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Technology Assessment Report

Aqueous Sludge Gasification Technologies

Prepared by:

Greenhouse Gas Technology Center

Operated by
Southern Research Institute

Under a Cooperative Agreement With
U.S. Environmental Protection Agency

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The data used in development of this report was derived from secondary sources. No attempt has been made by the U.S. EPA or Southern Research Institute to confirm source data quality.

ACKNOWLEDGMENTS

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ACRONYMS AND ABBREVIATIONS

APTB	Air Pollution Technology Branch
BEAM	Biosolids Emissions Assessment Model
Bbl	Barrel
Btu	British thermal unit
C	Elemental Carbon
CAP	Criteria Air Pollutant
CCCSD	Central Contra Costa Sanitary District
cfm	cubic foot per minute
CH_4	Methane
CO_2	Carbon dioxide
CO	Carbon monoxide
COS	Carbonyl sulfide
CS	Carbon monosulfide
°C	Degree Celsius
dscfm	Dry standard cubic foot per minute
EPA	Environmental Protection Agency
ETV	Environmental Technology Verification
Fe	Iron
FeO	Iron oxide
FT	Fischer-Tropsch
GHG	Greenhouse gas
GWP	Global warming potential
H	Elemental hydrogen
H_2	Hydrogen
H_2O	Water
H_2S	Hydrogen sulfide
HAP	Hazardous air pollutant
HCl	Hydrogen chloride
HCN	Hydrogen cyanide
HF	Hydrogen fluoride
Hg	Mercury
HHV	Higher heating value
ICE	Internal combustion engine
ICL	Imperial college of London
kg	Kilogram
kW	kilowatt
kWth	Kilowatt thermal
lb	pound
LHV	Lower heating value
ME DEP	Maine Department of Environmental Protection
MMBtu	Million British thermal units
MMm^3	Million cubic meters
MW_{th}	Megawatt thermal
N	Elemental nitrogen

N_2	Nitrogen
N_2O	Nitrous oxide
NH_3	Ammonia
NO_x	Oxides of nitrogen
NRC	National Research Council
NRMRL	National Risk Management Research Laboratory
NYSERDA	New York State Energy Research and Development Authority
O	Elemental oxygen
O_2	Oxygen
PAH	Polyaromatic hydrocarbon
PCB	Polychlorinated biphenyl
PCDD/F	Polychlorinated dibenzo-p-dioxins and polychlorinated dibenzofurans
PM	Particulate matter
POTW	Publicly owned treatment works
ppm	Parts per million
PV	Photovoltaic
QA	Quality assurance
R&D	Research and Development
RAG	Rheinbraun AG
S	Elemental Sulfur
SO	Sulfur monoxide
Southern	Southern Research Institute
SO_x	Oxides of sulfur
SWG	Supercritical water gasification
SWPCA	Stamford water pollution control agency
Syngas	Synthesis gas
TNSSS	Targeted national sewage sludge survey
TPD	Tons per day
TPY	Tons per year
TRL	Technology readiness level
UoS	University of Seoul
US$	U.S. dollars
VOC	Volatile organic compound
WWT	Wastewater treatment
ZnO	Zinc oxide

TECHNOLOGY ASSESSMENT REPORT:
AQUEOUS SLUDGE GASIFICATION

Summary

Southern Research Institute (Southern), under a cooperative agreement with the U.S. Environmental Protection Agency's Environmental Technology Verification (ETV) Program, has conducted a study to evaluate existing sludge gasification technologies, their impacts, and stages of development. Critical components and impacts of these technologies were identified and quantified to assess their development status, potential benefits and drawbacks, and environmental and economic impacts.

The study reveals that sludge gasification is a potentially suitable alternative to conventional sludge handling and disposal methods. However, very few commercial operations are in existence. The limited pilot, demonstration or commercial application of gasification technology to sludges, and the unique characteristics of each different technology and site make it difficult to provide an overall assessment of the impacts and economics of the entire technology category at this time. Gasification of sludges and biosolids should be considered an early commercial technology with limited data, and should be evaluated on a site and technology specific basis for potential commercial applications. However, the scarcity of commercial plants should not discourage the consideration of sludge gasification as a beneficial alternative. Given the potential benefits, continued research, development, and deployment of sludge gasification technologies should be followed as the technology progresses into full commercial availability.

1. Project Description and Objectives

Sludge production in the United States is increasing with an increase in population. It is estimated that 7.2 million dry tons of treated and tested sewage sludge and 5.5 million tons of paper mill sludge are generated in the U.S. annualy.[58,74] Consequently, there is an increased need for efficient and environmentally sound management practices for sewage sludge from publicly owned treatment works (POTWs) and sludge from pulp and paper mills. Traditional methods to dispose of the sludge can require significant energy inputs, utilize otherwise useful real estate, and sometimes result in negative environmental aspects, including impacts on air, land, water, and greenhouse gas (GHG) emissions. Municipalities and companies are under increasing pressure to become more energy and cost efficient in their sludge disposal methods, and to reduce their GHG emissions and carbon footprints. In addition, as land use, water quality, air emissions, public health and social pressures increase, the public and regulatory acceptance of traditional sludge disposal methods is rapidly diminishing. In response to these various pressures, other options for disposal or utilization of wastewater treatment and paper industry sludges need to be investigated.

Sludge gasification is a potentially viable solution to these issues. There is a general consensus among gasification experts that this technology, when properly configured, is capable of delivering net energy gains while reducing environmental impacts when compared to conventional management practices. Through independent, academic and government funded demonstrations and studies, the process of gasification has been successfully shown to convert numerous types of carbon based feedstocks into a synthesis gas (syngas) which can be directly combusted for heat and energy production, or further processed into a variety of liquid fuels and other chemicals. By significantly reducing the volume of the residual biosolids, gasification also reduces the costs associated with transportation and disposal in a landfill.

The growth and implementation of sludge gasification systems has been very limited, in part as a result of the lack of independent data, demonstration, and evaluation of technology impacts, economics, and capabilities. This lack of information results in contradicting claims from those who favor and those who oppose the technology, in terms of the environmental benefits, costs, and effectiveness. Vendors and technology developers claim that gasification is the optimal solution to sludge disposal, while some environmental organizations argue that gasification is no better than incineration.

This project sought to independently evaluate sludge gasification technologies based on a review of currently available data. The pros and cons of sludge gasification and its environmental impacts, sustainability, costs, and efficiency in converting sludge into usable fuels were studied. This independent assessment of gasification technologies provides unbiased information from a variety of sources to aid in decision-making and evaluation for purchase, implementation, regulation, and public acceptance of these systems.

1.1 Roles and Responsibilities

A primary objective of this project was to address some of the technical issues regarding the use of gasification technology to process water-laden wastes such as are found in paper manufacturing and sewage treatment processes. Gasification could recover some energy from the organic material in these sludges and reduce the burden of landfill waste, which would support EPA objectives of reducing solid waste and energy consumption. Even though the information in this report could be used by policymakers in EPA and other regulatory agencies, it should be used for technical guidance only and does not reflect EPA policy.

This project was funded by the EPA Office of Solid Waste and Emergency Response (OSWER), based on a proposal by EPA Region 1, as supported by the State of Maine, and the EPA National Risk Management Research Laboratory (NRMRL). The State of Maine Department of Environmental Protection (ME DEP) also provided funding to support the completion of the project. The project was completed by Southern and the Greenhouse Gas Technology Verification Center, which it operates under a cooperative agreement with NRMRL. Southern is an expert in gasification and is currently conducting research at bench and pilot scale for various clients at their facility in Durham, NC. However, Southern does not manufacture, sell or license internally developed gasification systems. In addition to funding support, the following participants provided input and support of the program as described below.

The ME DEP served in an advisory capacity, provided technical support, and served as a liaison with the Maine paper industry. Ultimately, the ME DEP will consider the results as the State re-evaluates regulations regarding the use of non-incinerator technologies in waste to energy applications, including those utilizing aqueous sludges. Specifically, the current Maine legislature passed a resolve requiring ME DEP to review whether facilities using emerging waste-to-energy technologies that provide environmental and energy benefits (e.g., gasification) should be excluded from Maine's statutory ban on the establishment of new commercial solid waste disposal facilities. It has been determined that, presently, the ban does apply, and that the overall regulatory structure under which a new incinerator proposal would be evaluated would apply to a new gasification proposal.

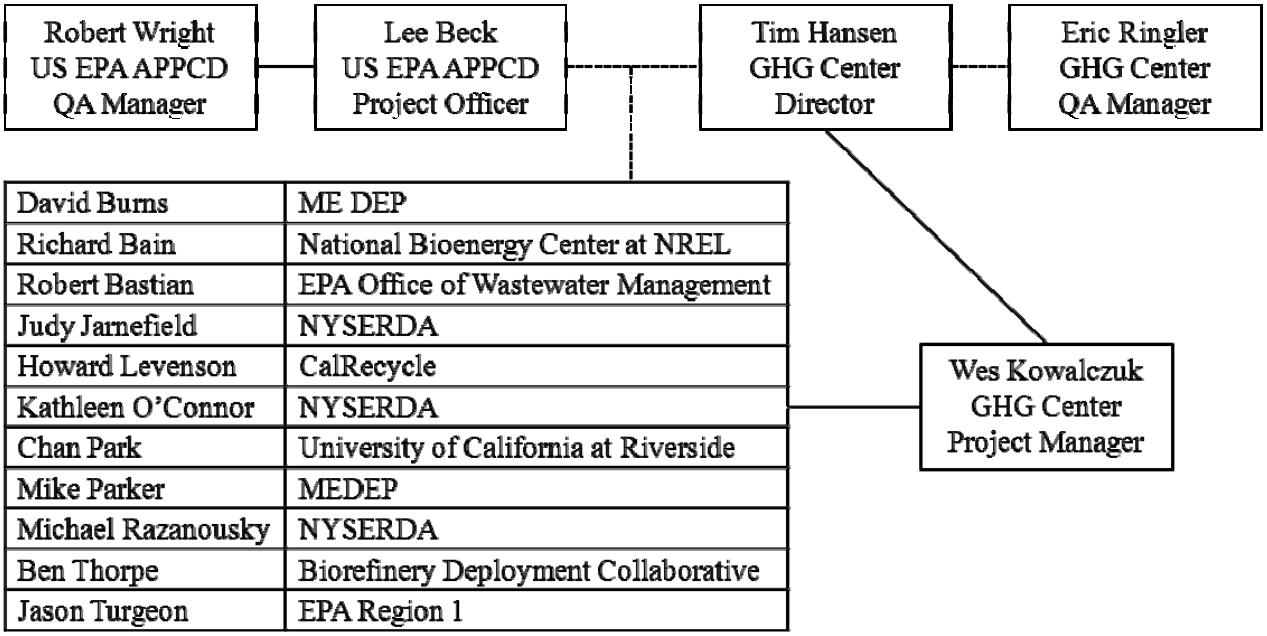
The EPA NRMRL ETV GHG Center is a public/private partnership between NRMRL and Southern. The GHG Center verifies the performance of technologies that produce, mitigate, monitor, or sequester greenhouse gas emissions, including technologies for advanced energy production, waste-to-energy conversion, oil and gas production and transmission, and other energy efficiency technologies. The ETV Program has a cooperative agreement with Southern. As a result, NRMRL contributed staff support for communications, reviews, and management. This support included the participation of the current ETV Project Officer and ETV Quality Assurance (QA) Manager, who provided reviews and approval of this final report.

As the operating partner in the GHG Technology Center, Southern Research managed the technology assessment project. In addition to synthesizing information available through literature review and interviews with developers, vendors and other stakeholders, the assessment aimed to determine whether verification testing under the ETV Program is needed to better characterize performance capabilities of gasification technologies.

As is typical with the ETV program, a multi-interest and balanced stakeholder group was established to help guide the assessment and verification efforts. Stakeholders were selected to represent a broad community of those with interests in sludge gasification technologies, and included regulators, researchers, and industry associations. Stakeholders reviewed and provided input on project plans and this final report. In addition, stakeholders provided technical input, contacts with technology vendors, supporting technical and regulatory data, and other information important to the assessment. The project hierarchy is listed in Figure 1, including stakeholder identification.

NRMRL's Air Pollution Technology Branch (APTB), with expertise and experience in conducting assessments of combustion-based processes, created a parallel report about the use of incineration technology in sewage and pulp and paper mill sludges.[52] The report focused on an evaluation of performance, emissions and cost for multiple-hearth and fluidized bed incinerators.

EPA Region 1 prepared the initial proposal for funding of the technology assessment project based on their needs to better understand the potential impacts of the emerging sludge gasification technologies, as more end users began looking at options for sludge disposal beyond traditional practices. The Region 1 staff participated in the development of the planned scope of work for the project, provided input regarding technology vendors and end users within Region 1 that had expressed interest in potential projects in the Region, reviewed project plans, and reviewed this final report.



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Kathleen O'Connor	NYSERDA
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Mike Parker	MEDEP
Michael Razanousky	NYSERDA
Ben Thorpe	Biorefinery Deployment Collaborative
Jason Turgeon	EPA Region 1

Figure 1 - Project Participants

1.2 Approach

The Gasification Technology Assessment Report aimed to summarize the anticipated benefits and limitations of commercial or near commercial sludge gasification systems, screen out systems with limited promise, and identify significant information gaps necessary to properly evaluate the gasification systems.

Data for the technology assessment was collected through literature searches; contacting knowledgeable industry stakeholders; and direct inquiries of manufacturers, project developers, and facility owner/operators. Literature search activities were facilitated through use of bibliographic databases and indices.

Data was obtained from the following source types, listed from highest quality to lowest:

1. peer reviewed journals or government reports – results based on independently measured validated data;
2. non peer reviewed government reports, conference presentations (non-marketing), peer-reviewed journal articles not based on independently obtained data;
3. direct contact with technology vendors or commercial project development team; and
4. non-reviewed articles, websites, marketing presentations, advertisements, press, etc.

An evaluation of each data source by type can be found in Table 19.

The list of candidate technologies that was developed includes gasifiers that claim or appear to be capable of handling the subject sludge streams. Those candidate technologies that appeared to be promising, in that they are demonstrated at a commercial or pilot scale, received a more detailed examination and analysis.

2. Conventional Sludge Disposal Practices

2.1 Overview

The most utilized methods of pulp and paper and sewage sludge management have been land disposal, land application and incineration. In 2006, the EPA released a report on biosolids management in the United States which details the current practices, quantities, and distribution of sludge disposal methods.[1] Figure 2 displays the breakdown of conventional municipal sewage sludge disposal practices.

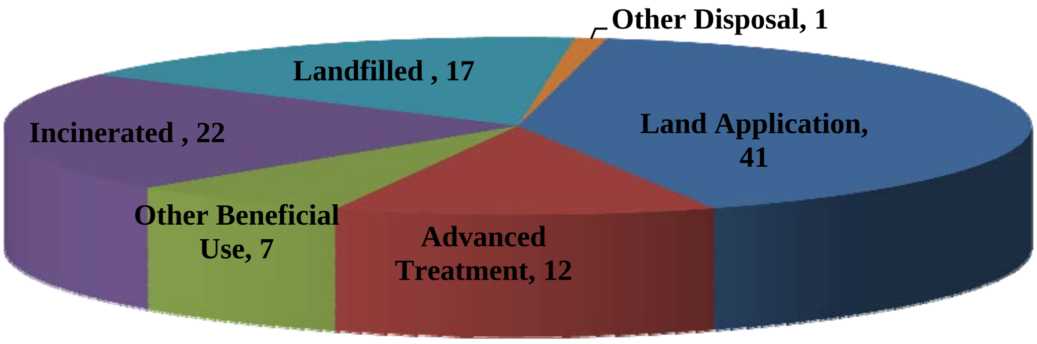

Figure 2 - Summary of Waste Water Solids Management in the U.S.[1]

In 2007, the Northeast Biosolids and Residuals Association (NEBRA) released a report that included data on sewage sludge management practices in the U.S. In short, the study found that 55% of the 7.2 million tons of biosolids were used in agronomic, silviculture, or land restoration of derelict land and/or stored for this use. The remaining 45% was disposed of in municipal solid waste (MSW) landfills, surface disposal units, and/or incineration facilities.[58]

Paper mill sludge disposal practices differ from sewage sludge, in that most (65%) is landfilled. Figure 3 gives a breakdown of the disposal methods as of 1995. The total is greater than 100% as some mills use multiple processes.

Landfills have been the primary approach for sludge disposal in the US. However, this option is becoming limited due to increasing disposal costs, diminishing landfill sites, and possible long term environmental impacts.[49] In a landfill operation, sludge, which has been mechanically dewatered to approximately 20% solids, is transported off-site to a landfill, where a tipping fee for disposal is paid. Some paper mills operate their own landfills, thereby negating the tipping fee, however there are costs associated with operation of a landfill. Due to the high moisture content of the sludge, a significant amount of resources are directed to the handling of water. Waste deposited in a landfill generally undergoes three steps. The first stage is degradation under aerobic conditions, where the aerobic micro-organisms consume the available oxygen in the waste. Once a majority of the oxygen is consumed, acetogenic and fermentative bacteria decompose the easily degradable portion of the waste, resulting in a lower pH , thereby increasing the solubility of inorganic substances such as heavy metals. In the last stage, methanogenic bacteria propagate rapidly to produce methane. The pH value increases, and the organic content of the leachate decreases.[47]

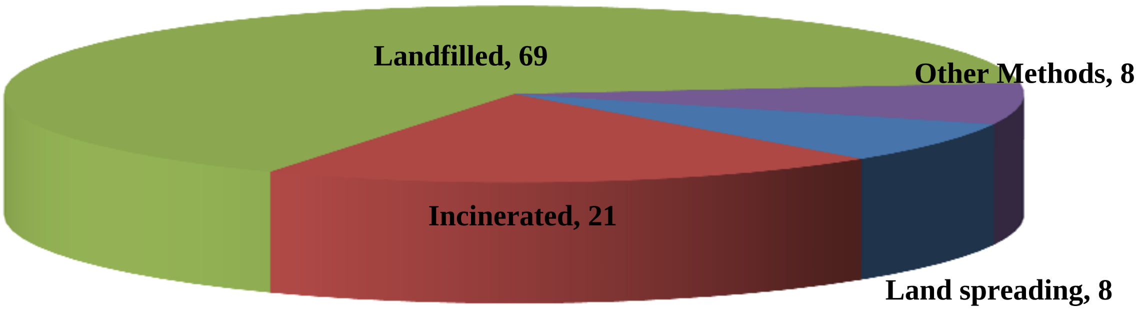

Figure 3 - Conventional paper mill sludge disposal practices in the U.S. [13]

The sludge incineration process involves heating, under excess oxygen, in order to completely oxidize the organic portion of a feedstock. Completely dewatering the sludge being fed is not necessary, but it will reduce the need for supplemental fuel.[52] The heat created during combustion is typically recovered and used to remove the moisture in the feedstock. In most cases, the heat recovery will be counterbalanced by the heat used for reducing the water content of sludge. The outputs of incineration are heat, ashes, flue gases and wastewater.[47] Most sludge combustion units fall into two types, multiple hearth (MH) incinerators and fluidized bed (FB) incinerators.[52] MH units are comprised of multiple zones for heating and burning sludge, whereas FB units have only one zone. In the U.S., 218 sewage sludge incineration units are owned by 97 entities. Of the 218 units, 55 are FB units and 163 are MH units. Additionally, there are 57 pulp and paper sludge combustion units.[3] Eastern Research Group, Inc (ERG) assessed the technological performance of the two types of incinerators, with the following conclusions.[52]

- The moisture content of sewage sludge for FB incinerators may be variable, however MH units are less amenable to variable sludge moisture levels due to MH units consisting of multiple zones. MH units generally require more supplemental fuel than FB incinerators for the same reason.

- Average capital costs and operating costs on a per-ton of dry sludge basis for the FB unit were found to be substantially less than MH units.
- The most common emission control devices used in sewage sludge incinerators are Venturi or impingement tray scrubbers.
- The most popular emission controls among pulp and paper sludge incineration units are cyclone separators, electrostatic precipitators, and Venturi scrubbers.

Incineration has particularly strong benefits for the treatment of certain waste types such as clinical wastes and certain hazardous wastes where pathogens and toxins can be destroyed by high temperatures. Examples include chemical multi-product plants with diverse toxic or very toxic wastewater streams, which cannot be routed to a conventional wastewater treatment plant.

Land application takes advantage of recycling the compounds of agricultural value present in sludge. The major benefit being the use of nitrogen, phosphorus, potassium, and calcium present in the sludge. Prior to recycling, the raw sewage sludge is aerobically or anaerobically digested, lime stabilized, heat dried/pelletized, or often composted with other organic materials.

2.2 Issues with Current Practices

Although many measures are instituted in order to properly seal landfills, there will potentially be leaks from breaches in the landfill liner system due to the high water content resulting from sludge disposal. Toxins contained in sludge that is disposed of in landfills may be collected in the leachate and enter ground water through the breaches in the liner system. If sewage sludge is placed in a landfill in which gas is vented to the atmosphere, a significant increase in GHG emission results, although in some cases this is avoided by recovery of the biogas and its use as a biofuel. In addition, landfill capacities are limited, and land use restrictions and social acceptance are limiting the development of new landfills, further decreasing the available options for landfilling of sludges.

Incineration is a combustion reaction. Outputs are flue gases, ashes, and wastewater, as well as the production of energy. During the incineration process polyaromatic hydrocarbons (PAH), heavy metals, polychlorinated biphenyls (PCB's), polychlorinated dibenzo-p-dioxins and polychlorinated dibenzofurans (PCDD/Fs), and acidic gases: SOx, HCl, HF, NOx, etc. are liberated or created and must be captured before sending the flue gas to the atmosphere. Incineration processes also produce fly ash and bottom ash, which must be treated and disposed of as a solid or hazardous waste, depending on the composition. Technological advances have been made regarding many of these issues; however, many of these advances have decreased overall system efficiency, thereby increasing investment and operating costs by nearly two thirds.[15, 16]

Wastewater sludge can be dewatered, dried or composted and then spread on agricultural and non-agricultural land to replace the use of conventional fertilizers. When land applying, POTWs are required to adhere to 40 CFR Part 503, which limits the amount of metals and organic pollutants contained in the sludge. The regulation is based on the cumulative loading of each pollutant, thereby eliminating a piece of land's availability for land application once the ceiling is reached. Individual states may also have regulations which are often more strict than federal regulations.[58, 59] In addition, social perspectives on sludge land application of sludges are becoming less favorable, with many environmental activists and communities increasing resistance to application as an acceptable disposal means. As suitable space for land application and disposal becomes less available, POTWs will be forced to seek alternate disposal methods.

3. Gasification Technology

3.1 Overview

The basic principle of gasification is to convert a carbon based material into H_2 and CO with the addition of heat and a combination of steam, oxygen and/or nitrogen in a reaction vessel. Other than H_2 and CO, the remainder of the syngas includes N_2, traces of CH_4 and other hydrocarbons, tar, particulates, and CO_2. Once produced, the syngas can be cleaned through the use of a variety of cleanup devices, including ash-capturing cyclones, solvent based tar scrubbers, and water, acid or caustic scrubbers for capturing nitrogen, chlorine, sulfur and various heavy metals. Once cleaned, the syngas can be converted to a liquid fuel using a catalytic Fischer-Tropsch (FT) process, fed into an internal combustion engine-generator for electricity production, combusted for heat recovery, used in fuel cell applications, or used for the production of a variety of chemicals. In theory, any form of biomass may undergo gasification. Limitations on the efficiency of the gasifier's operation include high moisture content of the feed, ash fusion temperatures, design of the feeding system, and the mixing and separation of the feedstock.[14]

The gasification process begins by preparing the feedstock by drying to the appropriate moisture content, typically between 10 – 20%. Once dried, the feedstock is then transferred to a feeding system, which can vary in design based upon the pressure in the gasifier and the physical properties of the feedstock. After entering the gasifier, the feedstock is then converted into syngas of varying compositions, depending on the gasifier type and feedstock composition. A cyclone installed downstream of the gasifier will capture additional ash/PM that is not captured in the gasifier. Heat can be recovered in the form of steam with the use of a heat recovery steam generator and fed into the dryer to supplement the drying system. The cool raw syngas is then treated through a liquid and/or dry cleaning system. Finally, the cleaned syngas is then fed into the conversion system to create electricity, heat, fuels, and/or chemicals. If using a combustion generator, additional thermal energy can be removed from the exhaust to further supplement the drying system. An example generic system is shown in Figure 4.

Generally speaking, in addition to the value of the end products, the availability of the feedstock, pretreatment requirements, gasification system efficiency, syngas conversion process and site specific energy costs all have a significant effect on whether or not a system will make it to commercial status.

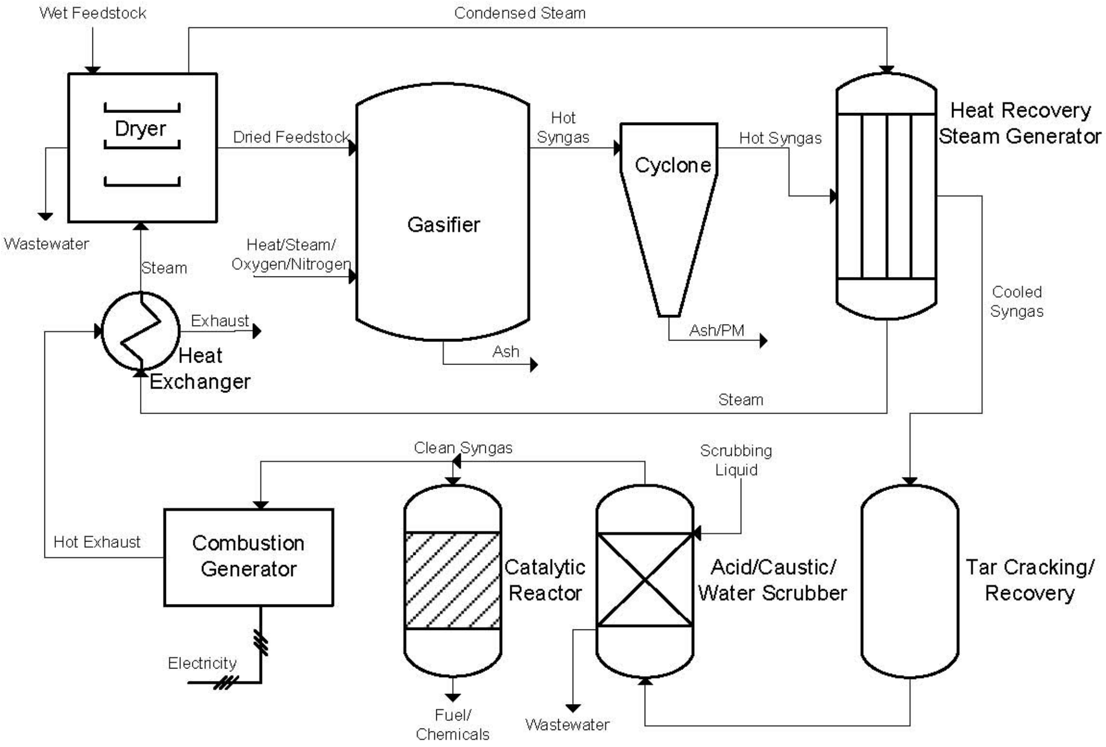

Figure 4 – Example Gasification System

3.2 Types of Gasifiers

There are a variety of gasifier designs currently being used for commercial applications in the production of fuels and chemicals. However, this report only covers the major types which could be applicable to sludges. These include fixed bed, fluidized bed and those grouped as plasma/other. A summary of some of the key aspects of the main gasifier types can be found in Table 1.

Historically, the fixed-bed process is the oldest form of gasification. Fixed-bed updraft gasifiers are characterized by a bed in which the feedstock moves slowly downward under gravity as it is gasified by a gasification medium that is in a counter-current flow to the feedstock. In such a counter-current arrangement, the hot syngas from the gasification zone is used to preheat and pyrolyze the downward flowing feedstock.[7] In a fixed-bed downdraft gasifier, the feedstock flows concurrently with the gasification medium. Figure 5 displays the updraft (left) and downdraft (right) process.

In a fluidized bed gasifier, the gasification medium and feedstock must pass through a bed of inert particles (e.g., alumina oxide). There are two types of fluidized bed gasifiers: bubbling and circulating. Bubbling fluidized bed gasifiers are typically appropriate for medium size projects of 25 MW_{th} or less, while circulating fluidized bed gasifiers can range from a few MW_{th} up to very large units.[11] Fluidized bed gasifiers offer extremely good mixing between feedstock and oxidant, which promotes both heat and mass transfer. This ensures an even distribution of material in the bed, but a certain amount of partially reacted fuel is inevitable and will be removed with the ash. This places a limitation on the carbon conversion of fluid-bed processes. The operation of fluidized bed gasifiers is generally restricted to temperatures below the softening point of the ash, since ash slagging/agglomeration will disturb the fluidization of the bed.[7] Figure 6 displays the bubbling and circulating bed processes.

Plasma gasification is a relatively new process with respect to traditional gasification. The primary heat source in a plasma gasifier is the plasma torch, where gas is passed through an electric arc and dissociated into ions and electrons creating extremely high temperatures (>5,000 °C). The high temperatures enable very large carbon conversion percentages and good control of the hazardous materials captured in the slag; however, plasma gasifiers are relatively costly and have relatively higher parasitic energy consumption when compared to traditional gasifiers.

Liquid metal gasification is a field which is being studied and even practiced at pilot scale by a handful of companies. Feedstock is introduced into a crucible filled with molten metal, usually iron, at around 1300 °C. Water in the feedstock is split into H_2 and O_2. In theory, the iron is then oxidized to FeO, then reduced back to iron after the O_2 reacts with carbon in the feedstock to make CO gas. The H_2 and CO gas are the main two components in the syngas. In order to favorably shift the equilibrium, oxygen gas can be introduced. The iron also helps to capture unwanted waste like chlorine and sulfur into a glass like material (slag).

Supercritical Water Gasification (SWG) is a process which utilizes super critical water (pressure > 320 psi, temperature > 600 °F) to convert organics into a hydrogen rich syngas. SWG requires feedstocks with moisture contents ranging from 70 to 95%. The reforming of biomass and biological residues in supercritical water is a rather novel process. Significant R&D work will be required prior to implementation and commercialization.[10]

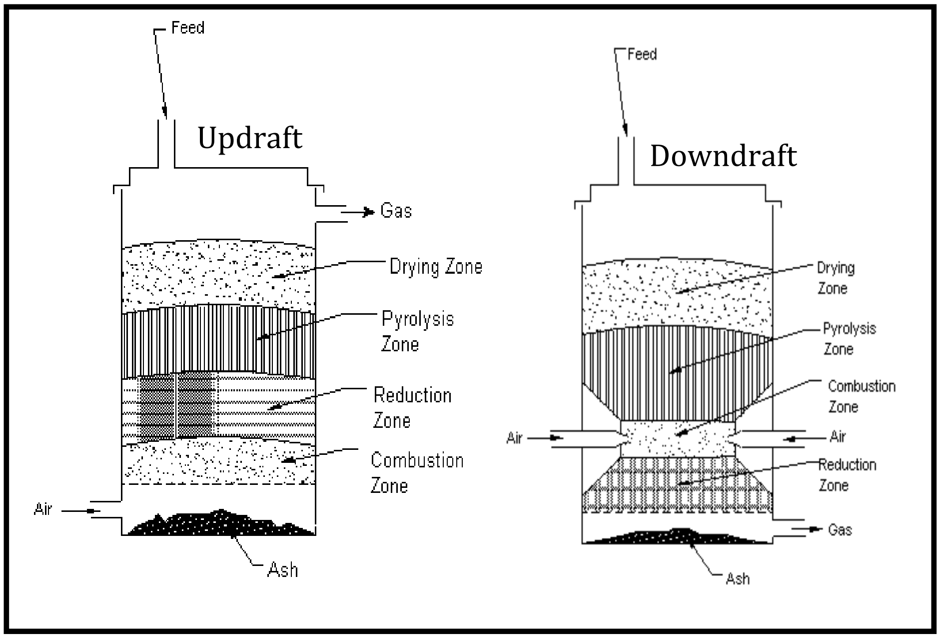

Figure 5 - Diagram of the zones in an updraft and downdraft gasifier

Table 1 - Summary of Gasifier Types[11]

Gasifier Type	Scale	Fuel Requirements		Efficiency	Gas Characteristics	Other Notes
		Moisture	Flexibility			
Downdraft Fixed Bed	5 kW$_{th}$ to 2 MW$_{th}$	<20%	· Less tolerant of fuel switching · Requires uniform particle size · large particles	Very Good	· Very low tar · Moderate Particulates	· Small scale · Easy to control · Produces biochar at low temperatures · Low throughput · Higher maintenance costs
Updraft Fixed Bed	<10 MW$_{th}$	up to 50% - 55%	· More tolerant of fuel switching than downdraft	Excellent	·Very high tar (10% to 20%) ·Low particulates ·High methane	· Small and medium scale · Easy to control · Can handle high moisture content · Low throughput
Bubbling Fluidized Bed	<25 MW$_{th}$	<15%	· Very fuel flexible · Can tolerate high ash feedstocks · Requires small particle size	Good	·Moderate tar ·Very high in particulates	· Medium scale · Higher throughput · Reduced char · Ash does not melt · Simpler than circulating bed
Circulating Fluidized Bed	A few MW$_{th}$ up to 100 MW$_{th}$	<15%	· Very fuel flexible · Can tolerate high ash feedstocks · Requires small particle size	Very Good	·Low tar ·Very high in particulates	· Medium to large scale · Higher throughput · Reduced char · Ash does not melt · Excellent fuel flexibility · Smaller size than bubbling fluidized bed
Plasma	<30MW	any	· Greater feed flexibility without the need for extensive pretreatment · solid waste capability	Very Good	· Lowest in trace contaminants; no tar, char, residual carbon, only producing a glassy slag	· Large scale · Easy to control · Process is costly · High temperature (5000°-7000°F)
Liquid Metal	<7MW	<5%	· Generally requires low moisture due to the possibility of steam explosion	Very Good	.Low trace contaminants; virtually no tar, char, residual carbon	· High syngas quality
Supercritical Water	UNK	70 - 95%	· Suitable for the conversion of wet organic materials	Good	· Suppressed formation of tar and char	· Short reaction time · High energy conversion efficiency by avoiding the process of drying step · Selectivity of syngas with temperature control and catalysts

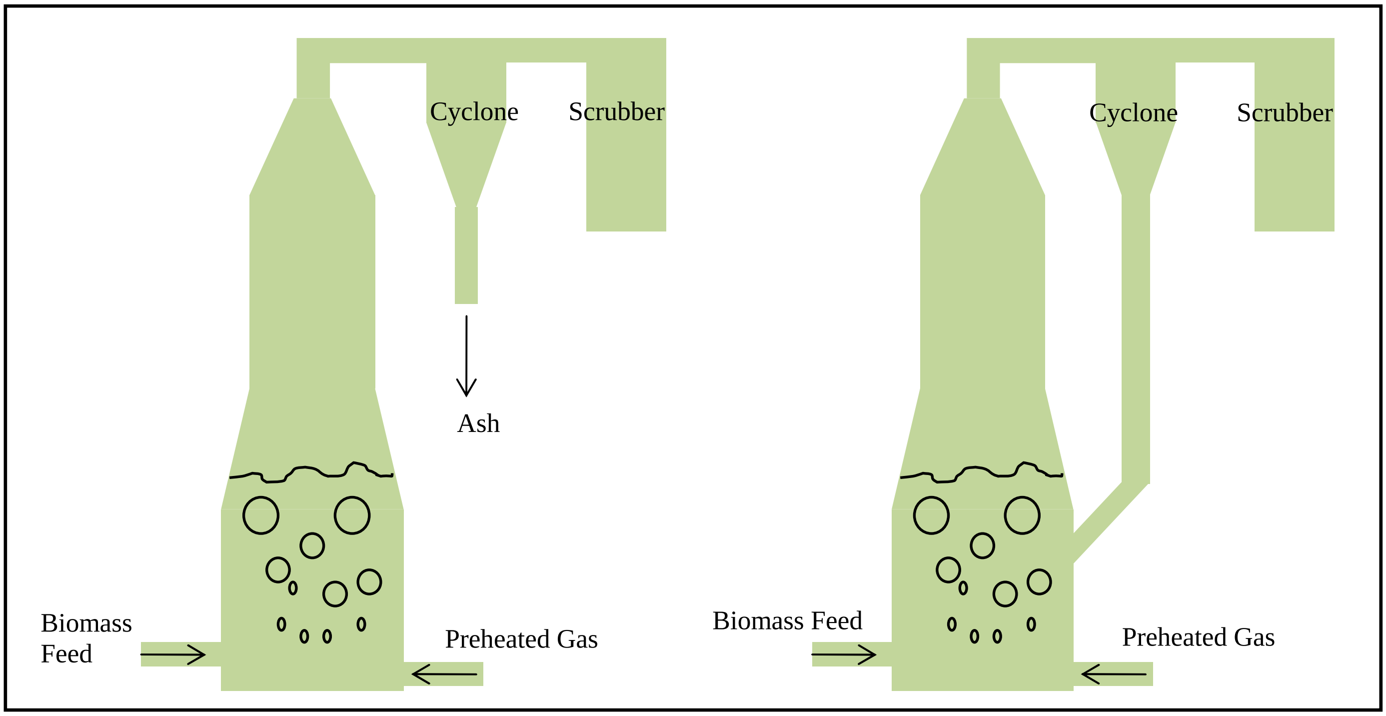

Figure 6 - Two types of fluidized-bed processes; Bubbling bed (left) and circulating bed (right) gasifiers

3.3 Historical and Current Applications

Towards the end of the 18th century, gas was produced from coal by gasification on a large scale. With the foundation in 1812 of the London Gas, Light and Coke Company, gasification finally became a commercial process. Ever since, gasification has played a major role in industrial development. The most important gaseous fuel used in the first century of industrial development was town gas, which was produced via coal gasification and used for lighting and heat.[7]

By far, the most abundantly applied form of gasification today is the gasification of coal. The last 10 to15 years have seen the start of a renaissance of gasification technology, as is clear from Figure 7. There are several reasons for this, but first and foremost is the dramatic increase in energy costs. For the 20 years prior to 2003, oil prices were between $20 and $30 per barrel. Prices since 2005 have mostly been in the $55 to $120 per barrel range. Similarly, with natural gas, the U.S. commercial price from 1983 to 2003 was mostly between $5 and $6 per MMBtu, rising slightly toward the end of the period; between 2005 and 2009 it remained consistently over $10 per MMBtu, peaking at $15 at the end of 2005.[7]

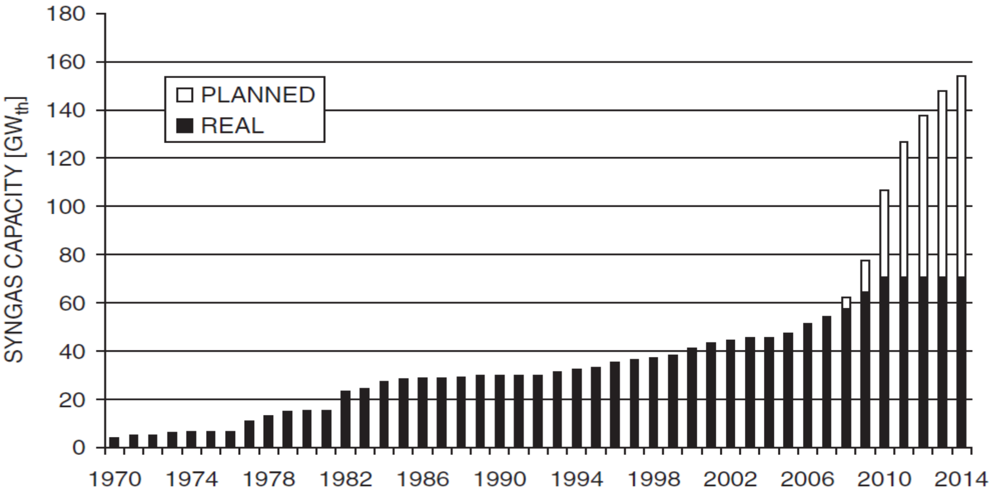

Figure 7 - Cumulative worldwide gasification capacity

Around the world, more than 100 biomass gasifier projects are operating or ordered.[11] The prospect of woody biomass gasification is being explored due to the abundance of timber in the United States and other areas, renewable energy standards and goals and greenhouse gas emission regulations and reduction goals. Woody biomass gasification is capable of delivering thermal and electrical energy, as well as liquid fuels. As these processes become more common, proven, and accepted, other similar systems processing more complex feedstocks will be demonstrated and commercialized, including those for sludges and municipal solid waste.

4. Sludge Gasification

4.1 Sludge Characteristics

Sewage sludge is the solid, semisolid, or liquid organic material that results from the treatment of domestic wastewater by municipal wastewater treatment plants (WWTPs), also known as publicly owned treatment works (POTWs). Paper mill sludge is representative of materials discharged from virgin pulp and recycle mills. The characteristics of these sludges vary widely, depending on the location and facility. Due to the varying compositions of sludge, it is difficult to show precise quantitative data that represents sludge as a whole across the United States. Typical and example compositions are provided in the sections to follow.

4.1.1 Pulp and Paper Mill Sludge

Generally, pulp and paper mill sludge is the solid residue recovered from the wastewater stream of the pulping and papermaking process. Sludge is produced at two steps in the process of treating the effluent. Primary sludge is recovered by the first stage of the processing at the primary clarifier. Primary clarification is usually carried out by sedimentation, but can also be performed by dissolved air flotation. In sedimentation, the wastewater to be treated is pumped into large settling tanks, with the solids being removed from the tank bottom.[13]

Secondary treatment is usually through aerobic digestion. The resulting solids are then removed through clarification as in the primary treatment. The resulting sludge is then mixed with the primary sludge prior to dewatering and disposal. In general, primary sludges are easier to dewater than the sludges resulting from the second stage.

The amount of sludge produced per bale of raw material received varies by plant type. Kraft, sulfite and deinking mills typically produce approximately 58, 102 and 234 kg of sludge per ton respectively.[13] These sludges contain approximately 40-50% water by weight and a heating value of about 3600 Btu/lb (dry).[55] The low heating value is a result of high levels of clay, calcium carbonate and titanium oxide. The ash content in paper mill sludge can be as high as 50%.

Not only do mills produce varying amounts of sludge, the sludges they produce are distinctly different in composition. High ash sludges have a significantly lower heating value than low ash sludges, which affect its suitability for certain disposal methods (e.g., incineration and gasification[13]).

Table 2 - Ultimate analysis of different types of paper mill sludge[13]

	Analysis (%)						
Sludge Type	**Solids**	**Ash**	**C**	**H**	**S**	**O**	**N**
Bleached Pulp Mill	33.4	1.9	48.7	6.6	0.2	42.4	0.2
Pulp mill	42.0	4.9	51.6	5.7	0.9	29.3	0.9
Kraft mill 1	37.6	7.1	55.2	6.4	1.0	26.0	4.4
Kraft Mill 2	40.0	8.0	48.0	5.7	0.8	36.3	1.2
Deinking Mill 1	42.0	20.2	28.8	3.5	0.2	18.8	0.5
Deinking Mill 2	42.0	14.0	31.1	4.4	0.2	30.1	0.9
Recycle Mill	45.0	3.0	48.4	6.6	0.2	41.3	0.5

4.1.2 Sewage Sludge

As defined by the EPA, final sewage sludge is the liquid, solid, or semi-solid residue generated during the treatment of domestic sewage, receiving secondary treatment or better, in a treatment works, which may include sewage sludge processed to meet land application standards.[12]

Wastewater entering a POTW is typically screened, then placed into a grit chamber, where sand, grit, cinders, and small stones settle to the bottom. In most cases, the wastewater then flows into a primary sedimentation tank where gravity, flotation, and chemical coagulation or filtration order to remove another portion of the solids (as primary sludge). Finer solids, organic matter and some dissolved materials are removed during secondary treatment, typically by attached or suspended growth biological processes. After these biological processes are completed, the effluent typically passes through a secondary clarifier, where additional sludge is removed (as secondary sludge).[17] Biological secondary sludge contains micro-organisms that retain water within tough cell walls, making mechanical dewatering difficult. It should be noted that during digestion, some carbon in volatile organic matter is converted into CO_2 and CH_4, thereby lowering the heating value.

Typical waste water entering a POTW contains between 0.01 and 0.04% suspended solids. Therefore, a plant processing 1 million gallons of water per day will produce between 800 and 3000 lbs of dry sludge per day.[39,57] After treatment, sewage sludge contains 79-99% water by weight, while the remaining part is solid, such as organic matter, metals and microorganisms. Table 3 gives the results of ultimate and proximate analysis performed on dried biosolids by five companies/institutions which have researched biosolids gasification. As with paper mill sludge, the composition of sewage sludge will determine if it is a suitable candidate for gasification. High ash contents yield low heating values, while high sulfur and chlorine content may foreshadow high costs in the removal of these chemicals in the syngas prior to combustion or from emissions after combustion.

Table 3 provides data on sewage sludge composition as reported by the University of California Riverside (UCR), Nexterra, M2 Renewables (M2R), the University of Seoul (UoS) and the Tokyo Institute of Technology (TIT) in separate reports relating to sewage sludge.

Table 3 - Ultimate and proximate analysis of different sewage sludge samples.

Analysis	UCR[18]	Nexterra[19]	M2R[20]	U of S[21]	TIT[22]
Ultimate Analysis	*Mass %, dry*	*Mass %, dry*	*Mass %, dry*	*Mass %, daf**	*Mass %, daf**
Ash	20.85	17.30	6.00	0.00	0.00
Carbon, C	41.62	44.40	45.00	55.50	69.20
Hydrogen, H	6.03	6.31	6.00	8.20	4.60
Nitrogen, N	7.82	5.10	3.00	7.40	2.20
Sulfur, S	0.95	0.00	1.00	1.10	1.70
Chloride, Cl	0.00	0.07	0.00	0.00	0.00
Oxygen, O (difference)	22.73	26.82	39.00	27.80	22.30
Total	100.00	100.00	100.00	100.00	100.00
Proximate Analysis		*Mass %, dry*	*Mass %, dry*	*Mass %*	*Mass %*
Volatile Matter	NA	72.41	80.00	66.80	39.30
Fixed Carbon	NA	10.29	15.00	0.80	19.40
Ash	NA	17.30	5.00	26.80	30.10
Moisture	NA	0.00	0.00	5.60	11.20
Total		100.00	100.00	100.00	100.00
HHV (Btu/lb)	NA	8490.00	8000.00	7380.00	NA

* Dry ash free

In 2009, the EPA released the Targeted National Sewage Sludge Survey (TNSSS) where 84 sludge samples from 74 WWT facilities in the U.S. were collected and analyzed for 145 different analytes.

The TNSSS was designed to: (1) obtain updated occurrence information on nine analytes of potential concern, and (2) obtain occurrence information on a number of contaminants of emerging interest identified by EPA and the National Research Council (NRC) that may be present in sewage sludge generated by POTWs.[12]

Briefly, the survey found:

- Nitrite/nitrate, fluoride and water-extractable phosphorus was found in every sample.
- 27 metals were found in virtually every sample, with one metal (antimony) found in 72 samples.
- Of the six semivolatile organics and polycyclic aromatic hydrocarbons, four were found in at least 72 samples, one was found in 63 samples, and one was found in 39 samples.
- Of the 72 pharmaceuticals, three (i.e., cyprofloxacin, diphenhydramine, and triclocarban) were found in all 84 samples and nine were found in at least 80 of the samples. However, 15 pharmaceuticals were not found in any sample and 29 were found in fewer than three samples.
- Of the 25 steroids and hormones, three steroids (i.e., campesterol, cholestanol, and coprostanol) were found in all 84 samples and six steroids were found in at least 80 of the samples. One hormone (i.e., 17α-ethynyl estradiol) was not found in any sample and five hormones were found in fewer than six samples.
- All of the flame retardants except one (BDE-138) were found in every sample.

The reason for the inclusion of the results of this report are to inform the reader that sewage sludge composition is much more complex than what can be found in a typical ultimate analysis. The effect of gasifying many of the analytes found in the survey has yet to be determined.

4.2 Unique Aspects of Sludge Gasification

During gasification, sludge undergoes a physical and chemical change, similar to other biomass feedstocks. Due to the high moisture content, (the mass of untreated sludge being 79-99% water) it is necessary for the sludge feed to be dried or dewatered in some way before entering the reactor (this is true for most reactors, although some technologies that operate at much higher temperatures, such as plasma gasification, have the ability to handle sludge without pre-treatment). The gasification process itself will not be influenced by the high moisture content, but because of the high energy demand required by the system to vaporize the moisture, the capacity and economics are affected.[14]

Perhaps the largest obstacle related to sludge gasification is reducing the water content to a level suitable for gasification. Mechanical processes are more desirable than thermal processes from an energy standpoint, but secondary (e.g., activated) sludge can only be mechanically dewatered to about 40% solids.[65] The difficulty in removing water from secondary sludge lies in the water trapped inside the sturdy cell walls of the organisms used to consume the biological oxygen demand of the wastewater that remains after primary settling. To remove this moisture, the cell walls must be broken.

Paper mill sludges are capable of being reduced to 50% moisture using a belt press followed by a screw press.[56] To finish the preparation process, thermal energy is required to remove the remaining moisture.

Biosolids are the nutrient-rich organic materials resulting from the treatment of sewage sludge (the name for the solid, semisolid or liquid untreated residue generated during the treatment of domestic sewage in a treatment facility). Sewage sludge becomes biosolids when treated and processed to achieve the pathogen and/or pollutant limits set forth by the EPA's Part 503 Biosolids Rule. The limits can vary based on the biosolids use or disposal and classification.[73]

Composting and lime stabilization are techniques that would be eliminated in a gasification scenario. Aerobic digestion would also likely be eliminated. Anaerobic digestion, although compatible with gasification, is not preferred as a pre-treatment step since much of the chemical energy of the biosolids is removed and thus unavailable for recovery in the syngas.

After the treated sludge is dewatered then dried to a low enough water content to be properly gasified (80-90% solids), the dried sludge enters the gasifier chamber, and undergoes the first step of gasification in a typical fixed bed downdraft gasifier, drying.[14]

In the drying zone, as with other feedstocks, the sludge descends into the gasifier and moisture is evaporated using the heat generated in the zones below. The rate of drying depends on the surface area of the fuel, the recirculation velocity, the relative humidity of these gases and temperature differences between the feed and hot gases, as well as internal diffusivity of moisture within the fuel. Sludge with less than 15% moisture loses all moisture in this zone.[14]

In the pyrolysis zone, the irreversible thermal degradation of dried sludge descending from the drying zone takes place using the thermal energy released by the partial oxidation of the pyrolysis products. The release of volatiles from sludge begins at about 250 °C, and 60–70% of sludge is converted to a complex liquid fraction comprising water, tars, oils, a gaseous phase including CO_2, CO, H_2, and a variety of other hydrocarbons, and un-reacted char and ash. As with other feedstocks, it is expected that pyrolysis of sludge in a reactor typically occurs at temperatures between 350 and 500 °C.[14]

In the throat zone (often referred to as the oxidation zone), the volatile products from the pyrolysis process are partially oxidized in highly exothermic reactions, resulting in a rapid rise in temperature (up to 1100 °C). The heat generated is used to drive the drying and pyrolysis of sludge and the gasification reactions. The oxidation reactions of the volatiles are very rapid and the oxygen is consumed before diffusing to the surface of the char. No combustion of the solid char can, therefore, take place. Oxidation of the condensable organic fraction to form lower molecular weight products is important in reducing the amount of tar produced. During sludge gasification, it is expected that oxidation zone temperatures would be between 1000 and 1100 °C. The products, including CO_2, CO, H_2, H_2O, high chain hydrocarbon gases, residual tars and char, then pass on into the gasification zone.[14]

In the reduction zone (often referred to as the gasification zone), the char is converted into gas by reaction with the hot gases from the upper zones. The gases are reduced to form a greater proportion of H_2 and CO. Temperatures of the gases entering this zone are about 1000–1100 °C and exit around 700 °C.[14]

Example: Pulp and Paper Sludge Energy Balance
Typical pulp and paper mill sludge energy content (HHV) is around 3600 Btu/lb, dry. If sludge at 10% moisture is fed into a fixed bed, air blown gasifier, the syngas energy content would be approximately 130 Btu/scf. If syngas coming out of a 5 ton/day gasifier is sent to an electrical generator with a 40% electrical efficiency, 108 kW of gross electricity could be produced. Taking into account a parasitic load from the gasifier, dryer, and cleaning system of approximately 75 kW, a positive net output is possible, but extremely difficult to achieve.

Example: Sewage Sludge Energy Balance
Typical sewage sludge energy content (HHV) is around 8000 Btu/lb, dry. If sludge at 10% moisture is fed into a fixed bed, air blown gasifier, the syngas energy content would be approximately 190 Btu/scf. If syngas coming out of a 5 ton/day gasifier is sent to an electrical generator with a 40% electrical efficiency, 240kW of gross electricity could be produced. Taking into account the parasitic load from the gasifier, dryer and cleaning system, a net output of about 165 kW can possibly be achieved. If this system is creating a syngas composition of 15% H_2, 15% CO, 3% CH_4, 17% CO_2 and 50% N_2, the emissions will be approximately 200 ppm NO_x and 2000 ppm CO at 5% O_2.[27]

4.3 Environmental Consequences

Most of the research conducted in the area of sludge gasification has been strictly on gasifier performance, with the syngas created immediately being combusted after exiting the gasifier. Although this is one option, most research efforts have been focused on coupling multiple processes. To accurately determine the effects on the environment, a gasifier would need to be coupled with a syngas cleanup system, syngas combustion or conversion system and thermal oxidizer (or whatever the final setup would be at commercial scale). Quantitative data relative to all waste streams of a gasification system is limited due to the lack of fully integrated processes. However, data relating to individual processes of different systems has been obtained and is presented in the sections to follow.

Despite the dependency on feedstock composition and process, there are some waste products which are produced in nearly all gasification processes which must be treated to prevent release into the atmosphere. The pathways and forms of the wastes are dependent on many conditions within the system, but should be accounted for when viewing the system as a whole. Criteria air pollutants (CAPs), hazardous air pollutants (HAPs), GHGs and waste water streams apply to nearly all gasification systems and need to be considered when determining the environmental impacts of a process.

4.3.1 Criteria Air Pollutants

The amount of SOx, CO, NOx and particulate matter (PM) created during the sludge gasification process will vary according to gasifier type, syngas clean up system, end use (combustion system and/or thermal oxidizer), and composition of feedstock.

Sulfur in the feedstock, when gasified, will produce H_2S, COS and low concentrations of mercaptans and CS_2. The sulfur content in the feedstock as well as the gasifier temperature will influence the distribution of sulfur in the product gas. Most of these sulfur compounds, unless removed through a cleaning system, will become SO_2 when combusted.[23] Using an alkali absorption solution or a dry sorbent (ZnO), most of the sulfur containing compounds can be captured. A study conducted by UC Riverside found that only 10% by mass of the sulfur in the feedstock was recovered in the ash. Based on UC Riverside's ultimate analysis, sulfur comprises 1-2% of the original dry feedstock mass.[18] Therefore, a 5 TPD processing plant would need to capture approximately 90 kg/day of sulfur in a cleanup system downstream of the gasifier for sulfur free emissions.

Carbon monoxide concentration in syngas is highly dependent on the gasifier and can range widely. CO produced during the gasification process is combusted in an engine, turbine or oxidizer, depending on the system. Therefore, the remaining portion of CO in the gas stream after combustion is dependent on the efficiency of the energy conversion system. Table 4 provides emissions values coming out of the exhaust of a commercial scale gasifier processing sewage sludge which is coupled with a thermal oxidizer and bag house in Sanford, FL. The heat produced in the thermal oxidizer and gasifier in this system is used to dry the feedstock entering the system.

Table 4 - Emissions data submitted by Maxwest to the Florida environmental agency.

Pollutant	MaxWest	Allowable	Unit (7% O_2)
Cadmium (Cd)	7.23E-05	0.095	mg/dscm
Carbon Monoxide (CO)	7.87	3800	ppmvd
Dioxin/Furan TEQ	0.0285	0.32	ng dscm
Hydrogen Chloride (HCl)	1.8	1.2	ppmvd
Lead (Pb)	8.19E-04	0.3	mg/dscm
Mercury (Hg)	7.98E-03	0.28	mg/dscm
Oxides of Nitrogen (NO_x)	432.17	220	ppmvd
Particulate Matter (PM)	9.6	80	mg/dscm
Sulfur Dioxide (SO_2)	4.17	26	ppmvd

HCl and NO_x values are greater than allowed, but MaxWest has three years to meet the HCl allowable limit and preliminary tests show that current NO_x technology on the MaxWest system are capable of meeting limits.

Due to the high nitrogen content in most of the sewage sludge samples, NH_3 and HCN, precursors to NOx, will be produced during combustion, if the syngas is used in a combustion process. Nitrogen containing compounds can be removed from the syngas stream by means of liquid scrubbing or through the use of dry sorbents. Removal of these molecules prior to combustion is ideal, thereby reducing NOx emissions after combustion, which can be costly.

Very little, if any, data is available on PM levels in a sewage sludge gasification plant. PM is typically captured using cyclones, water scrubbers and bag houses in the syngas cleaning process. Once again, the levels are dependent on the efficiency of the system being used. For the commercial scale Maxwest system mentioned earlier, 11.96 tons per year (TPY) of PM emissions are predicted by Maxwest without a baghouse and 0.12 TPY with a baghouse.[24]

4.3.2 Hazardous Air Pollutants

There are currently 187 HAPs regulated by the EPA.[41] As with CAPs, HAP levels are highly dependent on the process and can only be determined through empirical data analysis.

The amount of HCl and dioxins (chlorinated organics) created during gasification is dependent on temperature and feedstock composition. In the presence of oxygen, chlorine, organic compounds and temperatures above 300 °C, dioxins are formed. A substantial amount (50 to 90 wt %) of the chlorine is typically bound in the ash. The removal of HCl in the syngas can be achieved through liquid scrubbing systems or a dry system in which the syngas is passed through an absorbent such as sodium carbonate or calcium oxide. The production of dioxins decreases with an increased temperature (>850 °C), increased oxygen content, low Cl content in the feedstock and small (<2s) residence time.[23] Dioxin formation as a result of *de novo* synthesis occurs from the presence of unreacted carbon in fly ash or flue gas, Cl_2, O_2 and a metal catalyst[66], but research on the formation of dioxins during combustion of syngas could not be found in the references used for this report. It should be noted that very little carbon and Cl_2 are present in clean syngas that is fed into a combustion process.

In a study conducted by the University of Seoul (UoS), a number of metals were identified in the char produced during gasification of sewage sludge. The UoS used a laboratory scale two-stage gasifier in which the first stage was a fluidized bed and the second stage, a reactor filled with activated carbon for tar cracking. The activated carbon, as well as the char captured in the cyclone was analyzed for metals. The concentration of metals in the char is larger because the mass of the sludge is reduced while maintaining nearly the same mass of total metals. Table 5 shows how the metals entering the system are accounted for after gasification in the ash and activated carbon filter.[21] The UoS study did not provide information on the amount of sludge fed during the run, but the feed rate was 18g/min.

Table 5 - Metal concentrations in the different stages of the UoS study[21]

	Concentration (ppm) of metal in		
Element	Dried Sludge	Activated Carbon	Char
As	below 20	below 20	below 20
Cd	2.1	below 1	4.8
Cr	603.3	12.67	1278.0
Cu	633.9	13.3	1456.0
Hg	22.8	below 20	27.0
Ni	63.1	21.39	139.9
Pb	91.6	3.415	205.2
Zn	1377.0	41.7	2678.0

Based on the concentrations shown above, the amount of these metals processed in a 5 TPD plant is shown in Table 6. The metals can either be collected in the dry solids stream (ash or char), liquid stream from gas cleanup or in the flue gas stream after combustion.

Table 6 - Estimated amounts of metals processed during sludge gasification.

Element	Weight (kg/day), processed in 5 tpd plant
As	< 0.1
Cd	0.011
Cr	3.017
Cu	3.170
Hg	0.114
Ni	0.315
Pb	0.458
Zn	6.8850

In a separate study by the Imperial College of London (ICL), dried sewage sludge samples were collected from five European water companies. A trace and minor element analysis was conducted on the samples prior to being gasified in a laboratory scale fluidized bed gasifier. Table 7 shows the results of the element analysis.

Table 7 - The range of concentrations of metals in the five different samples analyzed by ICL[25]

	Composition of minor elements (ppm, wt)					Composition of trace elements (ppm, wt)						
Sample	Na	Mg	K	Al	Ti	Ba	Cr	Hg	Mn	Ni	Pb	Zn
1	2745	2740	4874	9421	1305	235	33	1.1	273	20	57	761
2	1058	4990	4684	22426	1665	406	94	2.1	203	31	250	789
3	2402	5120	3363	19563	1776	302	75	1.0	236	20	112	492
4	2393	6700	7140	25606	1507	438	224	2.1	188	55	215	966
5	2117	3687	3523	41259	1291	542	304	1.0	121	151	79	1095

The ICL then analyzed the composition of the trace elements in the bed material and fines collected in the gasifier. Their research concluded that virtually none of the mercury in the feed was retained in the char. Additionally, the research concluded that lead, zinc and barium can be released into the syngas stream, depending on gasifier temperature. This being the case, exhaust emission quality will be highly dependent on the gas cleaning system. Wet scrubbing systems are effective in removing all of the elements in the syngas except possibly mercury. An activated carbon system may be necessary for removing the mercury. Leachability of elements captured in the ash will need to be quantified to determine the effect on disposal to landfills, as little to no data are available.[25]

In general, the ICL study suggests that many processes in the gasifier bed contribute to the release of trace elements from the feed. Attrition, entrainment, and volatilization of trace elements in a gasifier can all have an effect on the distribution of the elements. The relative importance of these processes is influenced by both the mode of the occurrence and the chemical speciation of the trace elements. Trace elements that enter the gas phase may, in turn, be transformed back to a condensed phase solid or liquid aerosol as the gases cool after leaving the gasifier, by a combination of chemical reaction, homogeneous and heterogeneous condensation, and absorption mechanisms.[25]

4.3.3 Greenhouse Gases

CO_2, N_2O, CH_4 and fluorinated gases are all GHGs, which trap heat in the atmosphere. GHGs are often represented in terms of CO_2 equivalents (CO_2e), where the mass of the gas being considered is multiplied by a global warming potential (GWP) to give the CO_2e. N_2O has a GWP of 310 and CH_4 has a GWP of 21, while fluorinated gases can range from 140 to 23,900[26]. These potentially large numbers emphasize the importance of controlling these gases if identified in a process.

Table 8 displays GHG emissions of several sewage sludge treatment processes represented in CO_2e. The numbers presented in the table were extracted from five articles and represent a variety of processes. Each source used different boundaries and conditions, resulting in a large variance from one source to another. Varying energy production methods, assumed system efficiencies, distances traveled, feedstock composition, virgin fertilizer emissions and inclusion or exclusion of biogenic CO_2 may also be some contributing factors to the large ranges of values. Based on the information extracted from the articles, no clear conclusions can be made. Generally speaking, focusing only on the carbon pathway in the sludge, one ton of dry sludge at 40% carbon, if fully oxidized, will produce 1466 kg of CO_2e. This does not include energy consumed or created in the overall process. To provide an accurate representation of GHG emissions from multiple sludge disposal processes, a life cycle analysis catered to a specific set of conditions will need to be performed. This, however, is outside of the scope of this report.

Table 8 - GHG emissions in kg of CO_2 equivalents per ton of dry sludge processed.

Source	Process	CO_2e
Hospido 2005	Anaerobic digestion + Belt dewatering + Land application	1550
Hong 2009	Anaerobic digestion + Belt dewatering + Land application	251
Lundin 2004	Pasteurization + Land application	-77
Poulsen 2002	Anaerobic digestion + Dewatering + Land application	72
Hong 2009	Anaerobic digestion + Belt dewatering + Landfilling	728
Poulsen 2002	Anaerobic digestion + Dewatering + Landfilling	-179
Hospido 2005	Centrifuge dewatering + Incineration	1800
Hong 2009	Belt dewatering + Incineration	334
Hwang 2000	Thickening + Dewatering + Incineration	83
Poulsen 2002	Anaerobic digestion + Dewatering + Incineration	222
Hospido 2005	Press dewatering + Thermal drying + Pyrolysis (using only syngas)	1250
Hospido 2005	Press dewatering + Thermal drying + Pyrolysis (using syngas, char and tar)	1650
Hong 2009	Belt dewatering + Thermal drying + Gasification	1019

Using a GHG calculator tool (Biosolids Emissions Assessment Model, BEAM)[68], GHG emissions were estimated for composting, landfill disposal, fluidized bed combustion and land application of one dry ton of undigested, lime stabilized sewage sludge at 25% solids. Default values of 5% nitrogen, 1.9% phosphorus, 70% total volatile solids and 39.2% organic carbon were used in the model. For the landfill scenario, it was assumed that no electricity was generated from the collected methane, the combustion scenario assumed that no electricity was generated and 75% of the heat was recovered and the compost scenario assumed a windrow operation. The GHGs accounted for are strictly for the individual processes and not what occurs up and down stream. The results are displayed in Table 9.

In the composting and land application scenarios, the use of the sludge as a replacement for commercial fertilizer and the sequestration of carbon into the soil, significantly reduces the CO_2e. With the landfill option, CO_2e is large due to methane and nitrous oxide creation, as well as the CO_2 emissions from flaring the biogas. Similar to the landfill scenario, combustion values are large mainly as a result of nitrous oxide creation and the liberation of carbon in the combustion process.

Table 9 – GHG emissions using BEAM[68]

GHG	**Compost**	**Landfill**	**Combustion**	**Land Application**
kg CO_2e per dry ton	10	2880	1780	-300

4.3.4 Wastewater

Depending on the process, waste water production and disposal will need to be considered when analyzing a system. Potential sources of wastewater from a gasification process are from the drying process and gas cleaning process as represented in Figure 4. Once again, the composition of these streams varies, depending on the process. The moisture coming from the dryer will be feedstock and temperature dependent. When using high temperatures to dry a feedstock, some of the volatiles in the sludge may become liberated and will reside in the water stream once condensed. Data on the composition of the waste water stream from the dryer was not available for this report.

In the cleaning system, post gasification, a variety of methods may be instituted to remove pollutants. If utilizing a caustic, acid or water scrubber to remove contaminants, a wastewater stream will inevitably be created which must be disposed or treated appropriately. A complete syngas cleaning system was not identified for any of the systems researched for this report, therefore no quantitative data is available.

4.3.5 Direct Environmental Advantages of Gasification

Gasification, when compared to incineration, potentially poses several desirable environmental benefits by reducing and preventing many emissions. One reason for this is the ability to remove compounds through simple cleaning and scrubbing which would later form pollutants during the combustion process. In addition to many possible cleaning methods, gas flow coming from a gasifier is significantly lower than gas flow from an incinerator of the same sludge processing capacity. Typical fixed bed gasifiers require approximately 40% of the amount of stoichiometric air required[67] for complete oxidation, while incinerators typically require greater than 100% of stoichiometric air required for complete oxidation. The addition of this air in an incineration process increases the total gas flow through the system, requiring larger equipment and handling more dilute gas streams.

Many of the CAPs and HAPs mentioned in sections 4.3 and 4.3.2 are retained in the ash, which is captured in cyclones, removed from the bottom of the gasifier or in bag house filters. This allows better control of the pollutants which can be disposed of properly once consolidated. Pollutants in the gasifier product gas can be captured with water, caustic, or acid scrubbers or dry processes such as zinc oxide, sodium oxide, or calcium oxide beds. Removing these compounds prior to combustion helps to reduce emissions created during the combustion process.

Gasification also has the capability of reducing GHG emissions via utilization of a renewable waste feedstock to produce electricity or thermal energy production which may have been otherwise produced by fossil fuels. The magnitude of GHG reductions is highly site, technology and/or feedstock specific. The destruction of methane during the combustion section of the system and the control of nitrogen during the cleaning process will also help to reduce GHG emissions.

4.3.6 Social Sustainability

To be socially acceptable, new technology must often prove to be more beneficial in a variety of aspects than traditional practices. Ideally, an overall reduction in GHG emissions, more favorable HAP and CAP emissions as well as net energy gains, presented in a verified fashion, would quell any social concern. It is also critical to educate applicable populations in a clear and understandable manner, to eliminate the fear of the unknown.

Although this report provides some information, the lack of commercially deployed technology and associated independent data inhibits the ability to fully evaluate sludge gasification and its impacts on social acceptance.

The Blue Ridge Environmental Defense League (BREDL) has not published any reports specifically related to sludge gasification, but a report on solid waste gasification was published in 2009.[43] In the report, the BREDL describes a gasification process which immediately combusts the syngas upon exiting the gasifier without a cleaning process or energy conversion. The report also presents emission values from a system in which the only pollution control device is an electrostatic precipitator. More specifically, the BREDL claims that gasification plants emit nitrogen oxides, sulfur dioxide, particulate matter, carbon monoxide, methane, hydrogen chloride, hydrogen fluoride, ammonia, dioxins and furans, without presenting verified data. If restricted to these variables, gasification seems to be no different from incineration, however little to no gasification processes exist which follow this model. With proper syngas cleaning, most of the pollutants can be captured and contained, all while staying within EPA regulations.

The Sierra Club has created videos explaining the disadvantages of gasification, specifically of medical waste. Arguments made by the Sierra Club are similar to those made by BREDL, in that well engineered gasification systems are not considered and definitive data showing the alleged pit falls of gasification are not presented.

Regardless of the benefits of emerging technologies designed to dispose of sludge, there are coordinated programs that can help to alleviate the negative aspects of sludge disposal. As an example, Central Contra Costa Sanitary District (CCCSD) instituted a hazardous waste collection program along with an amalgam separation program through local dental offices, which helped to reduce mercury concentrations in the waste stream by 70% from 2004 to 2008. In concurrence with the amalgam separator program, CCCSD also worked with local hospital and schools to reduce Hg going into the sewer which also contributed to the decrease. The 70% decrease in Hg translated into an approximate 40 – 55% decrease in Hg stack emissions coming from their multiple hearth incinerator. To meet the proposed limits, discussed in section 6.0, it is imperative that prevention programs be instituted. A reduction in heavy metals in the influent greatly reduces the cost of capturing these metals after being incinerated.

Because of the wide variety of designs, including end uses and cleaning systems, processes may be developed that have negative impacts and are not socially acceptable. However, the systems that are designed that meet or exceed regulations will be favored. Users must be cautious in their evaluations and conclusions and remember that not all gasification systems are the same and must be evaluated on a case by case basis.

4.4 Brief Technology Comparison

Gasification and incineration are often compared as sludge management processes, in that they both convert hydrocarbon-based materials in sludge into simple, nonhazardous byproducts. However, the conversion mechanisms, chemical reactions, and the nature of the byproducts vary considerably.[16] The clear advantages of gasification are a more versatile product, as syngas may be used in a variety of applications, and lower costs associated with gas cleaning, depending on the ultimate goal, as syngas volume is significantly lower than flue gas volume from an incinerator of a similar processing capacity. The National Energy Technology Laboratory (NETL) revealed the key differences between gasification and incineration as summarized below in Table 9.

Table 10 – Brief Technology Comparison Incineration vs. Gasification[16]

Subsystem	Incineration	Gasification
Combustion/ Gasification	· Designed to maximize the conversion of feedstock to CO2 and H2O · Large quantities of excess air · Highly oxidizing environment · Operated at temperatures below the ash melting point · Mineral matter converted to bottom ash and fly ash	· Designed to maximize the conversion of feedstock to CO and H2 · Limited quantities of oxygen · Reducing environment · Operated at temperatures above the ash melting point · Mineral matter converted to glassy slag or ash and fine particulate matter (char)
Gas Cleanup	· Flue gas cleanup at atmospheric pressure · Treated flue gas discharged to atmosphere · Fuel sulfur converted to SOx during combustion and discharged with flue gas or scrubbed in a flue gas treatment system.	· Treated syngas used for chemical production and/or power production (with subsequent flue gas discharge) · Recovery of reduced sulfur species in the form of a high purity elemental sulfur or sulfuric acid byproduct

Subsystem	Incineration	Gasification
Residue and Ash/Slag Handling	· Bottom ash and fly ash collected, treated, and disposed as hazardous wastes	· Slag from a high temperature gasifier is non-leachable, non-hazardous and typically suitable for use in construction materials. Gasifier ash is handled similarly to Incinerator ash · Fine particulate matter recycled to gasifier or processed for metals reclamation

5. Commercial Status of Sludge Gasification

To determine the commercial status of sludge gasification, a list of known gasification vendors was first created. The list of known vendors was compiled from internet searches, marketing materials, journal searches and referrals from stakeholders.

5.1 Industry Assessment Results

Several case studies and pilot/demonstration plant projects have been completed and a few commercial facilities are in operation. Forty three vendors were originally identified for the purpose of this study, as potentially capable of sludge gasification, based on marketing material, journal searches, internet search engine searches, referrals, end user discussions, etc. Internet searches were performed for each vendor to verify that sludge was mentioned as part of their gasification capability. If the information found via the web based search did not provide enough information on the vendor's process to determine their technology readiness level (TRL, see Table 11), the vendor was contacted via phone, email or both to obtain additional information not found in literature. From that list, vendors who were not contacted via phone initially were then contacted to obtain data which was unavailable in literature searches. The vendors which could be confirmed, based on the data available, as having a TRL rating of 4 or 5 were selected for further analysis in this report.

Table 11 - Technology readiness level (TRL) parameters

TRL	Description	Examples
0	No data available or irrelevant technology.	Dewatering technology company or unsupported claim.
1	Data contains basic principles that are observed and reported.	Projected values, engineering assessment/modeling, literature studies of fundamental criteria
2	Sensible applications and theories from basic principles are devised. Basic principles are not only observed, but applied with reasonable awareness. These theories are still exploratory and may contain little or no commercial evidence to verify assumptions.	Analytical Studies; Modeling
3	Verification of a specific concept within a given technology.	Analytical Studies coupled with laboratory studies; bench scale measurements
4	Data confirmed in a relevant environment.	Pilot Plant
5	Data confirmed in an operational environment.	Demonstration scale/ commercial plant actual results; independent results

Of the 44 vendors (Table 12) originally identified as claiming to have the capability of sludge gasification, only two were identified as running consistently at commercial levels, Kopf and Maxwest. The quantity of data available for M2 Renewables and Nexterra, stemming from a significant amount of research and testing being done in the field of sludge gasification, along with a TRL rating of four, enabled a comparison with the Kopf and Maxwest systems. Based on the volume of literature available and research completed at bench, pilot, demonstration and commercial scale, it is clear that there is a significant amount of interest in sludge gasification. Despite the abundance of literature and research, very few companies have produced data necessary for a complete assessment. Necessary data are those from a pilot or commercial process, where sludge is being used as a feedstock. It should be noted that many companies have achieved TRLs for their gasifiers preferred feedstock, but the TRLs listed in this report only relate to sludge gasification. There are many potential reasons why there are so few commercial sludge gasification operations running at present, with the primary being economics, energy prices, regulatory restrictions, social acceptance and lack of capital.

Table 12 - Original list of vendors and the result of their investigation

No.	Company	Technology	Sludge TRL	Notes
1	ACTI	Fixed-bed Gasifiction	1	
2	Allied Syngas Corp	Fixed-bed Gasifiction	1	
3	BioConverters LLC	Biological Destruction	0	Not Gasification
4	Biomass Gas and Electric LLC	Fluid-bed Gasifiction	0	Company dissolved
5	Bio-Petrol	Pyrolysis	1	
6	Biosyn	Fluid-bed Gasifiction	1	
7	Carbona	Fluid-bed Gasifiction	0	
8	Coaltec Energy USA, Inc.	Fixed bed	0	
9	Community Power Corp	Fixed bed	0	
10	Ebara	Fluid-bed Gasification	3	Co-gasification with MSW
11	Energy Products of Idaho	Fluidized bed	0	Combustion
12	Enertech	Gasification	0	Fossil fuel gasification
13	Ensyn	Sludge Pyrolysis	0	
14	Foret Plasma Labs	Plasma Gasification	0	
15	Genahol LLC	Biomass Gasification	0	
16	Grand Teton Enterprises	Gasification	1	Type unknown
17	Green Planet Fuel and Energy	Gasification	0	Type unknown
18	Inetec	Anaerobic Digestion	0	Not Gasification
19	Innovative Logistics Solution	Gasification	1	Merged with Pyromex
20	Interstate Waste Technologies	Gasification	1	Type unknown
21	Lurgi	Catalytic process	0	Not gasification
22	Masada Resources Group	Hydrolysis	0	Not gasification
23	Maxwest	Fixed bed	5	Selected for report
24	Nexterra	Fixed bed	4	Selected for report
25	Omnifuel Technologies, Inc.	RDF Gasification	1	No sludge gasification

No.	Company	Technology	Sludge TRL	Notes
26	Pinnacle Biotech	No info available	0	
27	PRM Energy	Fixed-bed Gasification	1	
28	Prime Energy	Fixed-bed Gasification	3	
29	Princeton Environmental	Plasma Gasification	1	
30	Pyromex AG	Fixed-bed Gasification	4	Selected for report
31	Ren Waste	Gasification	1	Type unknown
32	Skelde	No info available	0	
33	Solena	Plasma Gasification	1	
34	Startech Environmental Corp	Plasma Gasification	1	Bankruptcy
35	Taylor Biomass Energy LLC	Fluid-bed Gasification	1	
36	TRI	Fluid-bed Gasification	1	
37	US Centrifuge	Dewatering technology	0	No sludge gasification
38	Westinghouse	Plasma Gasification	0	Only develop torches
39	Wright Environmental	No info available	0	
40	Ze-gen	Liquid Metal Gasification	0	
41	City of Stamford WPCA	Fixed bed	4	Selected for report
42	Bureau of Sewerage, Tokyo	Fluidized bed	5	Selected for report
43	Kopf	Fluidized bed	5	Selected for report
44	M2 Renewables	Dewatering technology	4	Selected for report

5.2 Selected Technology Profiles

In the sections to follow, a summary is given for four vendors which were identified for further analysis. Among the seven identified sludge gasification companies in Table 12, Nexterra and City of Stamford WPCA worked together on the project, M2R and Pyromex AG worked together as well. The summaries provided below are a combination of available literature, phone conversations and email correspondences with each vendor. Tables 13, 14 and 15 provide technical data on each of the processes.

5.2.1 Maxwest Environmental Systems[24, 28, 72]

Maxwest and its strategic partner, CPH Engineers, Inc., permitted, constructed and commissioned a commercial scale gasification system in September 2009 that focused on reducing sludge disposal costs and requirements. According to Maxwest, the system is estimated to save the city of Sanford, FL approximately thirteen million dollars on natural gas purchases over the contract life (20 years).

The system utilizes a continuous feed dryer system manufactured by Therma-Flite, Inc., which replaced the city’s existing batch fed dryer, and feeds into a fixed bed updraft gasifier. The syngas created during the gasification process is fed directly into a thermal oxidizer, while the ash is removed from the bottom of the gasifier. Once in the thermal oxidizer, the syngas is combusted (differentiating it from an incineration process) and the heat is recovered in an economizer, while the exhaust flows through a bag house and cooling tower/scrubber for PM and pollutant control. The heat recovered in the economizer is transferred via a thermal oil system. The hot oil is pumped to the continuous feed dryer to help dry the sludge being fed into the gasifier. A process flow diagram of the system is displayed in Figure 8.

During startup, natural gas is required to heat the dryer, gasifier and oxidizer. Once heated, the gasifier creates its own heat through the energy released in the exothermic reactions occurring in the gasifier. At this point, no natural gas is needed to heat the gasifier. Once syngas is being produced and fed into the oxidizer, enough heat will be created through the oxidizing of the syngas to maintain the temperature of the oxidizer without the need for natural gas. The heat collected in the economizer provides enough energy to dry the incoming sludge to the desired moisture content, thereby eliminating the need for natural gas in the dryer. Once fully running, the system is self-sustaining, achieving a net zero thermal energy demand, but electrical inputs will still be required.

Maxwest submitted an applicability determination to the EPA's Office of Enforcement to justify an exemption from 40 cfr §61.52, to differentiate the system from incineration. The regulation states that emissions to the atmosphere from sludge incineration plants, sludge drying plants, or a combination of these that process wastewater treatment plant sludges shall not exceed 3.2 kg (7.1 lb) of mercury per 24-hour period. Maxwest argues that because their system is not considered a combustor, the regulation does not apply. As of this moment, Maxwest has not received a response to the applicability determination. Mercury emissions from the MaxWest system based on the values in Table 4 are 0.00059 kg per 24-hour period.

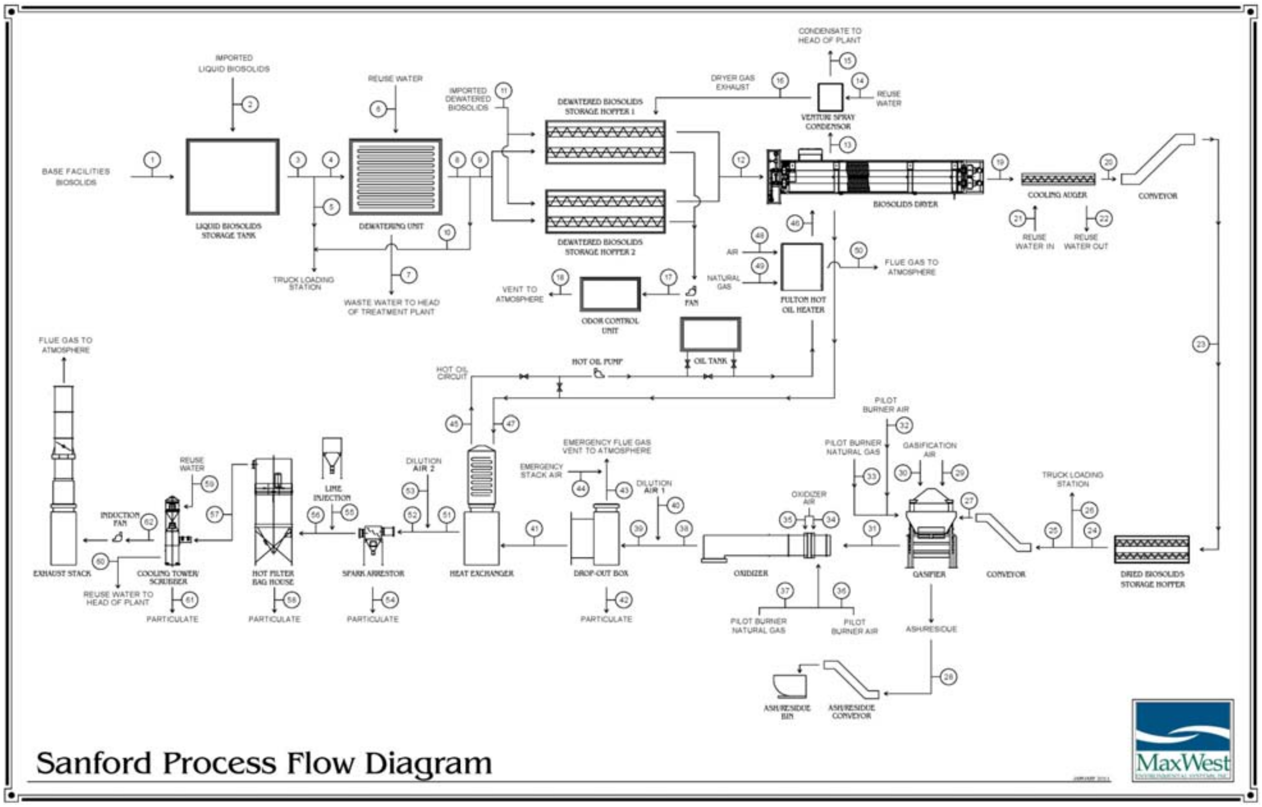

Figure 8 - Process flow diagram of Maxwest system after modifications

5.2.2 [*]M2 Renewables (M2R) & Pyromex AG[20, 30, 75]

M2 Renewables (M2R), formerly Micro Media Filtration, specializes in designing solids removal systems for POTWs using microscreen technology. Their systems are designed to create favorable, low moisture, sludge conditions for gasification. M2R is currently working with Powerhouse Energy, Inc. to develop a complete sewage sludge to energy system. The ultra-high temperature gasifier technology comes from Pyromex Holding A.G., which recently released a manufacturing and distribution license to Powerhouse. According to a M2R representative, the gasifier was recently certified by the European Union for the treatment of biosolids. To complete the system, M2R is in the process of selecting a post mechanical treatment dryer, syngas cleanup system and power generation system. A picture of the Pyromex UHT gasifier is displayed in Figure 9.

The gasifier operates at temperatures around 1,150°C in the absence of oxygen. A small amount of nitrogen is used as the gasification medium. This is achieved by using silicon carbide electric resistance heating elements to supply enough energy to complete the endothermic gasification reactions. The main source of oxygen and hydrogen in the syngas comes from the moisture contained in the feedstock. A representative from M2R states that a carbon to oxygen molar ratio of 1:1 in the feedstock is ideal for the UHT gasifier. This translates into a moisture content of approximately 20%, depending on the composition of the dry components in the biosolids.

After completion of a program to characterize its solids through a sampling and analysis protocol, M2R proceeded to test various biosolids samples in a1 TPD Pyromex pilot gasifier in Munich, Germany. A summary of the fresh solids analysis is shown in Table 3. In January and June of 2010, numerous tests were run with varying feedstock composition and the syngas was analyzed to determine its optimal use following gasification. Due to the high efficiency of the mechanical drying system, less thermal drying is required during pretreatment. This fact, coupled with the high energy density syngas produced in the air free gasification chamber, enables net energy gains.

Based on the testing done on the pilot unit, scaling calculations were performed by M2R to represent the energy balance of a system operating at a 20 MGD WWTP. The energy balance is based on the use of M2R's screening technology and the Pyromex gasifier using typical solids loading rates and biosolids composition. In summary, the WWTP would require a 1.8 MW ICE (derated to account for high hydrogen content), producing approximately 1.4 MW of power. The internal energy consumption is around 430 kW, with 63% being attributed to the resistance heaters. An energy balance based on the tests performed in the pilot unit is displayed in Table 13.

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[*] Following peer review, Southern was contacted by a representative of M2R with additional technical information. The information extracted from reference 75 is contained in the 2nd and 4th paragraphs of this section has not been peer reviewed.

Figure 9 - Pryomex Ultra High Temperature gasifier in Munich, Germany[20]

Table 13 – Maxwest and M2 Renewables overview

	Maxwest[24, 28, 72]	**M2 Renewables/Powerhouse/Pyromex**[20, 30]
Location	Sanford, Fl	Emmerich, Germany
Technology	Fixed Bed Updraft, refractory-lined steel gasifier	Ultra high temp electrically heated gasifier
Readiness Level	Commercial	Demonstration
Feedstock Pretreatment	Post digestion sludge at 2-3% solids is mechanically dried with a belt filter press to 16-18% solids. The sludge is then fed into a continuous indirect heat biosolids dryer to 80-90% solids.	M2 system: Fresh solids are dewatered to 30% solids w/ intergral screw auger, to 55% solids w/ hydraulic ram, then to 95% solids with indirect heat dryer. For this test, used 17% moisture.
Gasification System Performance		
Max Capacity (dry)	1440 lbs/hr	83 lbs/hr (1 TPD)
Internal Energy Consumption	10 MM Btu/hr	12 kW
Energy Output		
Gross Chemical (syngas)	NA	0.1 MM Btu/hr
Gross Thermal	10 MM Btu/hr	NA
Net Electrical	NA	12.6 kW
Net Thermal	NA	NA

	Maxwest[24, 28, 72]	**M2 Renewables/Powerhouse/Pyromex**[20, 30]
Syngas Composition	Not Available	63% H_2, 29.9% CO, 2.6% CO_2, 1.8% CH_4
Gas Cleanup	Baghouse	Liquid system using caustic and /or acidic solutions
By products/Waste Streams	Water from dryer, ash from gasifier, PM and ash from bag house	Ash from gasifier, water from dryer and liquids from scrubbers
Potential Emissions		Not available
Cadmium (Cd)	7.23E-05 mg/dscm	
Carbon Monoxide (CO)	7.87 ppmvd	
Dioxin/Furan TEQ	0.0285 ng/dscm	
Hydrogen Chloride (HCl)	1.8 ppmvd	
Lead (Pb)	8.19E-04 mg/dscm	
Mercury (Hg)	7.98E-03 mg/dscm	
Oxides of Nitrogen (NOx)	432.17 ppmvd	
Particulate Matter (PM)	9.6 mg/dscm	
Sulfur Dioxide (SO2)	4.17 ppmvd	
Product/Byproduct end use	The syngas is fed directly into a thermal oxidizer where an economizer captures the heat to run the dryer.	Syngas will be fed into an internal combustion engine or turbine for electricity production.
Economics	Not available	Scale up to a 15 MW plant is estimated at $60 million

5.2.3 Kopf[29, 35]

The main components of the Kopf gasification technology are: a solar drying unit, a fluidized-bed gasification unit, a gas engine unit for energy recovery and a post combustion chamber for burning excess syngas. Some of the specifics of the system can be found in Table 14 with a schematic of the system displayed in Figure 10. A unique feature of the process is the Thermo System solar drying unit, which dries the wet digested sludge to a solid content of between 70 and 85% over a period of 2 to 8 weeks, depending on the weather conditions. Since this thermal energy is ‘free’, the energy and operating cost requirements compared to other processes using fossil fuel for drying are substantially lower, with a reduced carbon footprint. With 36 sludge dryers operating in Europe, solar drying appears to be completely adaptable to the European climate.

In the gasifier, which operates at 900 °C, pre-heated air is used to ensure the fluidization of the bed. Inside the reactor, dried solids are converted into inert ash granules and combustible gas. The gas is recovered and cooled to a temperature below 35 °C, dried and fed into an ICE. The gas engine produces electricity, which is used to operate the gasification process and to offset the energy demand of the sewage works. Recovered thermal energy is used to heat the digesters at the waste water plant. Natural gas is required for plant start-up, but after the start-up phase, no external fuel is needed.

The Balingen Sewage Works treats an annual wastewater flow of 10 MM m^3. To utilize the energy content of the digested sludge, the local association for wastewater cleaning installed a sludge gasification plant. In August 2004, a fluidized-bed gasification plant, manufactured by Kopf was constructed at the WWTP for processing the digested biosolids and recovering energy.

The Balingen plant processes about 230 kg of sewage sludge per hour. Depending on the degree of drying, this is the equivalent of 160 to 180 kg of dry sewage sludge. According to the company, the ash produced amounts to about 85 kg/hour. The plant produces about 300 m^3 of exhaust per hour. Based on mass and energy balance data, 0.5 kWh of electricity is produced per kg of total solids (TS) treated. Only 0.1 kWh per kg of TS treated is used for the gasification installation and the remaining 0.4 kWh is used by the sewage plant.

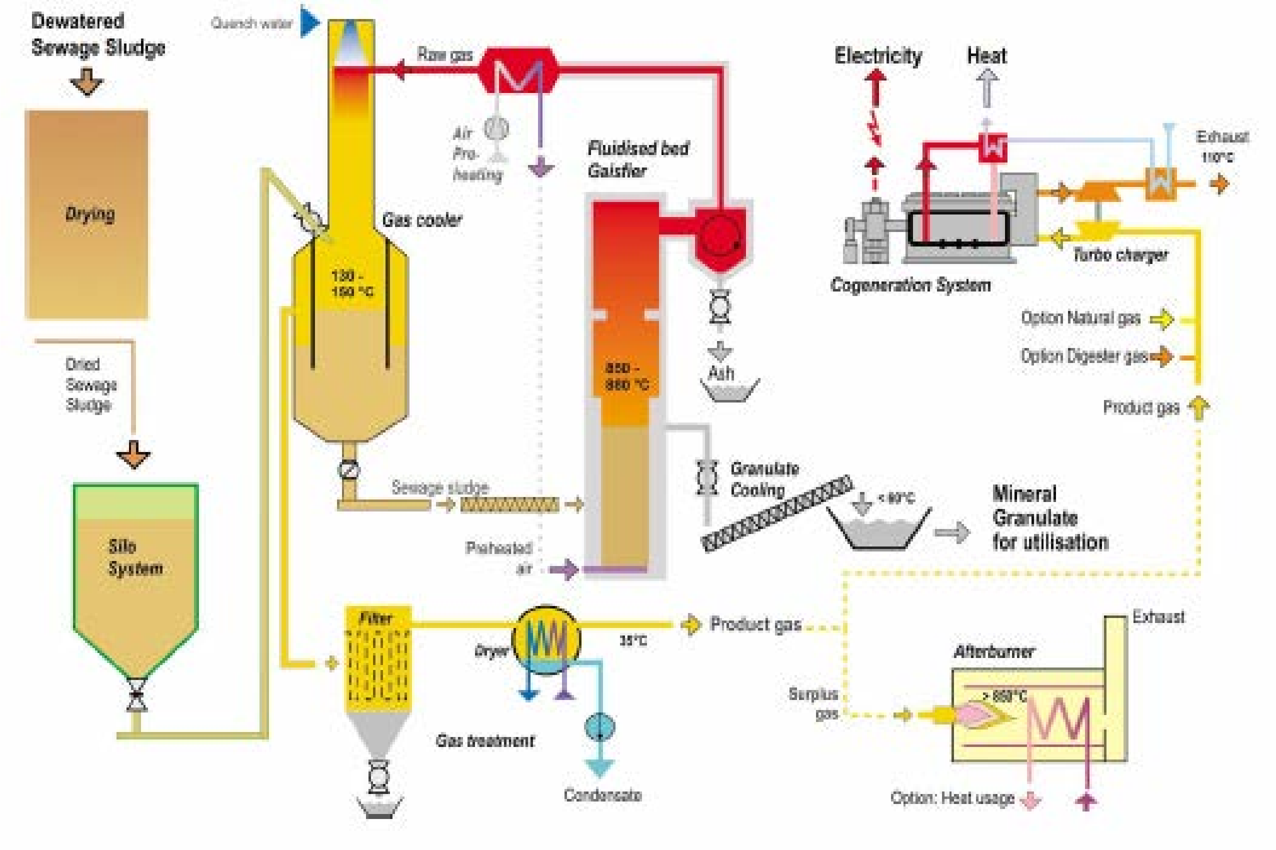

Figure 10 - Kopf PFD[29, 35]

5.2.4 Nexterra & City of Stamford WPCA[19, 31, 32, 33, 34]

The Stamford Water Pollution Control Agency (SWPCA) in Stamford, CT began research on the prospect of sewage sludge gasification less than five years ago to develop a process for managing the cities' sewage sludge disposal. After research and preliminary design, testing was done on a bench scale by a local contractor and then scaled up to pilot scale by the same contractor once the technology was proven.

Undigested class A biosolids, which were dried and pelletized to 6.7% moisture using an Andritz DDS 40 rotary dryer, were fed at a rate of 20 kg/hr into a trailer mounted pilot scale fixed bed updraft gasifier. The syngas gas produced in the gasifier was sent through a vortex particle separator followed by a dry filtering system to remove tars, particulate and other pollutants. Once cleaned, the syngas produced by the pilot plant was either sent directly to a flare or run through an internal combustion engine. The results of these trials enabled SWPCA to verify a biosolids gasification proof of concept using biosolds created in Stamford county.

While testing was being performed on the pilot scale gasifier in Stamford by the contractor responsible for building the trailer mounted unit, SWPCA sent sludge samples to three different demonstration/full scale gasifiers to be tested. The three facilities selected for the tests were not specified, but based on a presentation given by SWPCA[34], it can be deduced that the three gasifiers were Kopf, Nexterra and Prime Energy. SWPCA chose the Nexterra gasifier for its' commercial facility design based on the results of testing completed at Nexterra's facility in Canada.

The Nexterra trials were completed in 2009 at a research facility located in Kamloops, British Columbia. The facility is built around a fixed bed updraft gasifier which is capable of operation at a maximum capacity of approximately 8 MMBtu/hr. Some of the specifics of the system can be found in Table 13 and a schematic of the system is displayed in Figure 11.

According to Nexterra literature,[19] fuel, with a maximum dimension of 3 inches, is bottom-fed into the centre of the dome-shaped, refractory lined gasifier. Gasification air is introduced into the base of the fuel pile. Partial oxidation, pyrolysis and gasification occur at 1,500 to 1,800 °F, and the fuel is converted into syngas and non-combustible ash. The ash migrates to the base of the gasifier and is removed intermittently through an automated in-floor ash grate. In this process, the ash will typically contain only a small fraction by weight of carbon, indicating a high conversion efficiency of fuel into syngas. The syngas can then be directed through energy recovery equipment or fired directly into boilers, dryers and kilns to produce hot water, steam and/or electricity. The temperature of the syngas exiting the gasifier is a function of the fuel moisture content. Likewise, the overall system efficiency is directly related to the fuel moisture content, with dryer fuels resulting in higher system efficiencies.

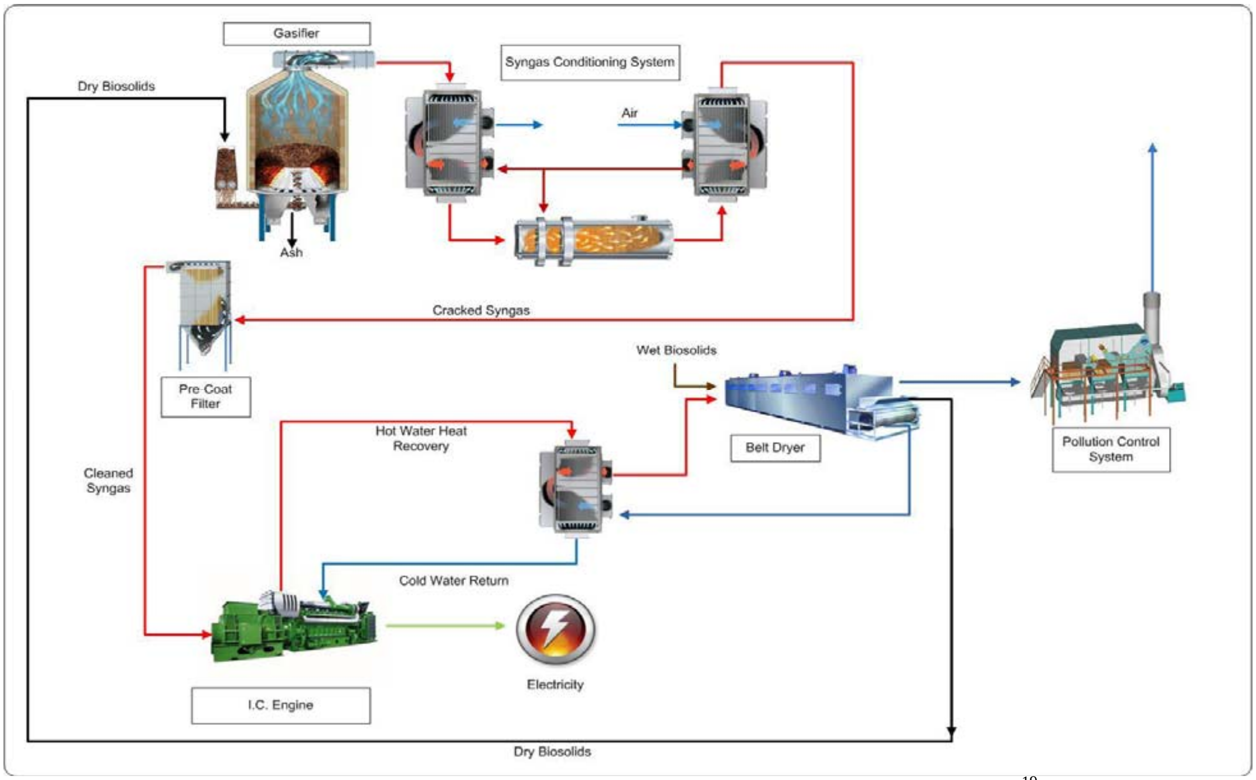

Figure 11 - Feasibility design for Nexterra, a possible PFD for electricity generation[19]

Table 14 – Kopf and Nexterra overview

	Kopf [29,35]	**Nexterra/Stamford WPCA/Jenbacher/Andritz**[19, 31, 32, 33, 34]
Location	Balingen, Germany	Kamloops, BC
Technology	Fluidized bed	Fixed Bed Updraft
Readiness Level	Commercial-Constructed in 2004	Pilot
Feedstock Pretreatment	Solar drying digested sludge to 70-85% solids in 2 to 8 weeks depending on weather. Any electricity needs for the drying system are supplied by PV panels.	Mechanically dewater to 22% solids, then use an Andritz DDS 40 rotary dryer reduce moisture 93% solids. @ 4000kg/hr using 12MM Btu/hr.
Gasification System Performance		
Max Capacity (dry)	375 lbs/hr	1354 lbs/hr
Internal Energy Consumption	17 kW	NA
Energy Output		Assuming 70% efficiency, syngas produced is 8 MM Btu/hr[31]
Gross Electrical	85 kW	NA
Gross Thermal	0.52 MM Btu/hr	NA
Net Electrical	69 kW	NA
Net Thermal	NA	NA

	Kopf [29,35]	**Nexterra/Stamford WPCA/Jenbacher/Andritz**[19, 31, 32, 33, 34]
Syngas Composition	8% H_2, 8% CO, 4% CH_4, balance N_2 and CO_2	Not available
Gas Cleanup	Not available	Syngas conditioning system, cyclone and particle filter
By products/Waste Streams	177 cfm exhaust gas (composition unavailable). 187 lbs/hr of mineral granulate produced. 80 gallons of condensate/ton of sludge is collected and sent back into the plant.	"A few thousand ppm, HCN" from N components in sludge. Cleaned out in Scrubber. The concentrations of metals found in ash samples fell within the guidelines for disposal at landfill locations. Siloxanes present in sludge produce silicon oxide compounds when combusted. NOx, SOx and PM are present in flue gas. Silicon Oxide compounds were found downstream of the thermal oxidizer.
Potential Emissions Exhaust flow rate	177 cfm Composition not available	Not available
Product/Byproduct end use	80% of energy produced during gasification is used to operate treatment plant. Mineral granulate is used for asphalt, phosphorus recovery and construction materials.	In this particular trial, the goal was to use the syngas to displace the natural gas needs of the dryer. Long term goals would be to create gas for an internal combustion generator.

5.2.5 Tokyo Bureau of Sewerage[60, 69]

At the 2007 Water Environment Federation Technical Exhibition and Conference (WEFTEC), the Tokyo Bureau of Sewerage presented a white paper on a 15 TPD fluidized bed gasification system that was constructed in Kiyose, Japan for the treatment of sewage sludge. Starting in 2005, the plant began demonstration tests and completed 3400 hours of testing prior to the 2007 WEFTEC.

In the Tokyo Bureau of Sewerage (TBS) demonstration plant, sewage sludge is dried to a moisture content of 20% in a drier and sent to the gasification chamber of an internally circulating fluidized-bed gasifier. Once the feedstock enters the gasifier, it is pyrolyzed at a temperature of 650 – 750 °C and reformed with air into syngas in a downstream gas reforming furnace at 800 – 900 °C. Heat from the syngas leaving the gasifier is used to dry the feedstock before being sent to a liquid gas scrubber. The syngas is then converted to motor power via an aeration blower or electricity via an internal combustion generator. The solids, unused carbon, and condensed water removed in the scrubber are fed into the combustion chamber of the fluidized-bed gasifier for stabilization. Hot exhaust coming out of the combustion chamber, heats the fluidization gas before going through a bag house and out to atmosphere. A process flow diagram of the TBS demonstration plant is shown in Figure 12.

According to TBS, scale up to a 100 TPD gasifier would reduce GHG emissions by 17,000 tons CO_2 per year versus a conventional system and 4,600 tons of CO_2 per year versus an incineration system.

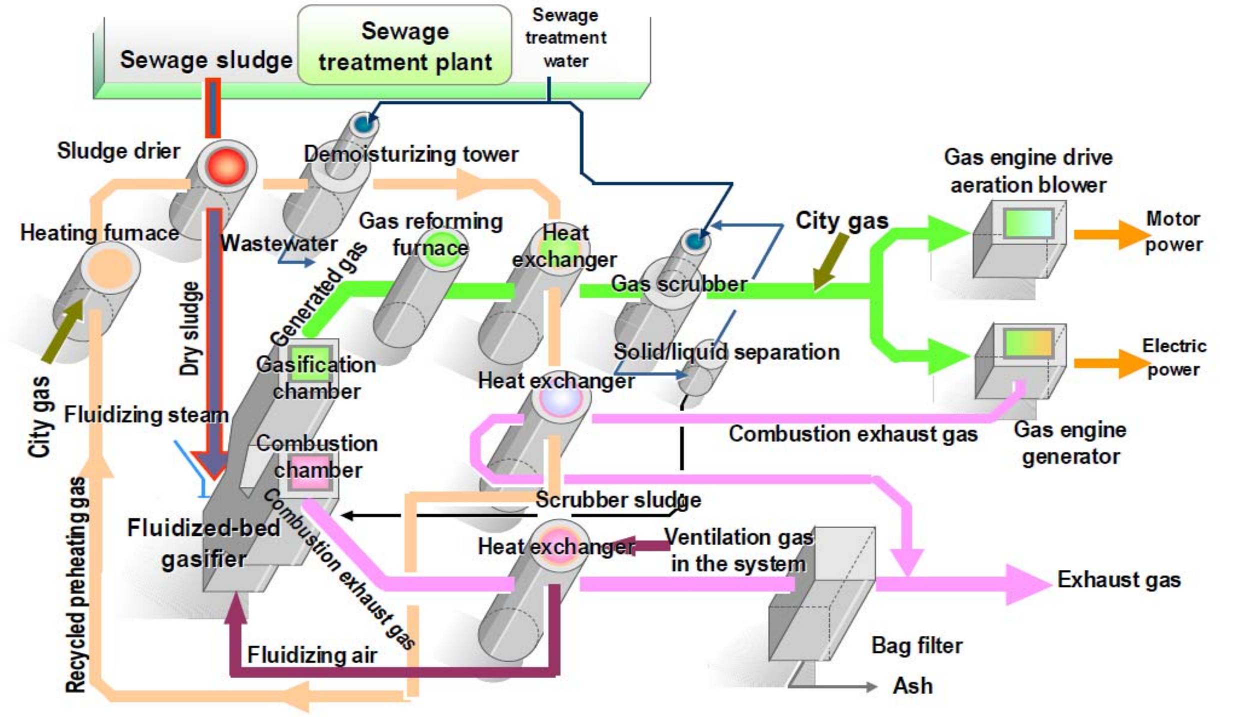

Figure 12 - Tokyo Bureau of Sewerage PFD[60]

In an email correspondence with the TBS, a 100 TPD gasifier was built and started processing sludge in July 2010. Further details on the 100 TPD system can be found in Table 15.

Table 15 – Tokyo Bureau of Sewerage overview

	Tokyo Bureau of Sewerage[60,69]
Location	Kiyose, Japan
Technology	Circulating Fluidized Bed
Readiness Level	Commercial – Constructed in 2010
Feedstock Pretreatment	Sewage sludge from the wastewater plant is fed into a high pressure screw press to a moisture content of 70-80% then fed into a drier that decreases the moisture content to 20%. The drier consumes 350 kW.
Gasification System Performance	
Max Capacity (dry)	8000 lb/hr
Internal Energy Consumption	500 kW
Energy Output	
Gross Electrical	NA

	Tokyo Bureau of Sewerage[60,69]
Gross Thermal Net Electrical Net Thermal	NA 150 kW NA
Syngas Composition	8.5% H_2, 11% CO, 11% CO_2, 7.5% CH_4, balance N_2 small amounts of C2 and C3 hydrocarbons
Gas Cleanup	Liquid gas scrubber and bag house
By products/Waste Streams	Wastewater from a de-moisturizing tower, ash from the bag house and flue gas
Potential Emissions	Not yet published
Product/Byproduct end use	The syngas in combusted in an ICE generator and aeration blower for electricity production
Economics	Estimated $100 million for operation of 20 years (includes construction, manpower, maintenance and operating costs)

5.3 Economic Assessment

Cost is a decisive aspect in energy and resource recovery from sludge. Two primary types of costs are associated with each technology: The capital cost and the operating and maintenance (O&M) costs. If the present worth cost (capital and O&M) of a technology that looks environmentally attractive is not affordable, the technology is unlikely to be adopted unless other market drivers come into effect.[29]

Determination of the economic feasibility of energy and resource recovery from sludge is a complex issue. For each technology, this depends on several factors. In general, the more complex the technologies are, the more costly they are. Capital and O&M costs depend on the type of technology, the size of the installation, the type and number of input materials for the operation of the installation, plus local conditions such as land and labor costs. Economic feasibility will also depend on the type of resource that is to be recovered, such as, electricity, heat, phosphorus, methane from digestion. The cost may also depend on the efficiency goals, product quality, or regulatory limits that must be met. Higher efficiency or quality typically requires higher capital and O&M costs.[29]

For the purpose of this report, a waste heat recovery and electricity generation gasification system was used as an example for a basic economic analysis. The model system consists of a dryer, gasifier, syngas cleanup, and internal combustion engine for electricity and heat production. Capital costs were estimated based on the average cost of a biomass gasification system.[64] O&M costs and profit from electricity generation were estimated by SRI using the U.S. Department of Energy’s proforma and compared under varying local conditions. In Table 16, capital costs, energy produced and annual operating cost are presented in USD per one dry ton (DT) per day of processing capacity. Four different scenarios were analyzed by SRI using different energy values, resulting in varying times for estimated payback. Table 16 gives the results of the analysis.

Table 16 - Summary of sludge gasification economics under varying local conditions

Case	National Average Wholesale Electricity Rate	New England Average Wholesale Electricity Rate	National Average Industrial Electricity Rate + $0.0435/kWh RE Tarriff*	New England Average Industrial Electricity Rate + $0.0435/kWh RE Tarriff*
Price of elec. ($/kWh)	$0.0420	$0.0495	$0.0855	$0.0930
Tipping Fee ($/DT)	$70.00	$70.00	$70.00	$70.00
Annual Operating Revenue, Electricity+Tipping Fees ($)	$41,624.00	$44,583.00	$58,783.00	$61,742.00
Annual Operating Cost ($)	($36,995.00)	($37,665.00)	($40,881.00)	($41,551.00)
Capital Costs ($)	($269,815.00)	($269,815.00)	($269,815.00)	($269,815.00)
CAPEX per kW ($/kW)	$4,651.98	$4,651.98	$4,651.98	$4,651.98
Payback Years	21	21	11	7

*RE Tariff = renewable energy tariff, which may be applied for electricity produced from renewable resources, for which biosolids gasification would apply

A representative of M2 Renewables estimated that a scale-up to 15 MW of their current design would cost approximately $60 million in capital.[30] Using these values in proforma, at the national average and New England average wholesale electricity cost resulted in pay back periods of 21 and 17 years respectively. Due to the lack of information on the planned M2R commercial system, accurate cost projections could not be calculated.

6. Cogasification

Cogasification is the process of combining sludge with feedstocks used in developed coal gasification or biomass gasification technologies. A study conducted by the National Institute of Engineering in Portugal found that the presence of sewage sludge has a positive effect on syngas quality, as it allows an increased energy conversion during cogasification with both coal and straw. The increased concentration of hydrocarbons results in a higher calorific value in the syngas.[36]

Activite de Promotion, D'Accompagnement et de Suivi (APAS), a clean coal technology R&D program supported by the European Commission, was set up to research the gasification of sludge, biomass and other wastes as co-feedstocks with coal. Included in the program was Rheinbraun AG (RAG), which uses a high temperature fluidized bed (Winkler Process) to gasify brown coal. Various tests were conducted by RAG in a 30 tonne/hr demonstration plant. In total, 504 tonnes of sewage sludge and 32 tonnes of loaded coke were co-gasified. Emissions were well below German regulatory limits and conversion efficiencies and syngas yield for the sewage sludge was adequate. RAG concluded that co-gasification of sewage sludge with dried brown coal offered significant potential for disposing of sludge without impairing plant efficiency and emissions.[36]

In a complementary study, the British Coal Corp. examined the use of sewage sludge as a partial feedstock with hard coal at its Coal Research Establishment. The tests involved adding up to 25 percent (dry) of sewage sludge to hard coal being fed into a fluidized bed gasifier. The study found that the addition of sludge did not adversely affect the gasifier operability or performance, providing a fuel conversion efficiency of 78 percent.[36]

Starting in February 2000, Ebara Corporation began the commissioning of a shredding residue (mostly vehicles) gasifier in Aomori, Japan. The gasifier also has the ability to process mechanically dewatered sewage sludge in the amount of up to 30% of the initial feedstock weight. As of April 2004, the plant had processed 300,000 tons of shredding residues and 60,000 tons of sewage sludge. The gasifier also has the ability to process hospital waste and bone meal. The thermal energy produced in the process is converted into electricity, which is used to operate other plants of the same company; the excess is fed to the grid[37].

Although co-gasification seems to be an appealing disposal method, one must consider the availability of existing gasification plants, ability of that plant to handle sludge, and proximity to the plant to sludge sources, which may limit its applicability. The dispersed nature and size of sewage treatment operations seems to favor simple small-scale plants operated at atmospheric pressure on sewage sludge alone, without the cost and infrastructure complexities of adding coal or transporting sludge long distances to large coal gasifiers[25].

7. Regulatory Requirements

Currently, there are no EPA regulations that specifically relate to sludge gasification. The applicable regulations will be determined on a case by case basis until regulations specific to sludge gasification have been established.

Starting in January of 2009, the EPA's Office of Resource Conservation and Recovery began proposing a new rule pertaining to the disposal of sewage sludge by incineration. After an open comments period, the rule proposed that sewage sludge be classified as a solid waste as regulated by section 129 of the Clean Air Act if it is processed for destruction rather than energy production. This ruling does not redefine sewage sludge or biosolids that are not incinerated (e.g., sludge that is composted, land applied, etc.) as solid waste, only sludge that is incinerated for destruction. It has yet to be determined if gasifying sludge for heat recovery will be included in this rule. If a gasification unit disposes of sludge as a "solid waste", the facility will be subject to Section 129 of the Clean Air Act[40]. There are separate emission limits for existing units and new (commissioned after October 14, 2010) units. Table 17 shows the emission limits for multiple hearth (MH) and fluidized bed (FB) incinerators instituted by the EPA under the 2011 Standards of Performance for New Stationary Sources and Emission Guidelines for Existing Sources: Sewage Sludge Incinerator Units.

Table 17 - Emission limits for existing and new sewage sludge incinerator units[3]

		Existing Facilities		**New Facilities**	
Pollutant	**Normalized Units** (7% O_2)	**MH**	**FB**	**MH**	**FB**
Cadmium (Cd)	mg/dscm	0.095	0.0016	0.0024	0.0011
Carbon Monoxide(CO)	ppmvd	3800	64	52	27
Dioxin/Furan (D/F TMB)	ng/dscm	5.0	1.2	0.045	0.013
Dioxin/Furan (D/F TEQ)	ng/dscm	0.32	0.1	0.0022	0.0044

		Existing Facilities		New Facilities	
Pollutant	**Normalized Units** (7% O_2)	**MH**	**FB**	**MH**	**FB**
Hydrogen Chloride (HCl)	ppmvd	1.2	0.51	1.2	0.24
Lead (Pb)	mg/dscm	0.3	0.0074	0.0035	0.00062
Mercury (Hg)	mg/dscm	0.28	0.037	0.15	0.001
Oxides of Nitrogen (NOx)	ppmvd	220	150	210	30
Particulate Matter (PM)	mg/dscm	80	18	60	9.6
Sulfur Dioxide (SO2)	ppmvd	26	15	26	5.3

A public hearing on the proposed rule was held on October 29, 2010 at the EPA campus in Research Triangle Park, NC. Numerous POTW representatives made comments during the hearing on the costs associated with the new standards along with the ability to technologically achieve the standards. During the hearing, no mention was made to how the new standards would affect gasification; this may have been due to the lack of sludge gasifiers in the United States.

As was mentioned in section 4.2.1, 40 cfr §61.52, which relates to mercury emissions, may also apply to sludge gasification. This regulation is not technology based, therefore a simple metric of mercury emissions released per day, regardless of throughput, is the standard. Once again, the applicability of sewage sludge gasifiers to 40 cfr §61.52 has yet to be determined.

As a reference to international standards, in 2000 the European Union issued the Directive 2000/76/EC for the incineration of waste. It was largely based on a German guideline, the 17th Ordinance for the Implementation of the Federal Act on Emission Control 1990 (17th BlmSchV). Due to deviations between both guidelines, the 17th BlmSchV was amended and completed in August 2003. Table 18 presents the emission limits defined in 2002 for sewage sludge in the EU regulation and the 17th BlmSch regulation.

Table 18 - Emission limits for EU and German waste combustion units in 2000[50]

		Existing Facilities	
Pollutant	**Normalized Units** (7% O_2)	**EU-Directive 2000/76/EC**	**17th BlmSch V* of 19/08/2003**
Cadmium (Cd)	mg/dscm	0.03	0.03
Carbon Monoxide(CO)	mg/m^3	32	32
Dioxin/Furan	ng/dscm	0.1	0.1
Hydrogen Chloride (HCl)	ppmvd	4	4
Leab (Pb)	mg/dscm	0.5	0.5
Mercury (Hg)	mg/dscm	0.03	0.02
Oxides of Nitrogen (NOx)	ppmvd	68	68
Particulate Matter (PM)	mg/dscm	-	-
Sulfur Dioxide (SO2)	ppmvd	12	12

8. Conclusion and Recommendations

8.1 Summary of Key Findings

Gasification offers a potentially viable option compared to conventional methods for sludge disposal. Gasification is capable of providing a clean and manageable process with the possibility of net energy gains. The variability and lack of information on commercial scale systems however, makes it difficult to ensure a complete analysis and concrete conclusions on sludge gasification's viability.

Unlike incineration, there is potential for sludge gasification to deliver negative GHG emissions. This is accomplished through energy production from biogenic sources and avoiding GHGs which would have been created in a different process. The emergence of systems, like the MaxWest system described in section 5.2.1, designed to process the sludge throughput of individual plants will also help to reduce GHGs through the avoidance of burning fossil fuels during transportation. As is mentioned in section 4.3.5, the magnitude of GHG reductions is highly site, technology and/or feedstock specific. Therefore, a general statement cannot be made that identifies gasification as having a lower carbon footprint than other management practices.

As can be seen in Table 16 in section 5.3, wholesale electricity prices will have a significant influence on the economics of a sludge gasification plant. Only through individual analysis of each system can an accurate cost projection be obtained. Once again, umbrella statements cannot be made on the economic feasibility of gasification as a whole.

There are many companies that claim to be able to gasify sludge, but supporting independent data on their processes is not available. In addition, many different system uses and designs are available, even among the handful of early commercial systems. As a result, a complete technical and economic analysis will only be feasible for this technology and industry when implemented more broadly through a case by case basis analysis. More specifically, when a pretreatment process, gasifier, clean up system and energy recovery process have been integrated and commissioned, the system can be thoroughly evaluated through collected data.

It is also difficult to evaluate and summarize the performance of a system without empirical data, because gasification's chemical and thermochemical processes are so diverse (e.g., hydrogen concentrations ranging from 10 to 60% and carbon monoxide concentrations ranging from 8 to 35%). At this time, only through direct measurement at existing pilot and commercial scale facilities, can we fully evaluate all of the impacts of the technology.

Once in place, EPA regulations may have a significant impact on the design, economics, performance and feasibility of a gasification system, because emission limits may dictate gas cleanup and gasifier technology requirements.

8.2 Conclusion

Based on the quantity of research data pertaining to sludge gasification, it is evident that there is significant interest around the globe in developing this technology to commercial scale. Although there are many options when it comes to novel methods of sludge disposal and utilization, gasification is currently receiving the most attention. Other novel technologies, such as, super critical water oxidation, which are less mature may be suitable options, but not enough research of these technologies has been performed. With a handful of gasification systems in the final stages of development, only a leap from pilot scale to commercial scale is needed, with more technologies following closely behind.

Although there is little detailed information on commercial sewage sludge gasification facilities, there is even less information on pulp and paper mill sludge gasification. A review of available literature and discussions with industry experts has revealed that pulp and paper mill sludge may not be a suitable candidate for gasification with current technology. The high moisture and mineral content in sludges result in low energy values, ultimately making full scale operation uneconomical, at least until sludge waste disposal becomes more problematic and costly.

8.3 Recommendations

Future work should include an independent assessment of existing systems with the goal of collecting and verifying performance and environmental data via direct measurement. The multitude of component combinations available in gasification systems makes it difficult to speak of the technology as a whole. Each system will need to be evaluated individually to determine its overall appeal. Prior to data collection, a number of items should be considered to determine if a system will meet a facility's objectives. This list includes:

- It is critical to investigate a system's ability to adhere to Clean Air Act standards along with any other applicable federal and state regulations. The design, economics and performance of a system will be influenced by waste stream restrictions. Approach this issue by taking full account of all elements entering and exiting the system (i.e., if there is mercury in the feedstock, there will be mercury in a waste stream).
- When considering performance, it is important to verify energy consumption of the entire process, including mechanical pretreatment, drying, gasifier energy demand and gross output. Keep in mind that if digested sludge is being used, there will be a loss of potential energy from removal and release of carbon in the form of CH_4 or CO_2 created during digestion.
- Capital costs, operating costs and maintenance costs should all be thoroughly investigated. Many of the chemicals in the sewage sludge may corrode a system, leading to unforeseen high maintenance costs.

Finally, continuous evaluation of emerging technologies should be conducted to ensure that impacts of sludge gasification technologies, both positive and negative, are determined prior to broad implementation. This diligence will help to ensure proper regulation, implementation and social acceptance of the technologies.

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Table 19 – Data Source Qualification

Peer reviewed journals or government reports – results based on independently measured validated data
1, 2, 3, 4, 6, 7, 8, 9, 11, 12, 15, 16, 17, 18, 21, 22, 23, 25, 26, 36, 39, 41, 42, 47, 48, 49, 50, 54, 55, 56, 57, 58, 59, 61, 62, 63, 65, 66, 67, 68, 70, 71
Non peer reviewed government reports, conference presentations (non-marketing), peer-reviewed journal articles not based on independently obtained data
13, 19, 20, 24, 29, 37, 44, 45, 52, 60, 64, 74
Direct contact with technology vendors or commercial project development team
27, 28, 30, 31, 32, 33, 34, 35, 38, 51, 53, 69, 72, 75
Non-reviewed articles, websites, marketing presentations, advertisements, press, etc.
5, 10, 14, 40, 43, 46