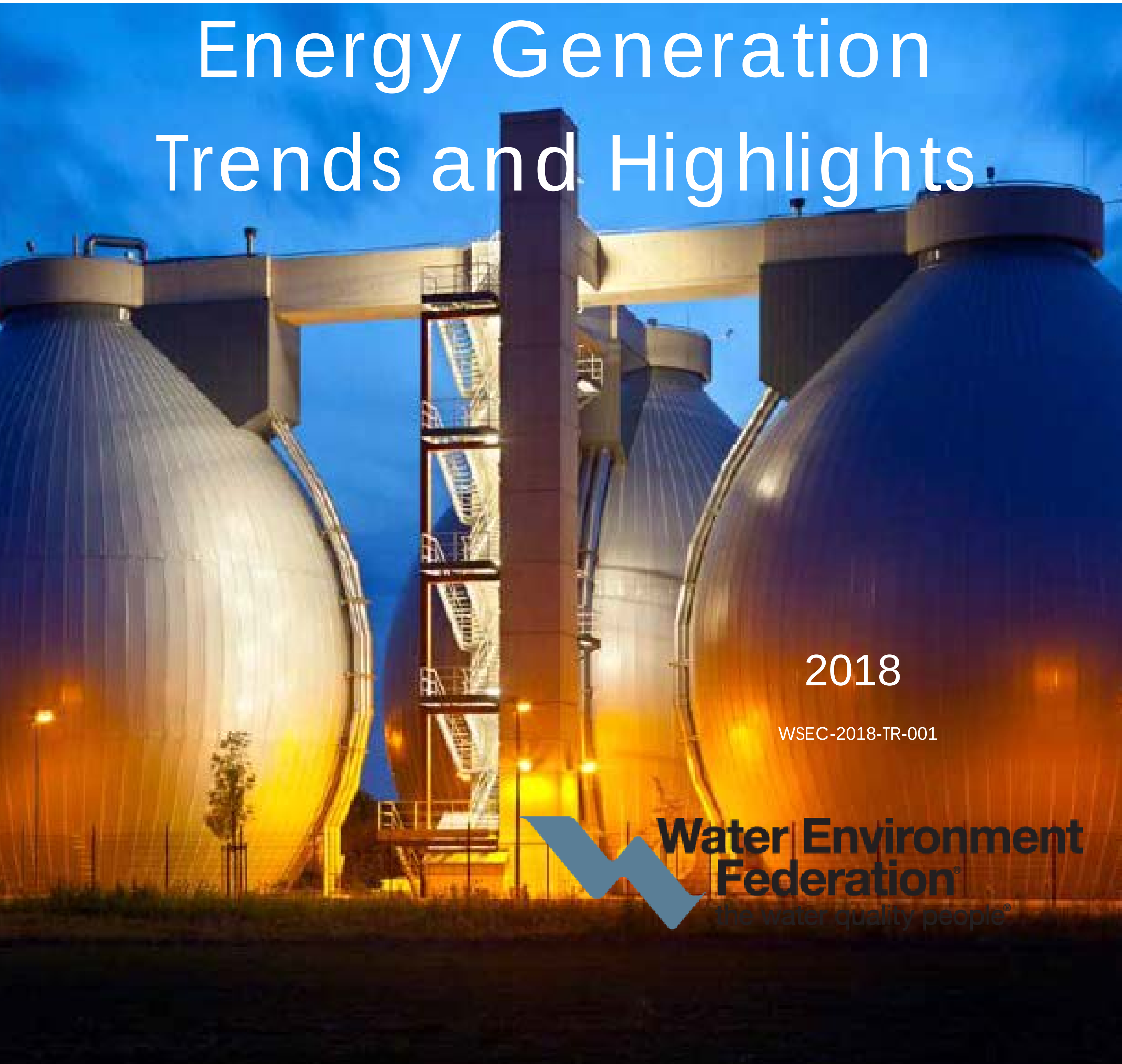
ENERGY

Water Resource Recovery Facilities

Energy Generation Trends and Highlights



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Contents

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Energy in Wastewater and Biosolids

Water Resource Recovery facilities (WRRFs) have the potential to be energy neutral or even net energy producers through holistic energy management approaches, incorporating efficient practices, and generating renewable energy from their by-products, such as biosolids. The energy contained in domestic wastewater and biosolids has been estimated to exceed the energy needed for treatment by a factor of five. The energy in wastewater exists in three forms: thermal energy, hydraulic energy, and chemical or calorific energy. The following table illustrates the energy content of wastewater. Thermal energy is controlled by the temperature of the wastewater entering the plant. Heat can be recovered using heat exchangers and the resulting low-grade heat energy can be used to satisfy building and process heating needs. Hydraulic energy is the energy of the moving water. Low head turbines on gravity flow can be used to convert kinetic energy into electricity (WERF Fact Sheet, 2012).

Constituent	Value	Unit
Average heat in wastewater	41,900	$MJ/10°C \cdot 10^3 m^3$
Chemical oxygen demand (COD) in wastewater	250 – 800 (430)	mg/L
Chemical energy in wastewater, COD basis	12 – 15	MJ/kg COD
Chemical energy in primary solids, dry	15 – 15.9	MJ/kg TSS
Chemical energy in secondary biosolids, dry	12.4 – 13.5	MJ/kg TSS

Table 1: Energy in Wastewater (Tchobanoglous and Leverenz, 2009)

The embedded **chemical energy** in wastewater is on average five times the energy needed for treatment, with values ranging from 0.4 to 6.3. At some WRRFs, recovering the chemical energy in solids alone is sufficient to achieve energy neutrality. Although the energy content of domestic wastewater tends to fall within a fairly consistent range, the energy to treat wastewater differs considerably, driven by the different technology options for treatment and by facility discharge limits. Using well-established processes (e.g., Biological Nutrient Removal (BNR) or enhanced nutrient removal (ENR)) for nitrogen conversion and treatment, WRRFs can expect to see an increase in energy demand plus the need for additional carbon for denitrifying. This additional carbon demand contributes considerably to a WRRF's primary energy consumption. Energy neutrality with nitrogen removal depends upon innovation and the adoption of emerging short cut nitrogen removal practices (Tarallo 2014).

Although wastewater possesses theoretically more energy than needed to operate a treatment facility, the number of net zero energy WRRFs is still low worldwide. The water sector is actively investigating barriers and solutions associated with reducing energy use and maximizing energy production, with the goal of operating solely on the energy from the water and wastes they treat.

Energy in Biosolids

Solids treatment provides the greatest potential for energy recovery and production using the chemical energy embedded in biosolids. There are many opportunities to convert the chemical energy in wastewater solids to a useable form (heat or fuel) through biological or thermal processes. Biosolids typically contain approximately 6,500 to 9,500 British thermal units per pound (Btu/lb) on a dry weight basis (2.3 kWh/lb), which is similar to the energy content of low-grade coal. The following table shows a comparison of the energy in biosolids to the energy in other fuels. For reference, the average daily residential energy use in the U.S. is 31 kWh per home, which would require the energy equivalent of 13.4 lbs of dry biosolids (Stone et al., 2010).

Fuel	Energy (Btu)
1 pound of dry biosolids	8,000
1 kiloWatt hour of electricity	3,412
1 cubic foot of natural gas	1,028
1 cubic foot of biogas	600 – 700

Table 2: Biosolids energy in perspective (Stone et al., 2010)

Driven by rising energy costs and sustainability concerns, utilities are recovering previously wasted resources – flared biogas and waste heat – to increase their energy self-sufficiency. A variety of well-proven energy recovery technologies are available for onsite energy production, and innovative technologies are poised to expand the options.

Path Towards WRRF Energy Neutrality

Recent research conducted in collaboration between the Water Research Foundation (WERF, now part of the Water Research Foundation) and the New York State Energy Research and Development Authority (NYSERDA) offers numerous insights to aid WRRFs moving toward net-zero energy status through best practices, energy conservation, demand reduction, and enhanced production (Tarallo and Kohl, 2015). Sankey energy diagrams of common WRRF process configurations were developed and evaluated with respect to energy usage and production. Findings related to solids management noted:

- Improvements to primary treatment and solids capture had the most significant total positive impact of all the best practices involved.
- Anaerobic digestion with combined heat and power (CHP) was the most lucrative approach for energy recovery, reducing energy requirements by up to 35%.
- Co-digestion of fats, oils, and grease/food waste in anaerobic digesters increased biogas production and energy production potential.

Energy Optimization and Recovery Technologies

WRRFs play a key role in carbon footprint reduction through the conversion of the energy in solids to a useable form (heat or fuel). Energy recovery options range from mature, well-established systems such as anaerobic digestion (AD) to emerging technologies, such as Supercritical Water Oxidation (SCWO) and hydrothermal gasification. These options fall into two main categories: bioconversion and thermal conversion.

Thermal Conversion: Oxidation, Pyrolysis and Gasification

The following sections describe thermal conversion technologies suitable to dewatered or dry solids: thermal oxidation (incineration), gasification, and pyrolysis, as well as the more innovative thermal conversion technologies suitable for a liquid medium. The equipment required for these three technologies is relatively similar. The difference among the technologies stems from the amount of oxygen available for the combustion reaction, which controls the oxidation of the fuel (solids). The incineration process uses excess oxygen, resulting in oxidation of all carbonaceous matter and generating ash. Gasification is performed in a sub-stoichiometric condition, with oxygen limited to 25% of the oxidation requirement. Pyrolysis is performed in a zero-oxygen environment.

While the theoretical energy available through thermal conversion is greater than that recoverable from bioconversion, a significant amount of the energy is used to drive off moisture in the feed, which is typically in the form of dewatered cake. Consequently, net energy recovery from incineration can be lower than experienced from anaerobic digestion. Gasification is another thermal conversion technology that has gained interest in recent years. Before feeding biosolids to a gasifier, it is usually necessary to dry them to 80 to 90% TS. The need for drying, be it in the incinerator or in a dryer prior to a gasifier, reduces the potential net energy output of the system.

Given the high moisture content of wastewater solids, there has been much interest in developing innovative technologies for thermal conversion suitable to a liquid medium, such as hydrothermal processing (HTP). These technologies are in their early stages of development but are promising in that they are developed for treatment of materials with solids concentrations ranging from 1 to 10% and allow the recovery of heat, nutrients, and marketable gases (syngas) or biocrude oil (hydrothermal processing).

Village of Ridgewood, NJ—WRRF Runs on 100% Renewable Energy

The Village of Ridgewood, N.J.'s Department of Public Works wanted to improve the affordability, resiliency, and sustainability of their wastewater treatment operations. In partnership with Natural Systems Utilities and Middlesex Water Company, enhanced existing anaerobic digesters produce an amount of renewable energy that is equivalent to up to 100% of the power demand of the plant. The project used financing through a public private partnership between the Village of Ridgewood and Ridgewood Green RME (RGRME) for constructing:

- waste receiving facilities, biogas conditioning and combined heat and power equipment at no capital cost to the Village of Ridgewood, and
- recovering the investment by selling power to the Village of Ridgewood through a power purchase agreement.

The municipality enjoys reduced electric costs, reduced sludge hauling costs, and a share of tipping fee revenues. The project won the American Biogas Council's Project of the Year Award in 2014. More info: http://www.americanbiogascouncil.org/projectProfiles/ridgewoodNJ.

Thermal Oxidation

Thermal oxidation (incineration) is the most established biosolids thermal conversion technology, having been used since the 1930s. Previously it has been practiced in the wastewater sector mainly as a volume reduction/sterilization method of biosolids management, but that perspective is changing as more municipal utilities actively look at energy recovery and production. Thermal oxidation involves the complete oxidation of all organic material by applying heat in the presence of excess oxygen. The volatile fraction of the feed material is converted to hot flue gases, while the non-volatile or inert fraction becomes ash. Thermal energy can be recovered from the high temperature flue gas and may be used to generate electricity using a steam turbine. The flue gas, however, contains contaminants that must be removed prior to emission to meet regulatory limits; consequently, air pollution control devices are integral parts of incineration facilities.

Incineration is used throughout the world and approximately 17 to 25% of solids produced in the U.S. are incinerated. Biosolids generally need to be dewatered to 26 to 35% TS to support autogenous incineration (e.g., have enough energy to be combusted on their own). The dominant incineration technologies are multiple hearth incinerators (MHI) and fluidized-bed incinerators (FBI) although MHIs are being phased out in many areas in favor of more efficient FBIs.

In the last decade, energy recovery from incineration has become a well-established practice in the U.S. Forward-thinking utilities with incineration energy recovery systems include the Metropolitan Council of Environmental Services (MCES), the Northeast Ohio Regional Sewer District (NEORSD), the Metropolitan District of Connecticut (MDC, Hartford), and Albany, NY. MCES has operated three FBIs with energy recovery for a number of years; Hartford's incineration facility started up in 2013; the NEORSD incineration facility is about to be commissioned; and the Green Bay facility is in construction with a completion date anticipated in 2018.

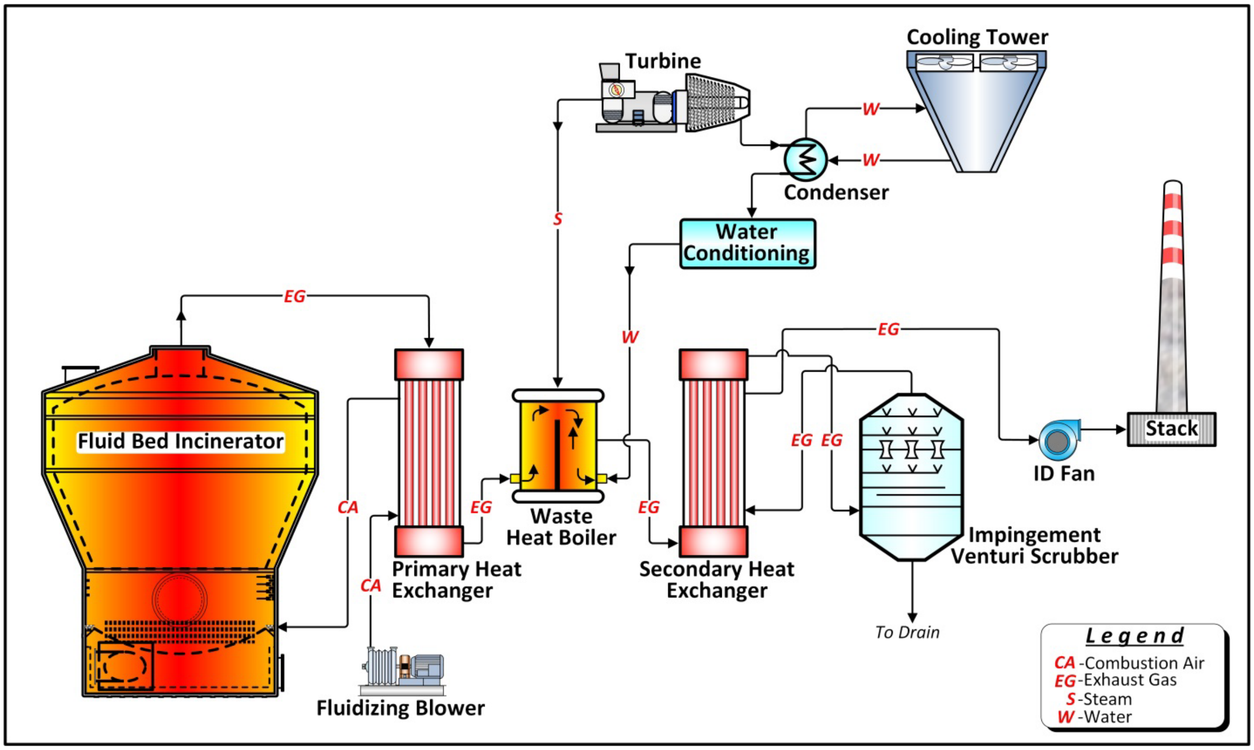

Figure 1: Schematic of an energy recovery system (source: Dominak, R., Hoener, W. 2016)

The Dominak, R., Hoener, W. 2016 schematic above shows a typical schematic of an energy recovery system. A portion of the heat available in the exhaust gases is first recovered in a primary heat exchanger to preheat the fluidizing air fed to the incinerator. Another portion of the heat is then recovered in a waste heat boiler, producing super-heated steam. The steam is used to run a steam turbine, generating electricity. The electricity generated can be significant.

The Hartford Water Pollution Control Facility (WPCF) in Connecticut is an example of one of the progressive utilities that is currently implementing power production from incinerator waste heat. The Hartford WPCF, an 80 mgd plant, processes dewatered solids in three MHIs, each rated at 2.5 dry tons per hour. Limited by air permit, the plant can only run two of the three incinerators at any one time. Exhaust gases from the incinerators are induced through the waste heat boilers to produce steam. The steam generated in the waste heat boilers is used to produce nearly 2 MW of electricity with a steam turbine-generator, which is equivalent to approximately 40% of the current plant demand.

Advances in incinerator design have made thermal oxidation of wastewater solids more efficient. Co-combustion with alternative feedstocks with fuel value properties (such as FOG or wood chips) offer the ability to increase energy recovery from thermal oxidation. Based on modeled projections, the quantity of renewable energy available from thermal oxidation of solids and residuals from domestic wastewater and associated feedstocks, have been estimated for several energy recovery scenarios in table 3. The energy recovery in all of the scenarios produced more electricity than used by the solids process, demonstrating that energy recovery from thermal oxidation is a viable way to make solids processing a net provider of power for treatment plants. For solids processing systems consisting primarily of thermal oxidation, co-firing products such as FOG and wood chips in a fluid bed incinerator (FBI) resulted in the greatest net power production (Dominak, R., Hoener, W. 2016).

Scenario	Net Power Produced kWh/dMt (kWh/dt)	Energy Recovery kWh/dMt (kWh/dt)	Incinerator System Use kWh/dMt (kWh/dt)	Natural Gas Use MJ/dMt (BTU/dt)
Typical Feed- Fluidized Bed (FBI)	84 (76)	369 (335)	285 (258)	0
High Heat Feed FBI	87 (79)	372 (337)	285 (258)	0
Fluidized Bed Boiler with Digestion	1535 (1392)	2083 (1890)	548 (497)	-1333 (-1.15 million)
Typical Feed – Multiple Hearth (MHI)	179 (162)	394 (357)	215 (195)	1401 (1.2 million)
Fats, Oil and Grease (FOG)- FBI	273 (248)	631 (572)	358 (325)	0
Wood Chips - FBI	269 (244)	635 (576)	367 (333)	0
FOG - MHI	229 (208)	420 (381)	192 (174)	0

Table 3; Thermal Oxidation Scenario Energy Recovery Summary (Dominak, R. Hoener, W. 2016)

The MCES Metropolitan WRRF (St. Paul, MN), operated FBIs for over 10 years, having the greatest operating experience in North America with power generation from incineration. The energy recovery facility generates 25% of the plant's electricity demand. Köhlbrandhöft WRRF (Hamburg, Germany), using fluidized bed boilers since 1998, has generated electricity savings valued at over €6.2 million. Albany County Sewer District operates the North WRRF (Menands, NY), the only municipal facility in the U.S. to use an Organic Rankine Cycle ORC system for energy recovery from two MHIs. (Dominak, R. Hoener, W. 2016). Although permitting a new thermal combustion facility can be difficult, utilities that have existing incinerators or are upgrading to newer technology should consider the benefits of energy recovery.

Off-site Co-combustion

Instead of incinerating biosolids at the treatment plant, biosolids can be used to supplement or replace coal in cement kilns and coal fired power plants. Biosolids must typically be dried to 90% TS or greater to make co-firing attractive to those industries.

Co-firing of dried biosolids is currently performed by the cement industry in a number of locations in Europe and in two locations in North America. Lehigh Cement owns a 2 million metric ton per year cement production facility in Maryland, which burns approximately 14,000 metric tons of dried biosolids annually, with plans to increase capacity to 36,000 metric tons per year. This represents approximately 3 to 5% of its average daily fuel use and is reported to have no adverse impacts to product quality (Maestri, 2009).

Gasification

Gasification is the thermal conversion of carbonaceous biomass into syngas, a gaseous fuel composed mainly of hydrogen and carbon monoxide, with impurities including carbon dioxide, water, methane, nitrogen gas, and tars. The conversion is accomplished by heating the biomass to temperatures of 500 to 1600°C under pressures ranging from 1 to 60 bar in the presence of a controlled supply of oxygen (Yassin, et al., 2005). Directly heated gasifiers are heated by combusting a portion of the feedstock. Alternatively, gasifiers can be indirectly heated with electric heating elements.

The moisture in biosolids can make it difficult to gasify without the addition of energy or blending with other materials, like wood waste. Before feeding biosolids to a gasifier, it is usually necessary to dry them to 50 to 90% TS, depending on the technology. Mechanical dewatering is preferred over heat drying, due to the high-energy use of thermal drying. However, mechanical processes can only dewater to about 20 to 30% TS. The need for thermal drying reduces the potential net energy output of the system resulting in insufficient energy for onsite electricity generation due to the additional energy necessary to drive off excess water. However, a major benefit of gasification over incineration is lower natural gas requirement (about 83% lower) (Tarallo and Kohl, 2015).

While the gasification of biomass is a commercial technology with many installations worldwide, there are limited commercial scale biosolids gasifiers, making it innovative with respect to biosolids. Gasification emissions do not fall under the USEPA municipal biosolids incinerator emissions requirements (SSI MACT), therefore reducing emission control requirements and permitting issues. Further restrictions on incinerator emissions may make gasification an attractive alternative in the future. Increased experience in the municipal biosolids market is necessary to develop further operational data and determine the economic viability of the technology/system. The following table describes the existing commercial, demonstration, and testing biosolids gasification facilities.

Summary of Biosolids Gasification Facilities

Vendor	Installation	Through-put	Description
KOPF	Commercial facility in Balingen, Germany operating since 2004	375 dry lb/hr	Solar-dried digested solids (75 to 85% solids) are fed to fluidized-bed gasifier. Gas is used in IC engines. Of the 0.5 kWh of electricity produced per kg of solids treated, 0.1 kWh is used to run the gasifier, and 0.4 kWh is used to displace electricity use of the WRRF.
Nexterra/ Stamford, CT WPCA	Testing facility in Kamloops, Canada	1354 dry lb/hr	Thermally dried biosolids (93% TS) fed to fixed-bed updraft gasifier. Tested solids from Stamford, CT WPCA in 2009.
Maxwest	Commercial facility in Sanford, FL operated 2009-2014	1800 dry lb/hr	Dewatered solids were received from several plants at an average dryness of 16% TS. Solids were thermally dried and fed to a fluidized bed gasifier. Syngas was combusted in a thermal oxidizer, from which heat was recovered to supply the dryer.

M2Renewables/ Pyromex	Demonstration facility in Emmerich, Germany operating since 2009	83 dry lb/hr	Solids are dewatered mechanically to 55%, then thermally to 80%. Ultra-high temperature gasifiers operate in the absence of oxygen. The source of oxygen and hydrogen for the syngas comes from the moisture in the feed. Gasifier is indirectly heated, producing high-quality syngas (63% hydrogen, 30% carbon monoxide)
Tokyo Bureau of Sewerage	Commercial facility in Kiyose, Japan, operating since 2010	8000 dry lb/hr	Thermally dried biosolids (80% TS) fed to a fluidized-bed gasifier. Heat from the syngas is recovered to dry the feedstock. Syngas is converted to motor power via an aeration blower or to electricity via an IC engine.
Aries Clean Energy	Full-scale facility in Covington, TN, since 2013 (July 2015 PHG Energy, now Aries Clean Energy assumed operation and fiscal responsibility for the system and operate for R&D)	12 ton/day	Uses downdraft gasifier to process wood waste and wastewater residuals. Wood is chipped, mixed with residuals, then dried before gasification. Syngas is combusted in a thermal oxidizer with heat recovered to drive an organic rankine cycle generator.
Aries Clean Energy	Full-scale facility under construction in Lebanon, TN, began operation in 2016 Plans for future facility in Pigeon Forge, TN planned to begin construction in 2016	64-ton/day	World's largest downdraft gasifier to process wood wastes, shredded tires, and wastewater residuals. Syngas will be combusted in a thermal oxidizer with heat recovered to drive an organic rankine cycle generator.
Sources: Greenhouse Gas Technology Center, 2012, and Aries Clean Energy, 2017			

Table 4: Summary of Biosolids Gasification Facilities

Pyrolysis

Pyrolysis is the thermal conversion of carbonaceous biomass in the absence of oxygen. Three products are generated through pyrolysis: a liquid fuel or bio-oil, a solid char, and combustible gas (Zhang et al., 2010). Pyrolysis processes are typically carried out at atmospheric pressure and temperatures ranging from 300 to 600°C (Venderbosch and Prins, 2010) and at lower temperatures than either gasification or incineration. The temperature and reaction time affect product generation. Slow pyrolysis, which occurs at low temperatures and low heating rates, maximizes char production; fast pyrolysis, involving moderate temperatures, fast heating rates, and short residence times, maximizes bio-oil production (Yurtsever et al., 2009).

Three fast pyrolysis facilities have tested the production of bio-oil from biosolids, with two installations in California and one in Australia. However, all three have ceased operations. Additional development is necessary to address technology limitations and costs that currently limit commercial implementation. One slow pyrolysis process has been operating successfully in Japan since 2007 (Oda, 2007). KORE Infrastructure recently completed a six-year pilot program to demonstrate its technology at the Los Angeles County Sanitation District (LACSD) facility in Carson. Following the successful completion of this pilot program, KORE secured entitlements to operate a commercial-scale waste conversion facility in Rialto to develop a biosolids processing facility to produce renewable natural gas (RNG) suitable as a transportation fuel (KORE 2018).

Thermal Conversion

The concept of applying thermal conversion to liquids is attractive, since it eliminates the need for moisture removal with reduced process energy requirements. Supercritical water (SCW) is a state in which water behaves as both a gas and a liquid and occurs at high temperatures (greater than 374°C) and pressure (greater than 221 bar). The gas-like properties of the SCW promote mass transfer, while the liquid-like properties promote solvation (dissolution). These properties, combined with high temperatures that increase reaction rates, result in a medium in which chemical reactions occur extremely rapidly. SCW oxidation is the complete oxidation of organic matter and achieves high destruction efficiencies of organics (greater than 99.99%) in reaction times less than 1 minute. However, the properties that make SCW a good reaction medium can also be a disadvantage, increasing the potential for corrosion in the reactor.

> Similar to incineration, supercritical water oxidation (SCWO) is the complete oxidation of organic matter. The key difference is that SCWO occurs in supercritical water.

The SCWO process has been used since the 1980s for military hazardous waste destruction. Heat can be recovered from the high-temperature, high-pressure liquid effluent for process needs or in a steam turbine to generate electricity. Carbon dioxide and nitrogen gas can be recovered as by-products for commercial sale. The use of SCWO technology for biosolids applications is still in developmental stages. Earlier super critical water systems for sewage sludge have experienced reliability issues due to build-up of salts within the reactor leading to frequent shut-downs (O'Regan, et al., 2008; Gidner et al., 2001).

Figure 2: Supercritical Water Oxidation Facility in Cork, Ireland

Genifuel's hydrothermal processing (HTP) of biosolids feedstock is receiving considerable interest. HTP was developed by the Pacific Northwest National Laboratory in partnership with other organizations in the research and development stage for 4 decades. HTP uses pressurized hot water at 350°C and 207 bar pressure to process wet wastes, such as dewatered solids, to create bio-crude oil and methane gas, along with an inert solids precipitate. Bench scale testing on was conducted with solids provided by Metro Vancouver, and the results showed greater than a 99% COD reduction in the effluent and a greater than 94% solids reduction. The bio-crude quality was approximately 80% of the heating value of petroleum crude and needs to be upgraded. (WE&RF, 2016). Further demonstrations of Genifuel HTP with biosolids are underway.

Bioconversion: Anaerobic Digestion

The bioconversion of chemical energy in organic solids, such as primary solids and waste activated sludge (WAS), is typically accomplished at many WRRFs using anaerobic digestion (AD). In AD, the readily biodegradable portion of the volatile solids is converted into biogas by microorganisms in the absence of oxygen. Modern digesters at WRRFs are high rate systems with supplemental heating, auxiliary mixing, uniform feed rates and solids thickening prior to digestion. High rate systems can be further categorized based on temperature: mesophilic (30-38°C) and thermophilic (50-60°C) (Kalogo, Y. and Monteith, H. ,2008). The most common AD system at WRRFs is the mesophilic AD system. This reflects the trend worldwide with digesters. Thermophilic digesters, mostly due to their higher temperatures, can digest material as much as 6-10 times faster than a mesophilic digester and often need less agitation or mixing. However, the heating requirements are substantial. If space exists for a larger digester that can process the organics more slowly, a mesophilic digester will more often make the most economical sense.

The produced wastewater solids derived biogas is composed primarily of methane (60 to 65%) and carbon dioxide (30 to 40%), with small concentrations of nitrogen, hydrogen sulfide, and other constituents. The methane portion of the biogas is a valuable fuel and, with conditioning, can be used as a renewable substitute for natural gas for many energy needs. After processing, the digested materials—the liquid and solids—can be turned into a wide variety of useful soil amendment products. Biogas systems can also recover nutrients.

U.S. Biogas Market

Today, the U.S. has over 2,116 sites producing biogas in all 50 states: 239 anaerobic digesters on farms, 1,241 WRRFs using an anaerobic digester, and more than 630 landfill gas projects. In a recent industry assessment conducted by the USDA, EPA and DOE (2015) as part of the Federal Biogas Opportunities Roadmap estimates nearly 13,000 sites are ripe for development: 8,241 dairy and swine farms and 3,681 WRRFs, which could support a digester, and 1086 untapped landfill gas projects. If fully realized, these new biogas systems could produce 41 billion kWh/year of electricity from 654 billion cubic feet of biogas/year. This is enough energy to power more than 3 million American homes or to produce the equivalent of 2.5 billion gallons of gasoline for vehicles, reducing emissions equivalent to removing up to 11 million passenger vehicles from the road. It would also result in an estimated $33 billion in construction spending, creating approximately 275,000 short-term construction jobs and 18,000 permanent jobs to operate the biogas systems and manage ongoing business activities.

Use of Biogas Systems at Water Resource Recovery Facilities

Currently operating WRRFs with AD/biogas systems range in size from over 300 million gallons per day (mgd) to as small as 0.32 mgd, bucking the rule of thumb that a WRRF must process at least 1 mgd to be able to economically support a biogas system. This suggests that another couple hundred AD/biogas systems might be developed in addition to those already recognized. For comparison, Europe has over 10,000 operating digesters and some communities are essentially fossil fuel free because of them. (ABC, 2018)

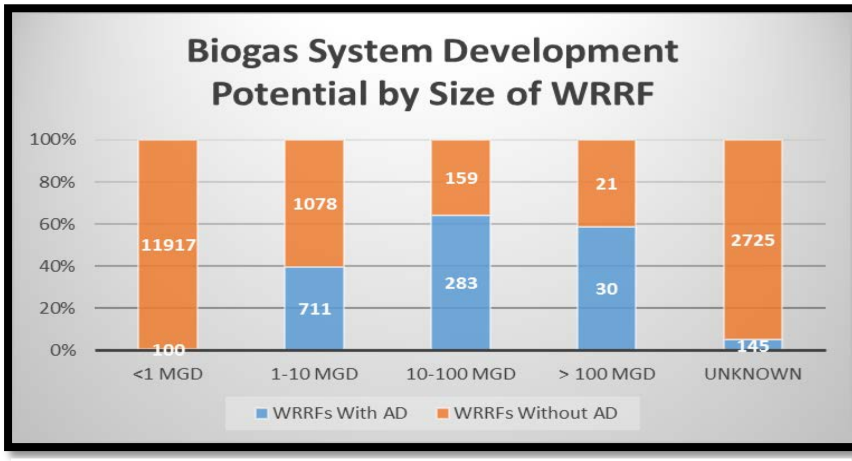

Figure 3: WRRFs ≥ 1mgd with Biogas Systems and Types

While only one quarter of the market for AD/biogas systems at WRRFs has been realized, in terms of the total number of biogas systems operational today, the majority can be found at smaller WRRFs that process 1-10 mgd. It is at the larger facilities, however, that AD/biogas systems have the most penetration—about 60% of all WRRFs greater than 10 mgd already have a biogas system. The larger the volume of wastewater solids, the larger the cost for the WRRF to handle the material and the larger the revenue potential if the organics can be managed on site to generate valuable energy with an AD/biogas system. For the WRRF, the biogas system can reduce post digestion biosolids handling costs and also save money through the generation of energy.

Biogas Utilization

For years, many in the wastewater and biogas industries have observed that large volumes of gas are being flared—wasted—since historically, the primary motivation for installing anaerobic digestion has been to reduce the volume of biosolids the WRRF has to handle. It is unclear how much gas is being flared. Even the most efficient facilities will flare occasionally when having issues with the equipment that uses the biogas.

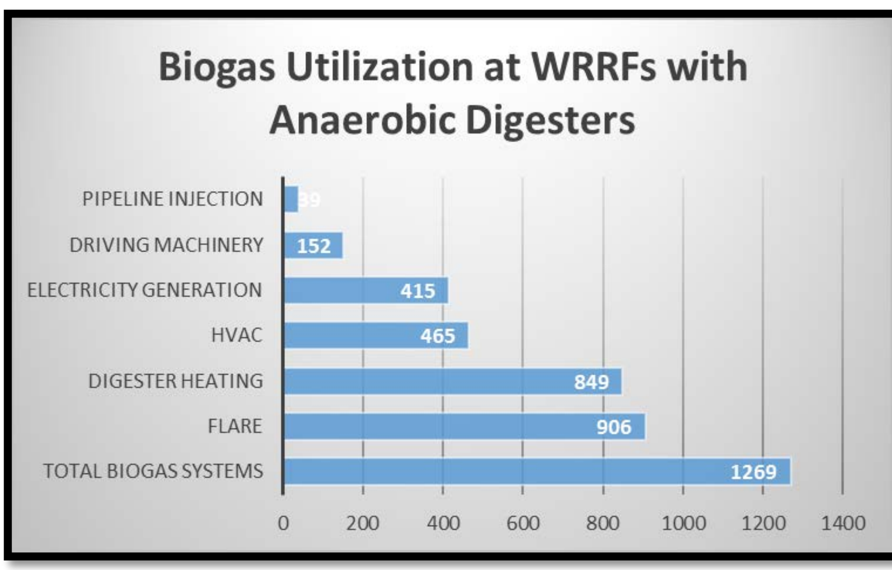

Figure 4: Biogas Utilization at WRRFs with Anaerobic Digesters

The biogas generated by AD systems is an extremely versatile fuel and can replace natural gas for heating and power generation needs. According to the WEF Biogas Survey, as of 2012, 85% of the WRRFs with AD beneficially used their biogas. With increasing fuel costs and sustainability concerns, many plants are trying to maximize the use of biogas in place of purchased energy. Beneficial use as heat for process needs or conversion to electricity or fuel was found to be more common in larger plants, with smaller plants burning biogas in flares.

The most common uses for biogas, other than flaring, include heating or cooling needs, and electricity generation—the most common energy needs at a WRRF. While a few facilities are upgrading their biogas to natural gas pipeline quality and selling it to the gas grid, only 39 facilities were doing this in 2016. The trend to upgrade biogas to renewable natural gas standards is increasing, primarily driven by Renewable Fuel Standards, air quality limits on IC engines in key areas like southern California, and increasing biogas yields from adding substrates like food waste.

Heat/Boiler

Heat recovery is by far the most common use of biogas, with a majority of facilities using biogas in boilers or recovering heat from CHP to heat digesters and/or buildings. The primary use of biogas at most facilities is digester heating. Biogas production is usually more than adequate for digester heating needs for all but the coldest months in colder climates and surplus biogas is often available during most months. Surplus gas can be used for building heat or other needs such as thermal drying or CHP. Surplus biogas can also be used in absorption chillers to cool buildings during the summer.

Combined Heat and Power (CHP)

With increasing fuel costs and sustainability concerns, many plants are trying to maximize the use of biogas in place of purchased energy. Increasingly, plants are using biogas in CHP systems to generate electricity from the biogas. Waste heat from the prime mover (turbine or engine) is used in the treatment processes or for building heat. The WEF Biogas Survey confirmed that 860 out of 1,269, corresponding to 68%, of plants with anaerobic digestion use their biogas to generate heat or power. This number is much greater than that reported by the U. S. EPA Combined Heat & Power Partnership (U. S. EPA – CHPP, 2011); that estimate was 104 plants which generated power. Power generation from biogas is particularly attractive in areas with high electricity rates.

The suitability of on-site CHP technologies varies with respect to size, fuel requirements, local air emissions requirements, efficiency, cost, and overall compatibility with the existing treatment processes. Biogas requires cleaning systems upstream of the combustion equipment for the removal of moisture, H_2S, and siloxanes and the level of gas clean up depends on the type of combustion equipment selected. Some established technologies, such as microturbines, are available in smaller capacities suitable for a range of WRRF sizes.

Comparison of CHP Technologies					
	Internal Combustion Engines	**Combustion Gas Turbines**	**Micro Turbines**	**Fuel Cells**	**Stirling Engines**
Development Status	Established	Established	Established	Emerging	Established
Size (kW)	110 – 3,700	1,200 – 4,700	30 – 250	200 – 1,200	~15 – 43
Electrical Efficiency (%)	30 – 42	26 – 37	26 – 30	36 – 45	~27
Thermal Efficiency (%)	35 – 49	30 – 52	30 – 37	30 – 40	~48
Equipment Cost ($/kW)	465 – 1,600	1,100 – 2,000	800 – 1,650	3,800 – 5,280	4,000 – 10,000
Maintenance Cost ($/kWh)	0.01 – 0.025	0.008 – 0.014	0.012 – 0.025	0.004 – 0.019	N/A
Biogas Cleaning Requirements	Medium	Low	High	High	Low
Emissions	Medium	Low	Low	Low	Medium
Source: Wiser et al., 2012 for IC engine, gas turbine, microturbine, and fuel cell data; Arespachaga et al., for Stirling engine data.					

Table 5: Comparison of CHP Technologies

The WEF survey found that 88% of the 292 WRRFs using biogas for CHP use either internal combustion (IC) engines or microturbines. Other CHP technologies, such as combustion gas turbines, are only economically feasible at the largest plants and are used by only 7% of WRRFs. Some locations with strict air quality regulations have turned to fuel cells (5% of WRRFs) with their clean emissions; however, current fuel cell economics often require financial incentives to make this technology attractive.

In addition to current CHP technologies, innovative technologies may become competitive in the future by reducing the need for biogas cleaning prior to use, therefore reducing overall complexity and equipment cost. Established and innovative CHP technologies are described in the following sections.

Internal Combustion Engines

Internal combustion (IC) engines are the most widely used CHP technology. They are often the most economical CHP technology for WRRFs and have combined electrical and heat recovery efficiencies higher than any other currently available CHP technology. Heat can be recovered from the engine jacket water and from the exhaust gas. The available size range for IC engines matches biogas production rates of most WRRFs, the technology is reliable, and available from a number of reputable manufacturers. IC engines typically have high power efficiencies relative to other power generation technologies. They are less sensitive to biogas contaminants than most other CHP technologies, reducing the gas cleaning requirements; however, cleaning is recommended to remove moisture, hydrogen sulfide, and siloxanes. One disadvantage of IC engines is their relatively high emissions as compared to other CHP technologies, such as microturbines and fuel cells. IC engine emissions can cause permitting difficulties in areas with strict air quality limits and may require additional emissions control, such as selective catalytic reduction to meet emission requirements.

Most IC engines installed since 2005 are lean-burn engines, with higher fuel efficiency and lower emissions than rich-burn engines, which were more commonly used before the 1970s. IC engine technology continues to improve. In 2001, national research laboratories, in collaboration with three large engine manufacturers, received contracts from the DOE to make further improvements to lean-burn engines. This resulted in a new generation of engines with even lower emissions and higher fuel-efficiency (Wiser et al., 2012).

The 370-mgd DC Water Blue Plains Advanced Wastewater Treatment Plant (AWTP) installed combustion gas turbines that will produce 10 MW net energy, providing energy for nearly half of the plant's total power demand.

Combustion Gas Turbines

Combustion gas turbines are often a good fit for the largest WRRFs. Like IC engines, combustion gas turbines are a reliable, well-proven technology available from several manufacturers. Large WRRFs in the U.S. use biogas-fueled combustion gas turbines for CHP with heat being recovered from the exhaust gas. Combustion gas turbines are relatively simple, containing few moving parts and consequently requiring little maintenance. While infrequent, the maintenance of combustion gas turbines requires specialized service (Wiser et al., 2012).

Microturbines

As the name suggests, a microturbine is a much smaller version of a combustion gas turbine. Microturbine capacities range from 30 kW to 250 kW and are often a good fit for smaller WRRFs with anaerobic digestion. Microturbines are relatively new, being introduced about 15 years ago. Microturbines have become the second most widely used CHP technology at WRRFs due to their small capacity and clean emissions. However, microturbine electrical efficiency is considerably lower than that of IC engines. They are available as modular packaged units that include the combustor, turbine, generator, and cooling and heat recovery equipment. Multiple units can be installed in parallel for higher capacity.

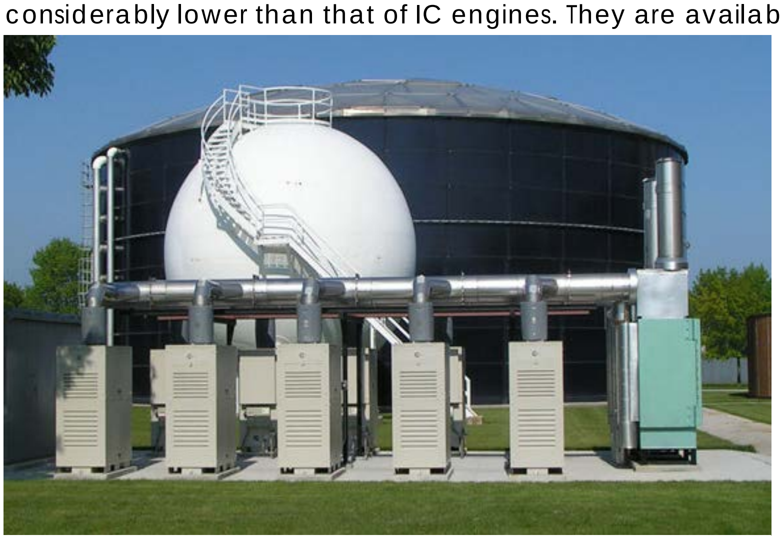

Figure 5: Microturbine Installation at the Sheboygan Regional WWTP

Microturbines require relatively clean fuel, increasing the performance requirements and cost of biogas treatment, but their exhaust emissions are among the lowest of all CHP technologies. Microturbines are currently available from two manufacturers (Wiser et al., 2012).

The Sheboygan Regional WRRF in Wisconsin has been successfully operating microturbines since 2006. The 10.5 mgd plant started with a generation capacity of 300 kW in 2006. In 2010, the plant added an additional 200 kW in order to use the increased biogas production resulting from their co-digestion program. The Sheboygan CHP installation is an example of positive collaboration with the electric utility. With the goal of adding biogas to their renewable energy portfolio, the local, privately owned power utility funded 80% of the capital cost of the microturbines (Willis, et al., 2012).

Fuel Cells

Fuel cells are unique in that they do not combust biogas to produce power and heat. Instead, fuel cells convert chemical energy to electricity using electrochemical reactions. Their benefits include high electric efficiency and extremely clean exhaust emissions. However, fuel cells are one of the most expensive CHP technologies in terms of both capital and operation and maintenance (O&M) costs. In addition, they are extremely sensitive to impurities in the biogas, requiring the highest level of biogas cleaning of all CHP technologies. For these reasons, fuel cell installations are typically limited to locations with strict air quality regulations and fuel cell-specific grants or incentives. For example, several installations in California have benefited from the Self-Generation Incentive Program (SGIP), which subsidizes the capital cost of fuel cells by $4,500/kW. Fuel cells suitable for use with biogas are currently available from only one manufacturer (Wiser et al., 2012). 19

Biogas Upgrading

Currently, only 1% of the biogas beneficially used is upgraded to natural gas quality for injection into the natural gas transmission system. Pipeline quality biogas has extremely low concentrations of contaminants and must be compressed to match the natural gas transmission line pressure. Biogas contaminants that must be removed include foam, sediment, water, siloxanes, hydrogen sulfide, and carbon dioxide. Technologies used for removal are listed in the following table. Following cleaning, biogas must be compressed for pipeline injection.

Contaminant	Removal Technology
Moisture	Water chiller
Siloxanes	Activated carbon or silica gel adsorption
Hydrogen sulfide	Vessel with iron sponge or proprietary media
Particulates	Particulate filters
Carbon dioxide	Pressure Swing Absorption, Cryogenic, Membrane

Table 6: Biogas Treatment Technologies

Biogas cleaning to pipeline quality has high capital and O&M costs. In January 2014, California adopted new standards for pipeline-quality biogas which requires a minimum heating value of 950-970 BTU/scfm or an average of 93% methane content. In addition, natural gas providers often have more stringent requirements before accepting renewable biogas. For example, the Southern California Gas Company requires a minimum heating value of 990 BTU/scfm or 96% methane. Biogas standards for pipelines also have specs for parameters such as CO_2, oxygen, water, hydrogen sulfide, ammonia and hydrocarbons (Shen, Y. et. al 2015).

If financial incentives are available, pipeline injection can become attractive as it can have lower operating costs, higher revenues, lower compression onsite, emission reductions as a result of offsetting transportation fuel, and limited required storage (WEF, 2016). As of 2016, there were at least seven WRRFs either already cleaning biogas to pipeline quality in the U.S. or in the development stage: NY City DEP, NY; San Antonio, TX; Newark, OH; Renton, WA, Phoenix, AZ, Raleigh, NC and Des Moines, IA.

Figure 6: BioCNG installation at Janesville, WI WWTP (BioCNG, 2012)

Biogas can be upgraded to displace CNG or liquid natural gas (LNG) in vehicles capable of using these fuels. In Europe, upgrading biogas to fuel vehicular fleets is an established practice whereas in the U.S. there are only a few installations. Purity requirements for vehicular fuel are lower than those for pipeline injection. The biggest barriers to CNG or LNG conversion are the lack of a widespread infrastructure for gas filling stations and the cost of vehicle conversion for CNG or LNG use.

Small-scale packaged CNG conversion systems and filling station equipment are available from a single manufacturer and include sulfur removal in a vessel with proprietary media, siloxanes removal in an activated carbon vessel and membrane carbon dioxide removal. There are currently three biogas CNG installations in the US: the Dane County, WI landfill, St. Landry Parish, LA WRRF and the Janesville, WI WRRF. Other facilities are currently in design stage, including Southwest WRF, St. Petersburg, FL, Lincoln, NE and Grand Junction, CO. The system in the photo has a 50 standard cubic feet per minute (scfm) capacity and can produce up to 275 gasoline gallon equivalents (GGE) per day (BioCNG, 2012).

Use of Biogas in Industrial Processes

There are several examples of efficient use of biogas by industries sited in proximity to WRRFs. In these situations, biogas that is untreated or minimally treated is provided to an industrial facility that utilizes the gas in its processes. For example, the Des Moines Metropolitan Wastewater Reclamation Authority sells 40% of the biogas it produces from co-digestion of wastewater solids, FOG, and other high strength organic residuals to a neighboring industrial facility (Greer, 2011).

Beneficial Use of Digestate

In 2016, 59% of WRRFs with a biogas system are beneficially using their digested material. Based on anecdotal evidence, most facilities appear to give it away. At most, 22%, or 282 facilities, may sell their digestate. The American Biogas Council believes that digestate is significantly undervalued and is working with the wastewater, agriculture, and food waste industries to create a standard testing and certification program for digestate with the hopes that validation of quality will help more facilities to sell their digestate, both increasing beneficial reuse and revenue.

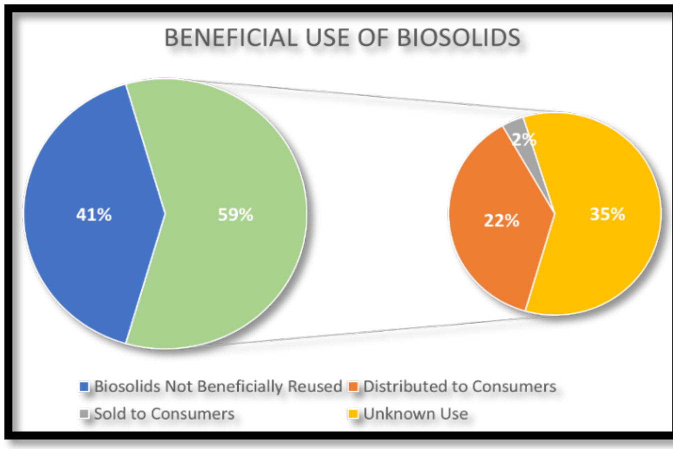

Figure 7: Beneficial Use of Digestate

Adding Food Waste to Anaerobic Digesters Located at WRRFs

Biogas yields increase by 25-50% when food waste (especially fats, oils and grease or carbohydrates) is added to an anaerobic digester when compared to manure or wastewater sludge digestion without this addition (Zahan, Z. 2016). Adding organic waste, usually food wastes, directly to anaerobic digesters at WRRFs, known in the water sector as co-digestion, is just beginning to catch on as a biogas enhancing mechanism. As of 2016, only 14% or 177 of the 1,269 operational biogas systems at WRRFs report adding additional organic material to their digesters (Goldstein, 2017). If a WRRF is considering adding food waste, there are reasons to do so:

- Additional revenue (or cost savings) generated from increased biogas production, and the electricity or fuel cost offset from this biogas.
- Additional revenue generated from tipping fees for accepting the food waste.
- Greater attainment of goals to increase environmentally sustainable practice. There are only two ways to recycle organic wastes: composting and biogas systems.

Although co-digestion has certain advantages, there also are concerns. Food waste, depending on the generator, can also include contamination and the impact of that contamination should be considered. Additional equipment may be needed for pre-processing, and some food wastes require additional processes or operational changes to make this work, but it can be well worth the extra effort.

Overview: Co-digestion of Organic Waste with Wastewater Solids

Co-digestion consists of adding readily biodegradable feedstocks, otherwise considered as waste by-products, directly into a digester located at a WRRF to co-digest them with wastewater solids. Fats, oils, and grease (FOG), for example, have high energy content and are readily biodegradable by anaerobic bacteria. Other high-strength organic wastes (HSWs) can also be co-digested to increase biogas production.

Types of High Strength Organic Wastes Being Co-Digested at WRRFs based on Survey Data:

HSW Type	Response Percent	Response Count
Fats, Oils, and Grease (FOG)	71%	20
Food Industry Waste (FIW)	61%	17
Septage	25%	7
Animal Processing Waste	18%	5
Post-Consumer Food Waste 14% 4	14%	4
Other	39%	11

Table 7: Types of High Strength Organic Wastes Being Co-Digested at WRRFs based on Survey Data

Source: Van Horne 2017.

Wastewater solids as a single feedstock have a low C:N ratio and relatively low biodegradeability (Shen, Y. et. al 2015). Co-digestion promotes biogas production through the higher loading rates possible by adding HSWs, which maximizes the cost-effective use of AD tankage for more biogas production per unit volume of digester tank. As a result, co-digestion of HSWs with wastewater solids represents an opportunity for WRRFs to increase biogas production using existing digester capacity. Co-digestion programs at WRRFs have resulted in rapidly growing body of operating practices in recent years (Appleton, A.R. et. al 2017) (Lackey, K., Fillmore, L. 2018).

FOG is the most common HSW co-digested with biosolids. Food Industry wastes from food processing, breweries, cheese and yogurt production are also common co-digested feedstocks. Animal processing by-products and food waste from institutional sources, such as school cafeterias, comprise the other typical co-digestion feedstocks (Van Horne, 2017). Feedstocks may include biodiesel production wastes and de-icing operations (glycols). Data regarding HSWs (post-consumer, institutional, commercial, or industrial sources) that have been successfully treated through co-digestion is part of WE&RF/NYSERDA research (Appleton, A. R. et. al (2017). This research expands upon previous WE&RF research (Parry, D. (2014) which focused on FOG, glycerol and cheese whey, and the suitability of these feed stocks for co-digestion.

A recent study which includes a comprehensive survey of WRRFs with varying levels of experience with co-digestion was conducted to best understand the different elements considered during the various stages of project implementation (Van Horne, M. 2017). A main goal of this survey was to identify the primary operational impacts that result from the receipt, pre-processing, digestion, residual handling, and dewatering sidestream management of the various high strength organic materials. Most WRRFs acknowledged the large capital expenditure required to construct a receiving and pre-processing facility, but indicated that pretreating the HSW was critical to project success.

Generally, the surveyed WRRFs indicated that there was no specific HSW threshold that resulted in operational issues; however, a few facilities operated conservatively (i.e., below general rules of thumb for digester loadings) in an effort not to disrupt operations. Only two responding WRRFs indicated a minimal need for additional operations and maintenance time due to co-digestion.

State of Co-Digestion Practice and Future Direction

Because of these benefits, most of the pilot-testing and research on co-digestion has focused on the effects of the additional HSW on digester performance, especially biogas production. HSW addition can potentially alter digester rheology, cation balances, and other characteristics; therefore, altering digester performance and downstream processes either positively or negatively (Higgins, et al., 2016). In a literature review of European co-digestion experience, researchers examined the co-digestion practices that enabled European WRRFs to advance co-digestion to better recover organic wastes, utilize existing, available digester capacity and generate renewable biogas (Rauch-Williams, T.; Schaum, C. 2018). Accepted procedures leading to more rigorous guidelines and consistent industry practice are emerging (Lackey, K., Fillmore, L. 2018). However, the relationship between fundamental properties of HSW and their effects need to be further researched under various anaerobic digestion configurations and dewatering processes to fully determine trends, interactions, and correlations between operational practice and performance.

Massachusetts: Advancing Co-digestion in Organic Action Plan

As part of the Massachusetts Organics Action Plan, the Massachusetts Department of Environmental Protection (DEP) banned certain large scale (e.g. institutional) organic wastes from landfills on October 1, 2014. While waste diversion is a primary goal, a cornerstone of its policy is supporting renewable energy in the state through its Clean Energy Results Program (CERP). Under the CERP, launched November 2011, MassDEP will continue to bolster energy efficiency and renewable energy. MassDEP will encourage expansion of recycling/ conversion of organics to renewable energy (via anaerobic digestion) with the goal of diverting 450,000 tons per year of organics from landfills and incinerators by 2020 and increasing energy production from aerobic and anaerobic digestion to 50 megawatts (from under 10mw today)."

Additionally, the state began funding efforts in 2012 to meet its long-term goals. With that funding, a number of MA utilities have assessed either constructing digestion facilities in their towns or co-digesting food wastes at their wastewater treatment facilities. At least one utility, the Greater Lawrence Sanitary District, has received grants (a total of $5,900,000) from the state to support the installation of a new digester, food waste receiving facilities, and a CHP (Mosher and Weare, 2015). Once complete, the facility is expected to meet up to 40% of the state's diversion goals and will produce more than 27 million MWhrs of electricity per year (Mass DEP, 2016) with 2-1.5 MW engines.

Drivers for Co-digestion Practice

Energy for wastewater treatment operations is a huge cost element for utilities. Energy is the second or third most expensive item in a wastewater utility's operations and management budget. Any effort to reduce purchased energy requirements benefits the utility by not only lowering operational costs, but also by decreasing its carbon footprint and increasing the sustainability of the operations. The impacts go beyond the utility boundary when a utility decreases its net energy use, since the local and national communities also benefit from increased energy security and fewer greenhouse gas emissions.

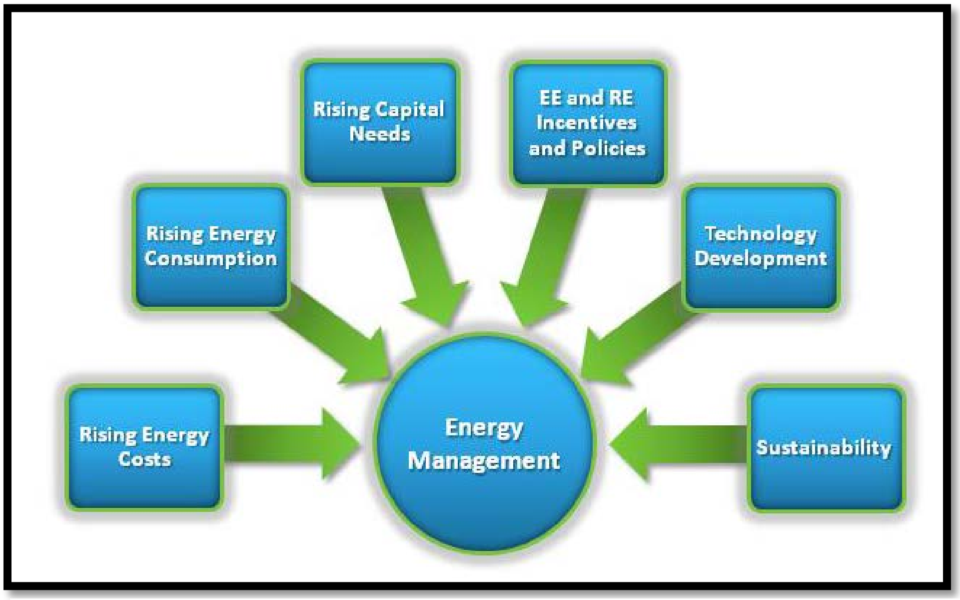

Figure 8: Factors driving utilities to reduce net energy consumption (Fillmore et al., 2011)

Financial Benefits

Co-digestion can add revenue streams through tipping fees, as well as reduce costs through additional gas production. However, recent energy efficiency and production study results revealed several financial and local barriers to maximizing energy generation at WRRFs. The market availability of feedstocks for anaerobic co-digestion was more of a limiting factor for energy recovery potential than digester capacity or operational constraints (Tarallo and Kohl, 2015). The market demand and fee structure for HSW are critical elements for a successful co-digestion program (Parry, D. 2014). Other notable economic factors include the need to upgrade or retrofit existing AD facilities to accept and manage the HSW and to accommodate the additional biogas production (Shen, Y. et. al. 2015).

Integrating Service with Community Food Waste Management Programs

The co-management of wastewater residuals and source-separated organics (SSOs) from municipal solid waste is increasing. Zero waste initiatives that seek to maximize the diversion of organics away from landfills across the U.S. are, in part, driving innovation and resource recovery at WRRFs. A 2014 survey indicated that 9 states had mandates to divert these materials from landfills and 18 states have disposal bans (Platt and Goldstein, 2014), with the number of states (and cities) with diversion mandates expected to grow. In the New England region, landfill disposal bans went into effect in Vermont, Connecticut, and Massachusetts in 2014 and in Rhode Island in 2016. All four states have revised their solid waste regulations to accommodate organic recovery options, but neither Connecticut nor Rhode Island has standards for co-digestion of food wastes at WRRFs (Jones, C. 2017).

The trend toward digesting FOG and food wastes at WRRFs has created a regulatory conundrum which stems from the traditional handling of these wastes under solid waste regulations (specifically the Resource Conservation and Recovery Act Subtitle D, which covers non-hazardous solid wastes, and 40 CFR Part 258, which covers landfills). Biosolids digestion, however, is regulated by Clean Water Act requirements. The question of how to permit co-digestion facilities is complicated by the fact that neither solid waste nor water-quality regulations were intended – or are well equipped – to accommodate mixed biomass recovery in digesters. Because solid waste and wastewater permitting are generally state-level activities, solutions are appearing at the state level as well. States can also be more agile and flexible than the federal government and are better positioned to enact changes to support local conditions and demands.

Although many states are grappling with this issue, several have already identified paths to facilitate resource recovery in WRRF-based digesters. The digestion of wastewater solids at Ohio WRRFs, for example, is regulated by the Ohio Environmental Protection Agency's Division of Surface Water through the National Pollutant Discharge Elimination System (NPDES) program, while food waste processing is regulated through the Division of Solid Waste and Infectious Waste Management. Faced with requests to process food waste in WRRF digestion facilities, the state has assigned primacy to the Surface Water Division for permitting involving biosolids but provides for feedback from other relevant divisions during the permitting process. This general permitting framework (primacy for one agency, in collaboration with others) is also applied for digesters at Concentrated Animal Feeding Operations, with the Department of Agriculture leading the permitting effort; facilities digesting other materials (i.e. that do not include biosolids or manures) are usually permitted through the Solid Waste Division (Greer,D. 2009).

Potential to Increase Biogas for Energy Recovery

Since co-digestion increases biogas production, it presents numerous opportunities for renewable energy recovery. Co-digestion can improve the economies of scale for on-site power generation, especially at small facilities. At the Village of Essex Junction WRRF in Vermont, co-digestion improves biogas production, allowing this small 2 mgd plant to run a successful CHP system. Fueling two 30-kW microturbines with biogas, the plant has reduced its electricity costs by 30% and is receiving renewable energy credits (RECs) for the electricity it generates (Willis, et al., 2012). The Derry Township Municipal Authority, PA has a separate receiving and treatment system for its imported wastes and has been co-digesting since 1991. Increased biogas production has been observed which correlated to the amount of outside wastes received. Annual power and heat recovery savings resulting from the project are estimated at $150,000 (at $0.10 per kWh) and $47,000 (at $2.365 per gallon of fuel oil), respectively (Van Horne, M.; Stone, L., 2017).

Renewable Fuel Standard

EPA developed the Renewable Fuel Standard (RFS) program in response to the 2005 Energy Policy Act as a mechanism to ensure that transportation fuels contain a minimum volume of renewable fuel. In 2007 the program was significantly expanded in response to the Independence and Security Act (EISA). By 2022, the RFS requires the use of 36 billion gallons of renewable fuels, including 21 billion gallons of advanced biofuels (derived from biomass and cellulosic materials).

Eligibility requirements for the RFS have evolved over the years but, until July 18, 2014, fuels derived from digester biogas at municipal WRRFs were classified as "advanced fuels". The EPA changed the classification of biosolids-derived fuel to "cellulosic fuels" (USEPA, 2014), a key distinction that can impact the economics of recovering digester gas. Specifically, EPA announced that the following "fuel pathways" meet the life-cycle GHG reduction requirements for cellulosic biofuels established under the RFS program:

- Compressed natural gas produced from biogas from landfills, municipal WRRF digesters, agricultural digesters, and separated municipal solid waste (MSW) digesters.

- Liquefied natural gas produced from biogas from landfills, municipal WRRF digesters, agricultural digesters, and separated MSW digesters.

- Electricity used to power electric vehicles produced from biogas from landfills, municipal WRRF digesters, agricultural digesters, and separated MSW digesters.

EPA notes that the inclusion of these fuels in the RFS program will help achieve program goals and, in many cases, provide credits (known as Renewable Identification Numbers, or RINs) to biofuel producers. Each gallon of renewable fuel in the RFS program equates to one RIN, which can be bought and sold as a commodity. For additional information, see WEF fact sheets*: Renewable Identification Numbers: A Guideline for Water Resource Recovery Facilities* (WEF, 2016a), and *Biogas to Renewable Natural Gas (RNG): A Guideline for Water Resource Recovery Facilities* (WEF, 2016).

Cellulosic fuel eligibility increases RIN value compared to advanced fuels. For example, in 2015, advanced biofuels (or D-5 RINs) traded for $0.70 to $0.90/gallon ethanol equivalent (GEE); cellulosic fuels (D-3 RINS) can provide a premium (added to the D-5 RIN) of $0.40 to $0.80/GEE (Willis, et al., 2015). Willis also notes that the potential value of biogas-derived vehicle fuels – and the potential return on investments – is further enhanced when the relative energy content of these fuels (compared to ethanol) is considered. However, the co-digestion of HSW, even food waste and SSOs, does not contribute to the biogas eligible for the cellulosic RINS, only for the D-5 RINS (U.S. EPA 2014).

Renewable Energy Incentives

Most WRRFs use electricity generated from their biogas onsite to run equipment. Often this enables these projects to reduce electric power costs at the WRRF since the cost to produce electricity onsite can be lower than the rate of electricity purchased from power utilities. This is particularly true of the cost of electric power in certain regions (e.g. Europe, Hawaii). Never-the-less, the low cost of conventional energy creates a financial barrier for many biogas recovery projects due to an unattractive return on investment. Limited capital funding and perceived lack of financial viability are prominent potential barriers to energy projects. Local policy and energy market conditions such as electrical rates, outside funding support, and availability of low-cost technical assistance can play a significant role in addressing these barriers (Willis, J. Andrews, N. et. al, 2015).

A feed-in tariff (FIT) is an energy-supply policy supporting the development of renewable power generation. In the United States, FIT policies provide a guarantee to eligible renewable generators that their utility will be required to purchase either electricity, or both electricity and the renewable energy attributes (USDOE, 2018). FITs typically guarantee interconnection with the grid to renewable energy projects, and renewable power generators are provided a fixed, above-market rate for a term of years. FITs provide an income structure that can be leveraged in a public-private relationship. Germany has years of experience with FITs (Rauch-Williams, T.; Schaum,C. 2018). Only a few states have FIT policies, but notable among them is California, which hosts several WRRF based energy generation projects (Hammond, E. 2017).

Net metering gives an electric utility customer the ability to supply electricity to the electric grid. This type of metering is useful to a WRRF when onsite generation exceeds the electric demand and the facility is able to become a net exporter of power. Net metering enables a WRRF generator get “credit” for exported power and “recover” the power at a later time, as long as their power produced does not exceed the power purchased. Local net metering and wheeling provisions affect the ability of a wastewater utility to be compensated fairly for exported power produced by biogas generation facilities. Without net metering, facilities are forced to sell their excess power at a low wholesale rate or not allowed to export at all. Net metering policy and goals are established by each state and differ nationwide (Willis, J. Andrews, N. et. al, 2015).

State Renewable Portfolio Standards

Renewable Portfolio Standards (RPS) (mandatory) or Goals (voluntary) are policies that encourage specific increases in renewable power generation in a state’s electric power generation mix. As noted in the UOTF publication (NACWA, 2013), nine states with an RPS (approximately 30 states currently have an RPS/G) do not include biogas-based generation as an eligible resource, reducing the incentives to invest in or buy power from these sources. Other states, such as California include “bundled” biogas, such as digester gas or landfill gas, as eligible renewable RPS generation as long as the power is exported directly to the California electrical grid. The RPS goals are 25% by then end of 2016 and 33% by 2020. New York state also includes digester gas as eligible renewable RPS generation with their current RPS goals of 30% by 2015(Willis, J. Andrews, N. et. al, 2015).

Other Local Programs and Goals

Renewable-Energy Certificates (RECs) represent the environmental attributes of one megawatt-hour of renewable generation. In states with RPS there is a compliance market for RECs. In other states, only voluntary RECs may be traded. If a wastewater utility obtains compensation for RECs, they are selling all benefits, emissions reductions credits, environmental air quality credits, offsets, etc. REC brokers connect renewable power producers with electrical utility customers that need to purchase RECs to comply with RPS goals. In general, the recent value of RECs has been very low. Compliance market RECs have some value, but the market for voluntary RECs is essentially nonexistent (Willis, J. Andrews, N. et. al, 2015).

Some states and regions have developed tracking structures to support REC trading. For example, in 2012, New York Assembly Bill A6114-C required the New York State Energy Research and Development Authority (NYSERDA, 2017) to establish a generation attribute tracking system (NYGATS) that records electricity generation attribute information within the state. It also requires

NYSERDA to process generation attribute information from energy imported and consumed within the state, in part to support the market for tradable RECs. Biogas CHP systems qualify as a "Customer Sited Tier" or "main tier" under New York RPS standards, with NYSERDA administering the procurement process for renewable energy that is counted toward the RPS. In California, compliance RECs are traded to facilitate electrical utility compliance with California's RPS. The California Public Utilities Commission has developed a "RPS Calculator" modeling tool that develops plausible portfolios of renewable resources that meet California's targets (CPUC, 2018). In August 2015, California passed a new bill (AB 1144) to reclassify the unbundled RECs from wastewater treatment plant renewable generation as Tier 1 RECs, dramatically improving their value and marketability.

Greenhouse Gas Reduction

Community interest in being good environmental stewards can be a motivator for advancing renewable energy/biogas projects. Many communities exert "cultural pressure" for community-wide sustainability and greenhouse gas (GHG) emission reduction which is part of the renewable energy picture. For example, the Western Lake Superior Sanitary District (WLSSD) in Duluth, MN operates in a community that places a high priority on environmental issues, including energy. The District has publicly communicated its biogas plans to local news outlets and produced a compelling "Roadmap to Sustainability" document outlining its energy program to its ratepayer community (Willis, J. Andrews, N. et. al, 2015).

Barriers: Economic and Others

Many of the barriers to energy recovery from biosolids are shared with the renewable energy industry at large. A survey of more than 200 respondents combined with the results of several focus groups identified the combination of economics and utility/community decision making practice as the foremost barriers to energy recovery projects at WRRFs (Willis, J., et.al. 2012). Economic barriers related to higher priority demands on limited capital resources or to perceptions that the economics do not justify the investment are common. For example, many decision makers rely on simple payback targets of less than a decade for energy projects that have a much longer asset life, omitting net benefits and savings over the whole term of the project. In addition to the dominant economic barriers, the figure below illustrates the importance of other barriers, many often related to common business decisions for energy projects within the water sector.

Economic barriers in general result from the enormous difficulties that come from having to compete with the fossil fuel industry. These economic barriers are often reinforced in the U.S. through legislation that does not recognize the renewable energy benefit from biogas, particularly the biogas generated from wastewater solids.

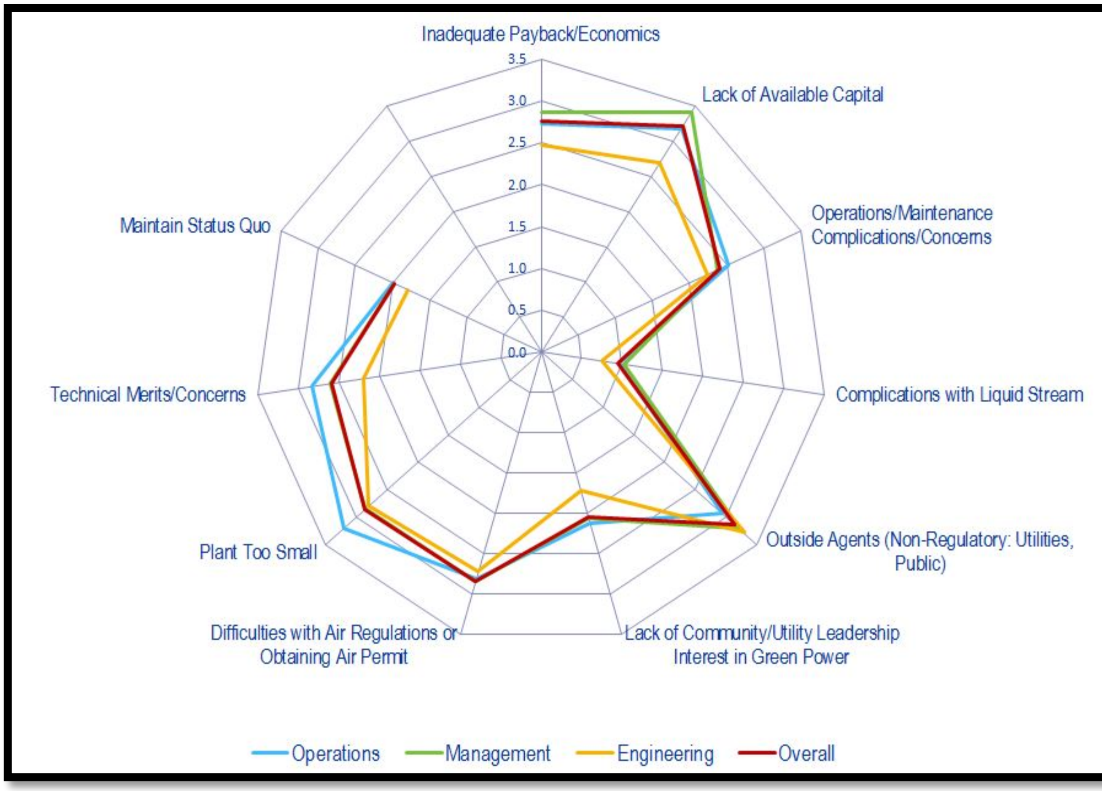

Figure 9: Key barriers to biogas use, as perceived by WWTP operators, managers, and engineers (Willis, et al., 2012)

Unexpected Limits to Return on Investment

NYSERDA, providing significant financial and robust programmatic support to WRRFs considering recovering electric power from wastewater-derived biogas, observed that relatively few New York State wastewater utilities moved forward with anaerobic digestion and biogas utilization projects (Andrews, N. 2017). Many of these projects were abandoned during the feasibility study stage due to plant specific limits to their return on investment from these energy recovery projects. Electric power rates vary between electric utilities, often driven by the electric utilities' function for either production or distribution, particularly in deregulated states such as New York where electric power distributors obtain their electricity from the competitive wholesale electricity market and many WRRFs have negotiated very favorable electric rates. Other barriers were found in the ways which individual electric utilities billed their industrial clients, including WRRFs. Negative billing provisions include significant demand charges, fixed standby fees, monthly minimum charges, and power factor or demand ratchets that erode the savings from reduced electric power consumption due to biogas CHP projects.

Andrews also found that WRRFs frequently under-valued non-monetary benefits of biogas projects. The benefits to communities and WRRFs of biogas projects that are often not fully considered include environmental and resiliency benefits. CHP projects at WRRFs increase diversity in the energy supply and provide a cost-effective fuel source to meet mid-day peak demand (Shen, Y. 2015). Project viability decision making should be based on whole life cycle returns and include a triple bottom line assessment to capture the non-monetary benefits. The wastewater industry also has increasing interest driven by economics in using or selling biogas as vehicle fuel or for pipeline injection as an alternative to more conventional CHP systems in light of cellulosic RIN eligibility.

Community Engagement and Perceptions

As water service utilities, WRRFs are often compelled to maintain low water and sewer rates. Although reductions in purchased energy costs from generating biogas can minimize operating budgets and help control sewer rate increases, the capital outlay to enable such projects and the financial risk of undertaking discretionary services, such as energy recovery or power generation, are often not popular with segments of the local community. Negative public sentiment or press coverage of an energy generation project can kill the project. As demonstrated in Rockland County, NY, unfavorable press coverage caused political backlash and brought a CHP project to a halt despite significant financial benefits (Hammond, et.al. 2017).

Energy projects with financial incentives from outside sources, however, can advance positive public relations. “Big cardboard checks” and other public events can be used to promote projects. Utilities experienced with numerous energy projects recommend regular face-to-face interactions between staff responsible for energy and senior leadership, usually monthly, to encourage open communication and understanding (Willis, J. Andrews, N. et. al, 2015).

Co-digestion projects present an opportunity to build positive engagement with local industries. For example, co-digestion programs not only provide a revenue source for the wastewater utility, they can be a service to industries by providing a local, convenient way to recycle waste organic by-products. In the case of the Des Moines Wastewater Reclamation Authority, local industry also serves as a customer for biogas produced at the WRRF. Likewise, several other co-digestion feedstock programs have synergy within a joint mission with the local solid waste authority and food waste collection program.

Moving Forward in light of Uncertainty and Risk

Due to their heavily regulated operations and mission to protect both environment and public health, WRRFs are generally risk adverse. In recent studies, the most prominent risks due to biogas CHP projects, after economics, were perceived biogas quality and staffing requirement unknowns (Andrews, N. 2017). However, survey studies found that co-digestion and biogas recovery projects required very little in terms of changes to staff time or skill sets (Van Horne, M. Stone, L. 2017). Often the greatest staff skill concern rests with state requirements for handling compressed gas and steam, ability to deal with equipment failures, and high local labor rates for engine mechanics required for CHP equipment.

Because co-digestion programs bring new relationships with feedstock suppliers, co-digestion projects have unique risks that need to be considered over and above the risks from biogas to energy projects. These are procurement of feedstock, including competition for potential feedstocks from landfills or other solids recovery facilities, and feedstock compatibility and consistency. Understanding the likelihood of the risk and proven approaches to mitigating these risks are key decision points for WRRFs considering a co-digestion biogas to energy recovery project.

Driven by rising energy costs and sustainability concerns, utilities are recovering previously wasted resources – flared biogas and waste heat – to increase their energy self-sufficiency. While the shift in the biosolids industry from waste disposal to resource recovery is already happening (albeit slowly), utilities face barriers to implementing sustainable energy recovery systems. An economic and regulatory environment that facilitates and promotes energy recovery is needed to hasten this shift towards an economically and environmentally sustainable biosolids industry. Legislative support through consistent, reliable financial incentives could turn this around, given renewable energy the opportunity to have a competitive starting point in the energy race.

Sharing the Risks and Returns

If a public WRRF proceeds with an energy project, their rate or taxpayers bear most of the risks (e.g., design flaws, construction cost overruns, higher maintenance costs, missed demand projections). These risks influence decision making for energy projects because the public sector is not well positioned to mitigate certain risks. Project delivery methods have emerged that expand a project's net benefit, such as public-private partnerships (P3) because controllable risk is allocated, and the related decision-making authority is delegated to the party that can best influence, manage or diversify it.

In addition to reducing operating budgets, there is value in making the energy portion of a utility operating budget more predictable. This motivation is particularly relevant when advancing renewable energy projects. While it is not always possible to justify energy projects solely on an operating cost savings basis, it is important to identify all aspects of the "value added" in an energy initiative and build the program around these concepts (Andrews, N. 2017).

Delivery Methods to Implement Energy Projects

A P3 is a contractual, institutional, or other relationship between government and a private sector entity that results in sharing the duties, risks, and rewards of providing a service in which the government has an interest, recognizing that the government retains ultimate responsibility for ensuring that social needs and objectives are achieved. P3s enable WRRFs to capitalize on energy drivers while tapping private sector expertise, attracting investments, and enabling a better return on investment through private sector tax incentives. A number of energy project-related risks can be appropriately transferred to the private partner, strengthening the likelihood of a good return on investment. As of January 2017, 37 states including Washington, D.C. and Puerto Rico have state enabling P3 legislation (Hammond, E. et al. 2017).

Energy Services Company

Performance contracting with an energy services company (ESCO) can be an alternative approach for WRRFs to implement energy efficiency and generation projects. An ESCO is a commercial business that delivers operational efficiency improvements in a progressive design-build environment. The facility owner benefits from the savings and pays a fee to the ESCO in return. ESCOs provide a guarantee of energy savings, which are specified in a performance contract and also provide a financial guarantee to project lenders that the savings generated will cover the debt service for any new required equipment. A typical engineering savings performance contract (ESPC) involves four phases: investment grade audit, proposed ESPC agreement, project execution, and measurement and verification.

The ESCO approach was taken by the Upper Occoquan Service Authority (UOSA), VA with the primary goal of financial efficiency, which resulted in energy projects that maximized payback and minimized capital costs (Willis, J. Andrews, N. et. al, 2015). The energy projects included a cogeneration facility (848 kW IC engine) and blower replacement with high-efficiency gearless turbo blowers. Another utility, Frederick-Winchester Service Authority (FWSA), VA, is also using an ESCO approach for energy savings upgrades including lighting efficiency, blower replacement, and a green energy project comprised of anaerobic digestion, HSW receiving and co-digestion, and cogeneration facilities.

Performance contracting provides alternative delivery options to utilities to implement energy projects. Increasing experience in the water sector has led to the development of best practices for utilities and ESCOs to follow. Active participation between all parties during each phase of the contracting process is a necessity, especially during the investment-grade audit and verification steps.

Power Purchase Agreements

Power Purchase Agreements (PPAs), contracts between buyers and sellers of electricity, are an option for implementing specialized power generation projects. PPAs have advanced as a means of financing small renewable projects. At least twenty-six states, plus D.C. and Puerto Rico, authorize some form of third-party PPA. However, at least nine states, (including Florida), expressly disallow PPAs for certain circumstances such as solar PV. Interested WRRFs must examine the status of PPA authorization in their state and any requirements as to the terms (Hammond, E. et al. 2017).

The Denver Metro was a pioneer in PPA for implementing its 6 MW biogas turbine project in 2000. Building on the experience with PPA for solar projects, interest in this approach has grown in recent years for biogas utilization. The City of Thousand Oaks, CA implemented both solar and biogas PPAs. The collaboration inherent in a PPA must be appropriately managed to reduce financial and process risks to the wastewater utility. Contracts must clearly establish all relevant boundary conditions for capital and/or operations. PPA operation of biogas-fired CHP systems are in the middle of the risk spectrum, with WRRFs like Nashville MWS actively considering a third party own-operate arrangement for its biogas development. Many of these arrangements get additional traction based on the premise that enabling private enterprise can create more community support than having a public utility do it themselves (Willis, J. Andrews, N. et. al, 2015).

Collaboration with Food Waste Management Industry

Many WRRFs also believe that source-separated organics (SSO) programs are an example of a good fit for private-sector involvement (via contracts to provide pre-processed organic waste for digestion), especially if this function occurs outside the plant fence line. Recognizing the growing interest and regulation resulting in food waste diversion from landfills, several companies in the solid and food waste management industry sought new solutions for processing food waste streams in addition to composting or landfilling. Building on their expertise in managing food waste and source separated organics (SSOs), these firms have researched and developed centralized approaches to separate and process food waste to produce a product suitable for co-digestion by WRRF partners. For example, Waste Management (WM) pioneered the CORe® process which produces consistent high-quality slurry called Engineered Bio Slurry (EBS™.) This process was developed through collaboration between WM and Los Angeles County Sanitation Districts and tested during a 2-year demonstration project (Coker, C. 2017). The process can be tailored to the food wastes received and the needs of the co-digestion program, so that it can be used in other locations. The EBS is delivered by tanker truck to the WRRF receiving facility and unloaded into sealed storage tanks. The slurry transfer is odorless and WM pays a tipping fee of about $10/ton. WM also has demonstration pilots using food waste slurry for co-digestion feed stock and renewable energy recovery underway at the Newtown Creek Wastewater Treatment Plant with New York Department of Environmental Protection (NYCDEP 2013) and in Greater Lawrence Sanitary District, Mass. Organics to Energy Project (GLSD 2018).

Advancing Our Knowledge Base

Currently, the wastewater sector AD practitioners have significant interest to better understand the science of co-digestion for enhanced biogas production rather than relying on empirical observations from practice alone. In a 2017 National Science Foundation workshop, researchers working on these topics discussed with AD practitioners the science behind certain operational practices in order to advance the state of the science, provide real-world applications based on research results, and develop a consensus framework to guide the practice of co-digestion for energy recovery (Lackey, K. ; Fillmore, L. 2018 pending). Furthermore, developing a research roadmap is important to maximize planned research investments from the wastewater and food waste industries, as well as Federal agencies.

In order to advance co-digestion as a common program at WRRFs with anaerobic digester capacity, it is critical that the industry clarify terminology and definitions within this practice and assess feedstock quality/ constituents based upon standardized characterization methodology. The industry must agree on who will manage the definitions, and if they apply nationally or internationally. Other researchers have compiled and translated the extensive experience in Europe with the practice of co-digestion for the benefit of more WRRF AD practitioners (Rauch-Williams, T.; Schaum, C. 2018 pending). Practitioners and researchers agree there is a need to identify or develop accepted methods for characterizing co-digestion feedstocks. For example, COD, a metric that shows promise as having useful applicability to characterize the organic content of HSW, currently is determined in the industry by methods which are not directly applicable to food waste, which is not homogenous nor a liquid. Standard Methods for Water and Wastewater may not readily apply.

Although research into the co-digestion of HSW is underway and many studies over the last decade expand the understanding of factors affecting co-digestion practice that can predict digester upset, to further advance this understanding of operational issues and identify operational strategies, the industry must improve anaerobic digester modeling of co-digestion practices so to be more useful in predicting upsets and optimizing performance. Specific loading regimes, genomics, mixing, proper versus problem operations and resultant impacts on digester operation (i.e. foaming, rapid rise) must be predictable from the next generation of AD models. Based on dry solid production rates, the industry needs to understand fully how the different quality and quantity of feedstocks impact the characteristics in the sidestreams, biosolids, and biogas over the long term. This will enable practitioners to reliably develop the relationships between factors that influence economic decision making while enabling successful co-digestion programs.

The industry would greatly benefit from guidance based on the experience of co-digestion leaders. The topics that these guides need to cover include information on contracts for accepting feedstock and agreements with haulers. Guidance that specifically and comprehensively identifies and valuates potential nonmonetary benefits (including environmental and resiliency benefits) from co-digestion is needed. Further guidance to establish default values for unit cost or tables of cost to valuate soft benefits (short term) in a triple bottom line, life cycle assessment is desirable. The industry should examine different business models beyond the standard WRRF-centric model so to consider broader impacts to the community and the cross benefits to stakeholders.

Practitioners would like to see more information on viable funding mechanisms to fund co-digestion programs (including the necessary infrastructure for these programs) through public private partnerships (P3) and other structures to illustrate by example how utilities around the country fund their co-digestion projects (Hammond et.al 2017). More importantly, within a water-energy-food nexus in a city/community, different agencies need to work together and manage competing goals to ensure the viability of co-digestion programs. The greatest need is to work across states and different sectors to advance regulations and incentives that are more amenable to co-digestion. The wastewater industry needs to collaborate with American Biogas Council (ABC), the US DOE and Department of Agriculture as potential resources. (For example, there is an EPA Agstar program with data on ag codigestion that might provide relevant experience or data.) Finally, WRRFs need better communication connections with state regulatory agencies to inform them of the advances and benefits of co-digestion so that any lack of understanding of co-digestion or related training in this emerging opportunity does not hinder development of these projects.

Practitioners and the research community identified key research areas to advance the successful practice of co-digestion at WRRFs (Lackey, K.; Fillmore, L. 2018). These include, but are not limited to:

1. Comprehensive characterization of feedstocks for co-digestion using consistent, accepted analytical methods and parameters.
2. Assess best practices for preprocessing of food waste/source separate organic fraction of municipal solid waste for co-digestion.
3. Expand understanding of factors in co-digestion practice that can predict digester upset or have negative impacts (causes of instability, inhibition and overloading) and identify operational strategies.
    a. Further examine if the co-digestion of food waste means more biosolids produced or not and under what conditions/ranges. Conduct future assessments based on dry solid content.
    b. Conduct more intensive monitoring of microbial/chemical structure and function of digesters with different feedstocks to evaluate ideal FM ratio and develop a

basis for the FM relationship. Identify better metrics for M, assess online COD for F, and validate the ratio and stability.

   c. Examine operational factors for their relationship to predict digester upset, specifically rapid rise and to test operational strategies to mitigate upsets.

4. Catalog/Document/Create a database with the operating condition of current facilities to redefine the window where co-digestion facilities can successfully operate.
   a. Define acceptable (or typical) loading rate ranges for the co-digestion of specific feedstocks based on practice
5. Evaluate advances in sensors/monitoring which are available to predict potential for process upsets. Are there new technologies for measuring froth level?
6. Examine available technologies which reliably and accurately measure wet, unscrubbed biogas and its constituents.
7. Develop other products from co-digestion such as pre or post methane [volatile fatty] acids from fermentation or bioplastics.

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