for oil, decreasing the emission of greenhouse gases, and increasing the number of new jobs in the biomass industry. This organization has taken several steps to educate the public (including state and federal level employees) about policies and regulations surrounding TCP, in hopes to increase public support surrounding the technology.

Another NGO, the Biofuels Center of North Carolina, has set certain goals within their state regarding the adoption of biofuel technologies. They want to replace 10% of the petroleum imported into North Carolina with biofuels that can be locally grown and produced. In addition, they would like to produce 560-600 million gallons of biofuel per year from renewable resources. Currently, the organization only works with cellulosic sources of biomass, but announced on February 4, 2013 that it will award up to $1.1 million for projects that address critical need for acceleration of the renewable fuels industry in North Carolina. This could provide our technology with a unique opportunity to set up a pilot plant if initial experimental trials are a success (Peña 2013).

Perhaps the most pertinent is the Bay Area Biosolids to Energy Coalition, a partnership of 19 water districts and municipalities in the greater San Francisco Bay Area (Quinn 2013). This group focuses on obtaining and distributing funding for pilot and commercial scale projects that can benefit the Bay Area. It was this group that received the match funding grant from the California Energy Commission and offered it to Intellergy, as mentioned previously. Currently, they are working towards developing a centralized Sludge processing facility that can be used by partners throughout the area. In the past year, they have issued two requests for qualifications (RFQs) and they have now released a request for proposals (RFP) from three companies that they have chosen. Coalitions like this one allow utilities and municipalities to pool resources, thereby creating powerful groups that can lobby for helpful legislation, obtain funding, and educate the public. An additional benefit is that coalition projects require less capital investment from each participating member, helping to mitigate the risk associated with pilot-scale plants.

This group as well as the others mentioned here, can help support the development of sludge-to-energy technologies, specifically combined anaerobic digestion and pyrolysis processes. More specifically, they provide key funding to allow the technology to advance. In addition, firms and NGOs can work together with citizens to educate the general public about the process of sewage sludge to energy, and hopefully impart a more accurate and positive outlook for the technology.

CONCLUSION

In summary, thermochemical processing (when combined with anaerobic digestion and CHP) has potential as a sustainable solution to sludge disposal, but it is not without faults. Environmentally, it can reduce greenhouse gas emissions, immobilize harmful chemicals and slow the flow of materials into landfills. Even so, the emissions of the thermochemical processes themselves and the combustion of their products raise concerns about NOx and furan compounds. The current political climate is amenable, but not necessarily supportive of TCP. The additional permitting required for facilities expansions may represent a real challenge for some WWTPs. The requirements to comply with emissions regulations may put a burden on utilities, and make a difficult market for bio-oil which has at least the same amount of fuel-bound nitrogen as coal. Also, public sentiment and the tendency to associate pyrolysis and gasification with incineration has lead to project cancellations. Public education and a shift away from this sentiment is necessary, especially in areas where public environmental concern could pave the way for early adoption. This will be difficult given the technical nature of the differences, but the relative like of toxic emissions and the other benefits discussed here should be highlighted. All of these barriers aside, current and potential environmental policy associated with climate change mitigation favors technologies like TCP and anaerobic digestion. Mandatory compliance may force utilities to expand plants and find previous unseen technological innovations. Similarly, making carbon into a commodity or taxing its emissions will encourage investment into technologies that can reduce emissions and energy use.

Businesses focused on thermochemical processing are finding moderate success, but not with sludge as a feedstock. One barrier is the lack of a market for bio-crudes like bio-oil because of the relatively cheap cost of petroleum. Because of the risk-adverse nature of the wastewater treatment industry, NGOs and utility coalitions have the potential to be powerful actors. Additional funding is needed to build a pilot scale plant and conclusively show that these processes either are or are not net-energy positive. A worst-case scenario analysis should also be performed to determine if there is a reduction in cost, energy use, and emissions (both criteria pollutant and GHG) even if the process is net-negative. Along similar lines, an analysis of combustion of bio-oil should be undertaken to determine if concerns about NOx and other pollutant are really a concern. Addressing these concerns will go a long way towards showing pyrolysis and gasification in a more favorable light. In short, it seems that thermochemical processing has broad application potential, as long as funding and data gaps can be overcome by a joint effort between industry groups, policy makers and an educated public.

REFERENCES

Agricultural Research Service, "Biomass Pyrolysis Research." (2010)
http://www.ars.usda.gov/Main/docs.htm?docid=19898

B. Alloway, A. Jackson, H. Morgan, "The Accumulation of Cadmium by Vegetables Grown on Soils Contaminated from a Variety of Sources." The Science of the Total Environment, 91 (1990) 223-236.

Assembly Committee on Transportation, "Assembly Bill 768 Bill Analysis." (2011)
ftp://leginfo.public.ca.gov/pub/05-06/bill/asm/ab_0751-0800/ab_768_cfa_20050428_183543_asm_comm.html

Avello Technology (2013)
http://www.avellobioenergy.com

Bay Area BioSolids, "Pre-Submital Conference Minutes: Bay Area BioSolids to Energy." (2012)
http://bayareabiosolids.com/yahoo_site_admin/assets/docs/PreSubmitalConferenceMinutesMay2012.136151156.pdf

Biofuels Center of North Carolina. (2013)
http://www.biofuelscenter.org/

Camp Dresser & McKee Inc., "Charting the future of Biosolids Management: The Final Report." (2011)
http://www.wef.org/biosolidsmanagement/

J. P. Cao, L. Li, K. Morishita, X. Xiao, X. Zhao, X. Wei, T. Takarada, "Nitrogen transformations during fast pyrolysis of sewage sludge." Fuel 104 (2010) 1-6.

J. P. Cao, X. Y. Zhao, K. Morishita, X. Y. Wei, T. Takarada, "Fractionation and identification of organic nitrogen species from bio-oil produced by fast pyrolysis of sewage sludge." Bioresource Technology, 101 (2010) 19: 7648-7652.

Y. Cao, Pawlowski, "A Life Cycle Assessment of two emerging sewage sludge-to-energy systems." Biosource Technology 127 (2013) 81-91.

Y. Cao, A. Pawlowski. "Sewage sludge-to-energy approaches based on anaerobic digestion and pyrolysis: Brief overview and energy efficiency assessment." Renewable and Sustainable Energy Reviews (2012) 16:1657-1665.

F. R. Caponi, E. Wheless, D. Frediani, "Dioxin and furan emissions from landfill gas-fired combustion units." Proc Air Waste Management Association Annual Meeting Exhibit (1998) 17.

Center for Climate and Energy Solutions, "Clean Air Act Cases." (2013)
http://www.c2es.org/federal/courts/clean-air-act-cases

A. Chakrabarti, Personal Interview. 12 April 2013.

C. Chiemchaisri, W. Chiemchaisri, S. Kumar, P.N. Wicramarachichi, "Reduction of Methane Emission From Landfill Through Microbial Activities in Cover Soil: A Brief Review." Critical Reviews in Environmental Science and Technology, 42 (2011) 4: 412-434.

Columbus Water Works, "Evaluation of Combined Heat and Power Technologies for Wastewater Facilities." (2012)
http://www.cwwga.org/documentlibrary/300_CHP%20-%20EPA%20(final)%20w-Apps.pdf.

J. Conesa, R. Font, A. Fullana, I. Martin-Gullon, I. Aracil, A. Galvez, J. Molto, M. Gomez-Rico, "Comparison between emissions from the pyrolysis and combustion of different wastes." Journal of analytical and Applied Pyrolysis (2008) 84: 95-102.

S. Czernik, A. V. Bridgewater, "Overview of Applications of Biomass Fast Pyrolysis Oil." Energy Fuels, 18 (2004) 2: 590-598.

Dow Chemical, "US EPA Regulations." (2013)
http://www.dow.com/sustainability/debates/dioxin/regulations/us_epa

L. Du, W. Liu, "Occurrence, fate, and ecotoxicity of antibiotics in agro-ecosystems, a Review. Agron. Sustain. Dev., (2012) 32:309–327.

East Bay Municipal Utility District, "Wastewater and Energy." (2012)
http://www.ebmud.com/water-and-wastewater/wastewater-treatment/wastewater-and-energy

Envergentech Technologies (2011)

http://www.envergenttech.com/

Environmental Protection Agency, "Clean Watersheds Needs Survey Report to Congress." (2008) http://water.epa.gov/scitech/datait/databases/cwns/upload/cwns2008rtc.pdf.

Environmental Protection Agency, "Emerging Technologies for Biosolids Management." (2006) http://water.epa.gov/scitech/wastetech/upload/2007_04_24_mtb_epa-biosolids.pdf.

Environmental Protection Agency, "Opportunities for Combined Heat and Power at Wastewater Treatment Facilities: Market Analysis and Lessons from the Field." (2011) http://www.epa.gov/chp/documents/wwtf_opportunities.pdf.

Environmental Protection Agency, "What is the EPA doing About Climate Change?" (2012) http://www.epa.gov/climatechange/EPAactivities.html

Genifuel Corporation. (2013) http://www.genifuel.com

S. Gross, "Honeywell's UOP Awarded U.S. Department of Energy Grant for Conversion of Waste Biomass to Green Transportation Biofuels." (2010) http://www.uop.com/honeywells-uop-awarded-department-energy-grant-conversion-waste-biomass-green-transportation-fuels/

S. Kambara, T. Takarada, M. Toyoshima, K. Kato. "Relation between functional forms of coal nitrogen and NOx emissions from pulverized coal combustion." Fuel 74 (1995) 1247-1253.

L. Kaufman, "The Scoop on Poop: Turning Sewage into Energy and Dollars." (2011) http://thinkprogress.org/climate/2011/07/11/264897/sewage-sludge-energy/?mobile=nc

R.F. Keefer, R.N. Singh, "Correlation of Metal-Organic Fractions with Soil Properties in Sewage-Sludge-Amended Soils." Soil Science 142 (1986) 1: 20-26.

P. Kharecha, C. Kutscher, J. Hansen, E. Mazria. "Options for Near-Term Phaseout of CO2 Emissions from Coal Use in the United States." Environ. Sci. Technol. 44 (2010) 4050-4062.

Y. Kim, W. Parker. "A technical and economic evaluation of the pyrolysis of sewage sludge for the production of bio-oil." Bioresource Technology 99 (2008) 1409-1416.

R. Kind, “HR 860-Biogas Investment Tax Credit Act of 2013.” (2013) http://www.govtrack.us/congress/bills/113/hr860

Y. Macklin, A. Kibble, F. Pollitt, “Impact on Health of Emissions from Landfill Sites: Advice from the Health Protection Agency” Documents of the Health Protection Agency (2011).

P. Manara, A. Zabaniotou, “Towards sewage sludge based biofuels via thermochemical conversion – A review.” Renewable and Sustainable Energy Reviews, 16 (2012) 2566–2582.

P. McCarty, J. Bae, J. Kim, “Domestic Wastewater Treatment as a Net Energy Producer-Can This be Achieved?” Environmental Science and Technology, 45 (2011) 17: 7100-7106.

M. Menendez, “How We Use Energy at Wastewater Plants…and How We Can Use Less.” (2009) http://www.ncsafewater.org/Pics/Training/AnnualConference/AC10TechnicalPapers/AC10_Wastewater/WW_T.AM_10.30_Menendez.pdf

A. Molino, M. Migliori, Y. Ding, B. Bikson, G. Giordano, G. Braccio, “Biogas upgrading via membrane process: Modelling of pilot plant scale and the end uses for the grid injection.” Fuel (2013) 107: 585-592.

National Research Council: Committee on the Use of Treated Municipal Wastewater Effluents and Sludge in the Production of Crops for Human Consumption, “Use of Reclaimed Water and Sludge in Food Crop Production.” The National Academies Press (1996).

National Research Council: Committee on Toxicants and Pathogens in Biosolids Applied to Land, “Biosolids Applied to Land: Advancing Stadards and Practices.” National Academies Press (2002).

B. Palmer, “Go West, Garbage Can!” (2011) http://www.slate.com/articles/health_and_science/the_green_lantern/2011/02/go_west_garbage_can.single.html#pagebreak_anchor_2

H. J. Park, H. S. Heo, Y. K. Park, J. H. Yim, J. K. Jeon, J. Park, C. Ryu, S. S. Kim, “Clean bio-oil production from fast pyrolysis of sewage sludge: Effects of reaction conditions and metal oxide catalysts.” Bioresource Technology, 101 (2010) 1: S83-S85.

K. Peña, Biomass Power Association. (2013)

http://www.usabiomass.org/pages/about.php

M. Peterson, "Reactive Metabolites in the Biotransformation of Molecules Containing a Furan Ring." Chem. Res. Toxicol. (2013) 26: 6−25.

E. Pokorna, N. Postelmans, P. Jeniceka, S. Schreurs, R. Carleer, J. Yperman. "Study of bio-oils and solids from flash pyrolysis of sewage sludges." Fuel 88 (2009) 1344–1350.

C. Quinn, Personal Interview. 1 May 2013.

Renewable Waste Intelligence, "Business Analysis of Anaerobic Digestion in the USA." (2013) http://www.renewable-waste.com/anaerobic-digestion-conference/pdf/e-brief.pdf

J. Richardson, "Sewage Sludge as Fertilizer, Safe?" (2010) http://www.foodsafetynews.com/2010/10/sewage-sludge-as-fertilizer-safe/#.UYALerWPN-0

W. Rulkens, "Sewage sludge as a biomass resource for the production of energy: an overview and assessment of the various options." Energy and Fuels, 22 (2008) 9–15.

L. Sabourin, P. Duenk, S. Bonte-Gelok, M. Payne, D. Lapen, E. Topp, "Uptake of pharmaceuticals, hormones and parabens into vegetables grown in soil fertilized with municipal biosolids." Science of the Total Environment 431 (2012) 233–236.

X. Shinbrot, "Biosolids or Biohazards?" Pesticides and You, A quarterly publication of Beyond Pesticides, 32 (2012) 3: 9-15.

M. Soleoki, A. Dougherty, B. Epstein. "Advanced Biofuels Market Report 2012." Environmental Entrepeneurs E2 (2012).

SNF Floerger, "Sludge Dewatering." (2012) http://www.snf-group.com/IMG/pdf/Water_Treatment_3_E.pdf.

The California Energy Commission (2013) http://www.energy.ca.gov/low_carbon_fuel_standard/

R.D. Tyagi, J.F. Blais, J.C. Auclair, N. Meunier, "Bacterial leaching of toxic metals from municipal sludge: influence of sludge characteristics." Water Environment Research, 65 (1993) 96–204.

Van Buren Township, “What is Recycling” (2003)
http://www.vanburen-mi.org/environmental/Recycling_home.html.

J. Walsdi, “Intellergy: The combustion free renewable energy solution.” (2011)
http://www.intellergy.com/

Wastewater Management Fact Sheet (2006).
http://water.epa.gov/scitech/wastetech/upload/2008_01_16_mtb_energycon_fasht_final.pdf

A. Williams, J.M. Jones, L. Ma, M. Pourkashanian, “Pollutants from the combustion of solid biomass fuels.” Progress in Energy and Combustion Science 38 (2012) 113 - 137.

X.Q. Wu, J.L. Conkle, J. Gan, “Multi-residue determination of pharmaceutical and personal care products in vegetables.” Journal of Chromatography, 1254 (2012) 78-86.

C. Xu, J. Lancaster, “Treatment of Secondary Pulp and Paper Sludge for Energy Recovery.” Energy Recovery (2009) 187-212.

L. Yong-Qiang, T Joo-Hwa and Y. Liu, “Combustion, Pyrolysis, and Gasification of Sewage Sludge for Energy Recovery.” Biological Sludge Minimization and Biomaterials/Bioenergy Recovery Technologies (2012) 405-427.

L. Zhao, Y.H. Dong, H. Wang, “Residues of veterinary antibiotics in manures from feedlot livestock in eight provinces of China.” Sci Total Environ 408 (2010): 1069–1075.