An overview of biogas production and utilization at full-scale wastewater treatment plants (WWTPs) in the United States: challenges and opportunities towards energy-neutral WWTPs

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Abstract

Recently the United States Environmental Protection Agency qualified biogas from landfills and anaerobic digesters as a cellulosic transportation biofuel under the expanded Renewable Fuel Standard (RFS2). Biogas is a renewable fuel that can generate Renewable Identification Number credits for the producer. The wastewater industry may not be able to keep pace with this opportunity. Less than 10% of WWTPs in the US have currently produced biogas for beneficial use. Supporting growth of the biogas industry requires implementation of new practices and policies. In this review, the barriers, gaps, and challenges in deploying biogas production technology are identified. Issues are classified as economic, technical, social or regulatory issues. Some of the critical challenges to the economics of digester operations are the slow rate of biogas generation, the low energy content of the biogas, and the costs to upgrade the biogas. Currently there is little biogas utilization at US WWTPs. Most biogas is flared while some is used for onsite process heat and power production. Case studies of co-digestion of biosolids with organic wastes at field-scale show the use of co-digestion could overcome significant economic challenges including higher methane yield, more efficient digester volume utilization and reduced biosolids production. These findings could provide guidance in retrofitting existing facilities or in designing new biogas production and utilization systems. The RFS2 ruling increases market certainty, hence reduces risk. The evaluation of applications of co-digestion at WWTP scales ranging from 1 million gallons per day (MGD) to 375 MGD determined its potential feasibility for different types of digester operation, organic waste and loading rate as well as effectiveness of providing energy self-sufficiency at the WWTPs. This work could improve economics of anaerobic digestion at WWTPs, enabling viable and sustainable biogas industry and offsetting costs for waste water management.

Contents

1. Overview of WWTPs and sludge treatment in the US

There are 14,780 municipal wastewater treatment facilities in operation in the United States as of October 2014, treating an average wastewater flow of 32,345 million gallons per day (MGD, 1 MGD = 3,785 m^3/day) [1]. Municipal wastewater treatment accounts for 3~4% of entire nation's electrical demand, equivalent to 30.2 billion kWh per year [2, 3], adding over 21 million metric tons of greenhouse gas (GHG) emission annually [4]. Electric power consumption is the highest cost for operation of WWTPs, representing over 30% of the total operation and maintenance cost [5, 6] and up to 80% of the GHG emission at WWTPs [7].

Sewage sludge, the byproduct of the wastewater treatment process, requires treatment prior to final disposal, and sludge treatment accounts for as much as 30% of a WWTP's operating costs [8]. Sewage sludge can also be stabilized into biosolids. Biosolids are nutrient- and energy-rich materials, which can be utilized for land application as a fertilizer substitute and/or soil conditioner for carbon sequestration [9] as well as a feedstock for renewable energy production. At US WWTPs, approximately 6.5 million metric ton (dry weight) of sewage sludge are generated annually, and this volume increases with growing population [8]. Anaerobic digestion (AD) is a common technology for sludge treatment at US WWTPs. The US Environmental Protection Agency (USEPA) reports that 1,484 WWTPs digest sludge to produce biogas [10]. About 48% of the total wastewater flow in the US is treated with AD [11]. A typical biogas composition of digested sludge is methane (CH_4, 50~70%) and carbon dioxide (CO_2, 30~50%). However, less than 10% of those plants utilize biogas for heating and/or electricity generation to reduce the cost of energy consumption [10]. Most WWTPs with AD but without combined heat and power (CHP) technologies merely combust biogas in boilers and/or flare biogas. Wastewater treatment was the 8th largest anthropogenic source of CH_4 emissions (12.8 million metric tons of

CO_2 equivalent) in the US in 2012 [12]. CH_4 as GHG has more than 20 – 200 times the radiative forcing per gram of CO_2 depending on evaluation emission time horizon [13].

Biogas production can be the main source of GHG emission from WWTPs when it is not managed properly. Therefore, efficient biogas production and utilization at WWTPs can significantly reduce the carbon footprint for WWTPs.

2. Biogas production and utilization at US WWTPs

2.1. Potential of biogas production

If captured and managed efficiently, sludge generated at WWTPs could yield substantial energy in the form of biogas, potentially turning WWTP into a net energy producer rather than a consumer [14]. Table 1 shows the overall potential of WWTP sludge-derived biogas production in the US, based on different feedstock resource investigations.

AD of sludge is not only important to maximize the energy production, but also to minimize the overall treatment costs at WWTPs. Table 2 summarizes the benefits of biogas production from sewage sludge. Utilization of biogas for power and fuel as natural gas has many environmental benefits since it can be substituted for fossil fuels to produce electricity and vehicle fuel, reducing the carbon footprint of WWTP operations.

2.2. Biogas utilization with CHP technologies

Water Environment Federation (WEF) released their phase 1 database (http://www.wrrfdata.org/biogas/biogasdata.php) providing information about US WWTPs operating AD systems and biogas utilization. Greater than 90 % of the 1241 plants in the database operate their AD systems at mesophilic temperatures; 40 plants operate digesters at thermophilic temperatures, while 34 plants operate them at both temperature ranges. 1,054 plants utilize biogas beneficially for energy displacement and production including heating digester, heating on-site building, power generation, powering on-site machinery and pipeline injection. There are 270 plants producing electric power and 74 of them export power to the grid. These power-generating plants use single or multiple CHP technologies as follows: internal combustion (IC) engines, microturbines, gas combustion turbines and fuel cells. Figure 1 summarized the above key findings.

The 1,241 WWTPs were classified into 4 categories based on average flow rates: plants with average flow rate of 100-1000 MGD, 10-100 MGD, 1-10 MGD and less than 1 MGD. For each flow rate category, biogas utilization has been classified as flared only (no utilization), unknown utilization or utilized with and without pipeline injection. Biogas CHP technologies are further categorized as IC engine, gas combustion turbine, microturbine, fuel cell, and versatile facilities with and without power export.

There are 29 WWTPs with average flow rate of 100-1000 MGD with AD systems (Figure 2). 26 of the plants utilize biogas, with 3 of them injecting upgraded biogas into natural gas pipeline. The 3 plants with biogas pipeline injection are all located in California. There are 13 plants (45% of WWTPs in this category) that generate electricity; among them, 4 plants generate electricity from IC engine, 1 from fuel cell, 1 from turbine, and the remaining 7 plants generate electricity from various technologies (Figure 2B). There are 6 plants export electric power to grid, accounting for 21% of the WWTPs in this category.

There are 276 WWTPs with average flow rate of 10-100 MGD with AD systems (Figure 3), including 13 plants only flaring biogas without any other utilization, 2 plants with no utilization and 23 plants with unknown utilization (Figure 3A). The remaining 238 plants (86% of the WWTPs in this category) utilize the biogas, with 12 out of them injecting upgraded biogas into pipeline. There are 123 plants that generate power, accounting for 45% of all the WWTPs in this category (Figure 3B). Among the 123 plants, 74 plants generate electricity from IC engine, 4 from fuel cell, 6 from microturbine, 2 from turbine and the remaining 37 generate electricity from various technologies. There are 32 plants supply the electricity to grid, accounting for 12% of all the WWTPs in this category.

The majority (56%) of WWTPs (690 plants) have an average flow rate ranging from 1 to 10 MGD with AD system operation on this scale (Figure 4). There are 505 plants utilizing biogas, with 10 of those plants injecting upgraded biogas into pipeline, while 87 plants only flare the biogas (Figure 4A). Totally 125 plants generate power, accounting for 18% of all the WWTPs in this category (Figure 4B). Among them, 68 plants generate power from IC engines, 23 from microturbines and remaining 34 use other technologies. There are 30 plants (4% of WWTPs in this category) supply the power to grid. The smallest plant supplying power to grid has design flow of only 2.3 MGD, located in Coos Bay, Oregon.

Although it was suggested that wastewater influent flow rate of 5 MGD or greater are required to produce biogas in quantities sufficient for economically feasible CHP facilities [10], there are 96 WWTPs with average flow rate of less than 1 MGD reporting AD operation (Figure 5). 55 plants utilize biogas, while 15 plants only flare it (Figure 5A). None of the plants injects biogas into pipeline, probably due to the economic scale of operations. Most of the WWTPs (75) in this category do not have power generation capabilities, while 5 plants generate power using IC engines and 1 plant located in Dextar, MI even supplies electricity to grid (Figure 5B).

3. Barriers for AD application at US WWTPs

Before the USEPA ruling on qualifying biogas as a cellulosic biofuel under RFS2, it was difficult to economically produce and utilize biogas from WWTPs. Less than 10% of WWTPs with AD utilize biogas for heating and/or power generation. In this section, the barriers to biogas production and utilization at WWTPs will be summarized [15], with aspects associated with economic, technical, social and regulatory issues (Table 3).

One technical barrier is associated with costly biogas cleanup and upgrading (Table 3). Biogas contains CO_2 and other contaminants, which must be removed prior to utilization in many applications, for example, CHP technology, natural gas pipeline injection and biogas-derived vehicle fuel [16]. Technology selection for contaminants removal and biogas upgrading depends on the gas composition, gas quality specifications, and grid injection standards. Gas quality specifications depend on both its country and end point utilization [17]. Most European countries have their own gas grid specs for biomethane standards. For example, Sweden requires methane content of biomethane no less than 97% for gas grid injection [17]. In the US, California adopted new standards of pipeline-quality biomethane in January 2014, which requires the minimum heating value of 950-970 BTU/scfm (i.e. 35.4-36.2 MJ/m^3, or average 93% methane content). Some primary natural gas provider companies establish standards even more strict than California and some European countries. For example, SoCalGas (Southern California Gas Company) has its Rule 30, requiring a minimum heating value of 990 BTU/scfm (i.e. 36.9 MJ/m^3, or 96% methane content). Furthermore, biomethane standards also have specs for other parameters, including CO_2, oxygen, water, hydrogen sulfide, ammonia and hydrocarbons [17]. Several biogas upgrading technologies are commercially available and some state-of-the-art technologies are under development at pilot-scale. The technologies dominating the current market of biogas upgrading are water scrubbing and pressure swing adsorption (PSA). Furthermore, other new technologies, including amine scrubbing, membrane separation and cryogenic separation, have gained larger market shares in recent years leading towards a more balanced market [18]. Recently ionic liquid based membranes have been used for gas separation due to their substantial advantages over the conventional polymeric membranes, including high selectivity, tunable physiochemical properties, high thermochemical stability and high permeability [19]. This may become a promising technology applied in biogas upgrading and cleanup [20].

Another challenge is high interconnection requirements or tariffs for standby rates (Table 3). The utility companies play an important role in the development of the sustainable biogas industry. The WWTP’s daily electricity consumption and production peak in midday while prices also tend to rise in midday. The utilities may restrict the sales of surplus electricity and heat to the grid because of the reduction in their sales. Biogas production at WWTPs does not only increase diversity in the energy supply, but also provides a cost-effective fuel source to meet demand during the midday peak. Energy cannot be readily stored in electrical and thermal forms for rapid dispatch at WWTPs.

Understanding public perception of AD will be helpful to identify social barriers and gain acceptance. Assessments of public attitudes and knowledge regarding AD will assist policymakers, regulators, and WWTPs in developing and implementing systems that are acceptable to the public.

4. Strategies to overcome barriers

Recently biogas derived from landfills, WWTP digesters, agricultural digesters, and separated municipal solid waste (MSW) digesters, has been qualified by USEPA as a new pathway for cellulosic biofuel (category D3) to meet renewable volume obligations (RVO) under the RFS2 [21]. This ruling promotes production of biogas for transportation and generation of D3 RINs, which will accelerate the development of sustainable and viable biogas industry. The biogas can be utilized as compressed natural gas (CNG), liquefied natural gas (LNG), or as power for electric vehicles. By the time of this writing (March 2015), both CNG and LNG D3 RINs have been generated, but electricity credits have not been reported. Before releasing of RFS2, the cellulosic biofuel RVO by 2014 was 1.75 billion gallons. The cellulosic biofuel RVO by 2022 increases to 21 billion gallons. These volumes are far greater than the expected volumes for full utilization of biogas from WWTP. Hence, the RFS2 creates both a defined market and provides fungible financial incentives for biogas. Moreover, the costs of biogas production from WWTP digesters are significantly lower than those of cellulosic-derived liquid fuels [22]. Therefore the RFS2 can potentially overcome the economic barriers to digester operation and biogas production.

Table 4 lists the reported full-scale WWTP endeavoring to achieve energy self-sufficiency in North America and Europe and the strategies they adopt to overcome the barriers. Case studies will be used to review each strategy and investigate some examples from Table 4.

4.1 Co-digestion of sludge with organic wastes

4.1.1 Overview

Over 251 million tons of MSW are generated annually in the US [23], among which only 87 million tons are recycled and/or composted, while most MSW discards (164 million tons) are landfilled or disposed improperly. Landfilling may cause water pollution and soil contamination and landfill sites may become reservoir of pathogens. Moreover, landfills were the 3rd largest source of anthropogenic CH_4 GHG emissions (103 million metric tons CO_2 equivalent) in the US in 2012 [12].

AD is a better practice than landfilling for MSW management, attributing to high solid destruction efficiency (~90%) with biogas production, much smaller site space and reduced GHG emissions.

Sewage sludge is usually characterized by its low digestibility; therefore, performance of AD systems might be limited with such a single feedstock. Co-digestion of sludge with other organic wastes has received increasing attention in recent years, as WWTPs will potentially benefit from this practice in terms of various aspects described as follows.

First, co-digestion increases digester gas production. The improvement in methane yield resulting from co-digestion of sludge and organic waste has been widely reported [24-27]. Biogas production at new European co-digestion plants ranges from 2.5 to 4.0 m^3 biogas/day/m^3 digester tankage, whereas biogas production at the US WWTPs sludge only digesters ranges from 0.9 to 1.1 m^3 biogas/day/m^3 digester tankage [28]. Sewage sludge as a single feedstock is characterized by low C:N ratio (less than 10) and relatively low anaerobic biodegradability. Addition of carbon-rich co-digestion material can potentially improve the overall C:N ratio of feedstock towards the ideal range (20~30) for optimum AD performance [29, 30]. Furthermore, hydrolysis has been recognized as the rate-limiting step in sludge AD process [31, 32]. Organic waste rich in easily biodegradable matters such as carbohydrates and lipids can accelerate hydrolysis to provide more soluble substrates for subsequent acidogenic and methanogenic processes. The attractive co-digestion feedstock include fats, oil and grease (FOG), food waste and scrap, organic fraction of municipal solid waste (OFMSW), food/beverage processing waste (e.g. brewery waste, dairy product wastewater streams), energy crops, agricultural residues, livestock manure, biofuel by-products (e.g. corn-ethanol stillage, crude glycerol, spent microalgae) and other high strength waste (HSW). Figure 6 presents biogas yield and specific biomethane potential of various organic wastes as co-digestion feedstock. It should be noted that sewage sludge has a methane potential ranging from 240 to 340 L CH_4 per kg volatile solids (VS) loaded [28]. Hence, co-digestion of sludge with such organic waste will promote the overall AD performance for biogas production. Moreover, co-digestion allows higher organic loading rate of AD process, which will maximize cost-effective use of AD tankage for more biogas production per unit volume of digester tank.

Second, co-digestion will generate extra revenue for WWTPs with a tipping fee charge. For example, the tipping fee of food waste varies from $50 to $170 per dry ton in the US [33]. Economics is one of the most important driving forces for integration of co-digestion facilities at WWTPs. Revenue streams have to be greater than expenses by large margin to make a positive business case.

Third, co-digestion with enhanced AD performance will lead to an integrated waste-to-energy process with mixed feedstocks sourced locally. This practice is advantageous over separate AD or individual processing of each waste stream at different locations, because it provides more efficient use of the digester and the gas upgrading facility. However, the implementation of co-digestion into WWTPs faces significant site-specific and infrastructural hurdles to overcome. Several technical and engineering concerns associated with co-digestion occurring at WWTP digesters have been reviewed elsewhere [27, 34-36]. The key concerns are summarized as follows:

- **Need for facility upgrading/retrofitting at existing WTTPs:** installation and/or upgrades may include receiving station, storage tank, pipelines, pumps, mixers and biogas upgrade equipment and CHP facility; design criteria should be made to prevent process failure such as pipeline clogging, insufficient mixing and to enlarge digester volume
- **Design of new WWTPs in the future:** co-digestion should be added into the design criteria for design of new WWTP constructions in the future
- **Digestion instability:** high variability of co-digestion feedstock characteristics (variations in composition and volume) may cause process instability such as pH fluctuation due to rapid accumulation of volatile fatty acids (VFAs) in the digester. This may be alleviated by adopting a staged-AD process to separate hydrolysis/acidogenesis and methanogensis for enhanced process stability and methane production. Several US WWTPs have been reported implementing this technology [37] and some of them are presented in Table 4.
- **Digestion inhibition:** depending on composition of co-digestion feedstock, inhibitory substances may be generated during AD process, including ammonia (due to protein-rich organic waste), long-chain fatty acids generated from lipid-rich waste such as FOG and food waste and heavy metals (high concentration found in OFMSW).

- **Digester overloading:** co-digestion feedstocks such as FOG and food waste lead to high organic loading of digester resulting from their high volatile solids (VS) and chemical oxygen demand (COD), which may cause foaming issues and process upsets [38-40].

Co-digestion has been a common practice for many European WWTPs. Although it was estimated that 216 WWTPs in the US receive organic waste for co-digestion with sewage sludge [11], little information can be found in literature. Table 4 also presents the detailed information of 19 full-scale WWTPs incorporating co-digestion projects in the US.

4.1.2 Case studies

East Bay Municipal Utility District (EBMUD) wastewater facility with an average flow rate of 70 MGD is located in Oakland, CA , and became the first energy-neutral WWTP in North America in 2012 [41]. Various waste streams including FOG, food waste and winery waste are collected off-site and then transported to the waste processing facility with a capacity of 120 ton/day. The pretreated mixed waste pulp is fed into EBMUD's thermophilic digesters for co-digestion with sewage sludge, boosting the biogas production by almost 70%. EBMUD installed a 4.6 MW jet engine-sized turbine in 2012, which expanded the total capacity of its power generation station to more than 11 MW, enough to handle the current biogas production rate of 38,000 m^3/day. The biogas from the digesters is first subjected to moisture removal in the chilling unit and then passes through a series of activated-carbon canisters for siloxane removal. With the co-digestion project and upgraded CHP facility, EBMUD is producing electricity to meet 126% of the WWTP's electric power demand, while the surplus electricity is supplied to the grid. During fiscal year 2012-2013, EBMUD generated $2 million in revenue from FOG/food waste co-digestion [42].

Des Moines Metropolitan Wastewater Reclamation Authority (MWRA) WWTP treats an average flow rate of 59 MGD of wastewater from metropolitan Des Moines, IA area [15]. The WWTP has advanced secondary treatment facility for enhanced nitrogen removal. The city of Des Moines metro area has adopted the FOG ordinance mandated by the EPA since 2006, which requires each municipality to install a FOG control program to prevent sanitary sewer blockage and overflows. All food service establishments must have grease removal devices maintained by a certified grease hauler once they reach 25% of the design capacity. This was the key driving force for the plant to initiate their Bioenergy Master Plan in 2007 for co-digesting FOG and HSW (whey, food processing waste, biodiesel production waste and waste from dissolved air flotation of biodegradable packing plant) with municipal sludge. The plant receives 26 million gallons (98421 m^3) of FOG and HSW per year, averaging approximately 500,000 gallon (1893 m^3) weekly. The mixed feedstock generally consists of 42% of FOG and HSW and the remaining primary and secondary sludge [43]. Since 2008, MWRA has maintained a joint partnership with Cargill, whose oilseed processing facility is adjacent to the WWTP, to sell excess biogas to Cargill through a delivery system between the two sites. Nowadays the plant sells 40-50% of biogas to Cargill, generating $460,000 to $800,000 in annual revenue. The digester complex, gas distribution system and CHP facility were upgraded in 2010 to accommodate the increased organic loading rate and to generate energy from biogas more efficiently. The submerged fixed covers and internal draft tube mixers have been selected as effective strategies for better control and easier removal of foam. MWRA also installed two 1.5 MW cogeneration units to expand the power generation capacity from 1.8 MW (3 × 600 kW IC engines) to 4.8 MW. This came along with a PSA unit for biogas cleanup and upgrading. MWRA recently proposed to operate a biogas-based compressed natural gas (CNG) fueling station to utilize biogas in excess of 160,000 ft^3/day (4531 m^3/day) instead of flaring biogas [44].

F. Wayne Hill Water Resource Center (WRC) is one of the three WWTPs operated by Gwinnett County Department of Water Resources, treating 33 MGD of wastewater from northeast metropolitan Atlanta, GA [15]. The WRC started to co-digest FOG with sludge in 2012. Four FOG receiving stations have up to 75,000 gallon (284 m^3) daily receiving capacity. FOG and on-site sludge together with the sludge from Yellow River Water Reclamation Facility are digested in five 1-MG egg-shaped digesters, where FOG and mixed sludge are combined at volume ratio of 1:10 (Table 4). With FOG co-digestion, biogas production was increased from 425 m^3/hour to approximately 595 m^3/hour. Prior to its utilization at the CHP facility, biogas is purified by using refrigerant drying for moisture removal, iron sponge for H_2S removal and activated carbon based scrubber for siloxane removal. The biogas is utilized for boiler heating and subsequently upgraded to power a 2.15 MW IC engine. The power generation from the biogas CHP facility (~ 13 GWh/year) can supply approximately 50% of the plant's demand. FOG co-digestion and upgraded CHP systems can offer a simple payback period of 4 to 9 years [45].

South Columbus Water Resource Facility (WRF), with an average flow rate of 35 MGD, employs a novel $CBFT^3$ (Columbus Biosolids Flow-Through Thermophilic Treatment) process (Figure 7) consisting of a thermophilic continuous stirred tank reactor (CSTR) with mean cell residence time of 6 days, two thermophilic plug-flow reactors (PFRs) operated in serial with batch contact time of 30 min and two mesophilic CSTRs operated in parallel with HRT of 15 days each [46]. It should be noted that such a two-staged configuration was developed to separate hydrolysis/acidogenesis and methanogenesis for the AD process, in such a way the process stability and methane productivity can be enhanced [47]. This new process can also produce Class A biosolids for increased pathogen reduction. A 12,000-gallon receiving tank was installed in 2011 to initiate FOG co-digestion. With the $CBFT^3$ process coupled with co-digestion project, the biogas production rate is increased to 422 scfm (717 m^3/hr), which is enhanced by 25 to 50% compared to sludge-only digestion. The plant has two 1.75 MW cogenerators with 38% gross electrical efficiency, generating 1.38 MW net electricity which provides 40% of the plant's power demand. Moreover, the $CBFT^3$ process, FOG co-digestion and CHP operation will lead to a net GHG emission reduction of 9600 metric tons CO_2 equivalent per year. The payback period of CHP facility is estimated to be less than 10 years [46].

4.2 Sludge pretreatment

4.2.1 Overview

It has been widely accepted that pretreatment methods, such as thermal hydrolysis, mechanical disintegration and high-performance pulse technique, have the potential to double the biodegradability of sewage sludge and hence increase biogas production as well as biosolids' dewaterability [48-50]. Some technologies that have been applied successfully to full-scale WWTPs in US and Europe will be reviewed briefly, including Cambi™ (thermal hydrolysis), Exelys™-DLD (thermal hydrolysis) and BTA® Process (hydromechanical screw-mill).

4.2.2 Case studies

Blue Plains Advanced Wastewater Treatment Plant (AWTP), operated by District of Columbia Water and Sewer Authority (DC Water), is the largest plant of this kind in the world, averaging 370 MGD (Table 4), which provides advanced nutrient removal (i.e. nitrification and denitrification, multi-media filtration and chlorination/dechlorination) [51]. The plant used to generate Class B biosolids for land application by 100% lime-stabilizing and dewatering sludge (primary, secondary and nitrification/denitrification). Currently DC Water is implementing their new Biosolids Management Program (Figure 8) that includes four Cambi^{TM} thermal hydrolysis process (THP) trains (6 reactors each train) for sludge pretreatment, four 3.75 MG (14200 m^3) mesophilic anaerobic digesters for biogas production and three 4.6 MW gas turbines for power generation and heat recovery [52]. In each THP train, pre-dewatered raw sludge (TS ~16.5%) is preheated in the pulper tank to 97 °C for homogenization for 1.5 h and then treated in THP reactors at 165 °C and 6 bar for 20 min. The pressurized sludge is subsequently transported to the flash tank, where cell destruction occurs resulting from pressure drop. The sludge temperature is decreased to approximately 102 °C by flashing steam back to the pulper tank. THP generates hydrolyzed sludge (TS 8~12%) with lower viscosity allowing mixing at higher solids concentration and more readily biodegradable materials for subsequent AD process, which results in remarkably higher biogas production compared to conventional digestion. Biogas will be utilized to fuel the CHP facility to generate 11.8 MW of power and supply steam for THP simultaneously, which will not only offset 33% of the power consumption but also reduce the plant's GHG emissions by 40%. The THP-pretreated sludge can be fed to digesters at higher organic loading rates with reduced digester volume, which further enhances the economy of the project [53]. This process will also generate pathogen-free Class A biosolids for soil amendment. Blue Plains AWWTP will be the first facility in North America that adopts full-scale THP technology for sludge pretreatment prior to AD. This practice will potentially reduce the plant's carbon footprint by approximately 60,000 metric tons of CO_2 equivalent annually, resulting from biogas-based energy generation, elimination of lime for sludge stabilization and reduced truck use for biosolids disposal and transportation [52].

Csepel WWTP is an AWTP located in Budapest, Hungary with biological nutrient removal (BNR) process, treating an average flow of 350,000 m^3/day (93 MGD) [54]. Previously primary sludge mixed with BNR sludge were firstly pasteurized at 70 °C for 30 min and subsequently subjected to thermophilic digestion with 12-day HRT. With this configuration, electricity production (78.1 MWh/day) from a biogas fueled CHP facility could only offset 49% of the power demand. It should be noted that a significant proportion of the raw sludge fed into digesters is activated sludge from BNR units, which has a very low biogas potential. An Exelys^{TM} thermal hydrolysis system and a second digester (6300 m^3) operated at mesophilic temperature were recently incorporated in the plant, forming a unique Exelys^{TM}-DLD (Digestion-Lysis-Digestion) configuration to promote biogas production and power generation (Figure 9). The main difference between Exelys^{TM} and Cambi^{TM} processes is that Exelys^{TM} can handle sludge with ≥ 25% TS, while the latter has a design basis of 16.5% TS. However, Exelys^{TM} process does not have a recycle steam system and therefore it is more energy-intensive. The new biosolids management design (Figure 9) can potentially increase the electricity production to 106.2 MWh/day, improving the power self-sufficiency to 65% [54].

Baden-Baden WWTP is one of the very first co-digestion plants in Germany, which has been carrying out municipal biowaste/sewage sludge co-digestion since 1993 [55]. Prior to digestion, municipal biowaste and sewage sludge are firstly subjected to a BTA® hydromechanical pretreatment process consisting of a screw mill, a pulper, a hydrocyclone and a buffer tank [56]. The plant would need to upgrade the existing digesters to a two-stage AD process consisting of a hydrolysis reactor (473 m^3, HRT 23 hours) and two digesters (each 3,000 m^3, overall HRT 14.3 days) to accommodate the increased organic loading rate (sewage sludge at 220.5 m^3/day, municipal biowaste at 82.7 m^3/day and food waste 8.8 m^3/day) (Figure 10). All these rehabilitations will improve the biodegradability of feedstock by 18.5%, reduce the total HRT by 25%, and enhance biogas production by 12.8% [55].

4.3 Process optimization

4.3.1 Overview

Municipal wastewater contains 10 times as much energy as is required for treatment to meet the effluent discharge standards [57, 58]. However, there are many challenges to recover that energy for utilization in wastewater treatment. Among various units at a typical WWTP, aeration consumes the most energy used (54.1%), followed by AD (14.3%) and wastewater pumping (14.2%) [7]. Therefore, it is important for the WWTPs to reduce the energy demand of these processes towards energy self-efficiency, via using energy-efficient equipment and configuration optimization. Some examples of energy-neutral and net-energy-positive WWTPs will be briefly discussed as below, while detailed information can be found elsewhere [59-63].

4.3.2 Case studies

Strass WWTP in Austria is a net-energy-positive plant with an average flow rate of 6 MGD (Table 4). It has a two-stage activated sludge process consisting of a high-loaded A-stage (HRT 30 min; SRT 12~18 hours) for COD removal and a low-rate B-stage (SRT ~10 days) for BNR. Over the past two decades, the plant has adopted several strategies for process optimization to achieve 100% energy self-sufficiency. Firstly, the DEMON® process was implemented in 2004 for sidestream deammonification [64] in a single-sludge suspended-growth sequencing sludge reactor (SBR) system (500 m^3, capacity 300 kg N/day), which was operated under 8-hour cycle. This deammonification process based on anaerobic ammonia oxidation (i.e. anammox) can reduce energy demand for aeration by 63% [65, 66], compared to conventional nitrification/denitrification configuration. In order to prevent rapid nitrite (NO_2^-) accumulation (which inhibits deammonification) and secondary aerobic nitrification (NO_2^- to NO_3^-, catalyzed by nitrite oxidizing bacteria (NOB), which compete with anammox bacteria for available nitrite substrate) simultaneously, intermittent aeration is controlled by both dissolved oxygen concentration (0.06 ~ 0.3 mg/L) and pH level. Partial nitrification (NH_4^+ to NO_2^-) decreases pH, while anammox increases pH. The successful DEMON® operation relies on a tight pH bandwidth (0.01 unit) for aeration control [67]. With the implementation of DEMON® process, energy demand for sidestream BNR was reduced by 44%, from 350 kWh/day to 196 kWh/day; furthermore, the higher proportion of A-stage sludge fed into digesters increased the methane content of biogas from 59% to 62%. Secondly, ultra-high-efficiency aeration strips were installed to replace the conventional fine-bubble diffusers [59]. Thirdly, cogeneration unit was upgraded for biogas utilization with electrical efficiency boosted from 33% to 38% [59]. The DEMON® deammonification technology was expanded towards mainstream application at Strass WWTP in 2011 [68]. A hydrocyclone system was installed to separate ammonia oxidizing bacteria and anammox bacteria due to slower growth rate of the latter organisms. This biomass selection strategy successfully enables enrichment of anammox granules in the mainstream and wash-out of NOB flocs to maintain the process stability [66, 69].

Mainstream deammonification is a promising process to drive a paradigm shift in wastewater treatment industry towards energy-neutral or even net-energy-positive WWTP with BNR in the future, as it could not only provide substantial reduction in energy demand for aeration (by 63%), sludge generation (by 80%), organic carbon requirement (by nearly 100%) and need for additional alkalinity (by nearly 100%) [66], but also enhance biogas production by 25% [65]. The first full-scale anammox-based deammonification process in the US went online in 2012 for sidestream nitrogen removal at Hampton Roads Sanitation District (HRSD)'s York River WWTP in Seaford, VA [70]. Another two WWTPs located in the Chesapeake Bay watershed, Alexandria Sanitation Authority WRF and HRSD's James River WWTP, have been upgraded to implement DEMON® process [66, 71] to meet the increasingly stringent Total Maximum Daily Load (TMDL) requirement of total nitrogen in effluent discharged into the Chesapeake Bay and its tributaries [72]. Moreover, pilot-scale anammox-based BNR process has been under evaluation as benchmark for future scale-up [73]. However, no data have been reported about biogas production or energy self-sufficiency associated with implementation of anammox process at those WWTPs.

Prague's Central WWTP in Czech Republic is a large WWTP for 1.6 million population equivalent (PE) [62]. Recently the plant claimed 100% energy self-sufficiency by boosting biogas production from 15 to 23.5 kWh/(PE·year) with the following strategies: (1) enhanced primary sludge separation; (2) upgrading sludge thickening device to lysate-thickening centrifuges for efficient sludge disintegration; (3) operating digester at 55 °C with increased organic loading capacity (6.0 kg TS/m^3/day, compared to 4.5 kg TS/m^3/day at mesophilic temperature); (4) providing continuous mixing for both primary and secondary digesters; (5) replacing old gas turbines with three 1 MW$_{el}$ (electric power only) and two 1.2 MW$_{el}$ cogenerators [63].

While the above two plants focus on sludge-only digestion, the following case study will investigate a potentially energy-neutral WWTP with multiple forms of renewable energy production. Gresham WWTP in Oregon, US is a mid-sized WWTP treating over 13 MGD of wastewater [74]. The plant operates two mesophilic digesters producing biogas from sludge digestion to fuel a 400 kW cogenerator that can offset almost 50% of the plant's power demand.

Recently two high-efficiency turbo-blowers were implemented and ultrafine-bubble air diffusers were added in the aeration tank, together reducing the plant's energy consumption by over 6.5%. Another important energy-conserving strategy was to replace old 40-HP (horse power) gas mixers with the 5-HP vertical linear motion mixers mounted on top of each digester tank, which will further reduce the overall energy consumption by 8.5%. In addition, about 8% of the plant's electric power demand is generated from a set of 420 kW solar panels, making Gresham unique among WWTPs in the US. Lastly, a second 400 kW cogenerator was installed and came online in summer 2014 to utilize the excess biogas produced from FOG co-digestion project, which will bridge the remaining 27% energy demand gap. With adopting all the strategies shown above, Gresham WWTP can achieve energy-independence by end of 2014 [75].

5. Conclusions

This review paper examined the utilization of anaerobic digester technology in the US WWTPs. While biogas production at WWTPs has less publicity than other renewable fuels, such as solar or wind, it provides reliable and sustainable low-cost energy for the WWTPs as well as reduces the GHG emissions of WWTP operations. The recent expansion in the definition of "cellulosic biofuel" under the RFS2 is expected to greatly increase the demand for biogas production and utilization because of eligibility of biogas-derived fuels to generate D3 RINs. However, the wastewater industry may be unable to increase biogas production to keep pace with demand. Although growth of the biogas industry in the US is a complex process, deployment of new practices will not only improve the economics of biogas production and but also provide solutions to many technical challenges. Among the many efforts to improve digester performance at US WWTPs, co-digestion of sludge with other organics is very promising because of high methane yield, more efficient digester volume utilization and less biosolids production. Development of new strategies is important to maintain energy self-sufficiency at WWTPs. This is helpful not only for developing a viable and sustainable biogas industry, but also for providing valuable insight to state and local regulators and community officials and other stakeholders.

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Table 1. Summary of reported data on energy content of biosolids generated from WWTPs in the US

Resource	Basis	Thermal energy (MMBtu/year)	Electric power (kWh/year)	Total energy potential (MMBtu/year)	Reference(s)
40 billion gallons of wastewater per day	1 MGD wastewater equates 26 kW of electric capacity and 2.4 MMBtu/day of thermal energy	3.52×10^7	9.11×10^9	6.65×10^7	[10, 23]
6.5 million dry tons of biosolids per year	Sludge energy content = 8,000 Btu/dry lb CHP electric efficiency = 30% CHP thermal efficiency = 40%	4.59×10^7	1.01×10^{10}	9.86×10^7	[8, 10]
WWTPs with average flow rate > 1 MGD (CHP available in 133 WWTPs, feasible for additional 1,351 sites)	Available: 190 MW Electric power 18,000 MMBtu/day Thermal energy Potential: 400 MW Electric power 38,000 MMBtu/day Thermal energy	2.04×10^7	5.17×10^9	3.81×10^7	[10]

Table 2. Benefits of biomethane production and utilization as transportation fuel

Economics	**Energy**	**Environmental**
• Turns waste liabilities into new profit centers • Adds value to negative value feedstocks • Reduces operating / energy costs • Reduces water consumption • Reduces reliance on energy imports • Creation of green jobs • Potential revenue from green energy and carbon credits • Potential revenue from sales of digested sludge (liquid and solids)	• Net energy-producing process • Generates high-quality renewable fuel • Produces surplus energy as electricity and heat at WWTPs • Reduces reliance on energy imports	• Reduces GHG (CH_4,CO, and CO_2) ammonia and particulate emissions • Captures nutrients for reuse & reduces use of inorganic fertilizers • Promotes carbon sequestration • Increases beneficial reuse of recycled water • Reduced groundwater and surface water contamination potential • Reduce disposed waste volume and weight of solid waste to be landfilled

Table 3. Barriers to biogas production from WWTPs in the US (adapted from [15])

Barriers	**Details**
Economic	• Inadequate payback • Lack of available capital • Lack of incentives • Plant size • Lack of knowledge about the financial merits of biogas production and utilization • Equipment cost • Low prices of electricity and natural gas to justify the investment • Biogas quantity and quality • Unpredictable market conditions
Technical	• Lack of knowledge about the merits of biogas production • Challenges in operation and maintenance of AD • Impact on liquid stream operations • Need for the treatment of recycled liquid from digesters • Plant capacity • Safety issues • Need for specialized technical staff and expertise • Availability of other sludge treatment methods • Requirement of energy intensive biogas cleanup and upgrading processes and operations • Reluctance of gas and electricity utilities to work with the plant
Social	• Lack of community and/or utility's interest in renewable energy • Public perception • Political support • Desire to maintain status quo • Odor complaints
Regulatory issues	• Discrepancies across government agencies • Regulated fees and tariffs • Interconnectivity issues • Challenges in meeting effluent discharge limits, such as nitrogen and phosphorus compliance • Challenges in meeting air permit • Challenges in obtaining air permit (Clean Air Act Title V)

Table 4. Energy self-sufficiency of full-scale WWTP with AD of sewage sludge and co-digestion of organic waste in North America (US and Canada) and Europe

Plant	Location	Flow rate	Feedstock (Loading rate)	Digester capacity	Digester operation	Biogas cleanup/upgrading technology	Annual biogas production	Biogas utilization (CHP technology)	Energy self-sufficiency	Reference(s)
Average flow rate < 5 MGD										
Millbrae WPCP	CA, US	2 MGD	WAS (28000) + FOG (3000) = 31000 GPD	2 × 1900 m^3	Mesophilic HRT 38-58 d	N/A	N/A	1 MBTU [g] Boiler Microturbine	68%	[77]
Essex Junction WWTP	VT, US	2 MGD	Sludge + FOG + HSW (brewery and oily waste)	2 × 1350 m^3	Two-Stage Mesophilic HRT 25-30 d	PSA-water stripper	1.7 GWh	2 × 20 kW Microturbine	38%	[15]
Grevesmuhlen WWTP	Germany	4 MGD	PS (10%) + WAS (60%) + Grease skimming sludge (30%) = 1840 ton TS/yr	2 × 1000 m^3	Mesophilic HRT 17.5 d	N/A	1.95 GWh	210 kW IC Engine 1.7 GWh/year Electricity	100% Sale > 20%	[78]
Wolfgangsee-Ischl WWTP	Austria	5 MGD	Mixed PS + WAS	N/A	Two-Stage Mesophilic HRT 80 d	PSA	3.0 GWh	High-efficiency (34%) Cogenerator 1 GWh Electricity	100% Sale 10%	[60, 61]
Velenje WWTP	Slovenia	5 MGD	Sludge + Organic waste (1.01 COD kg/m^3/d) = 1100 ton/yr	2 × 1000 m^3	Mesophilic HRT 20 d	N/A	2.8 MWh	365 MWh/year Electricity 1645 MWh/year Heat	N/A	[79]
Treviso WWTP	Italy	5 MGD	WAS + OFMSW (1 ton OFMSW per 10 m^3 WAS)	2000 m^3	Mesophilic HRT 22 d	N/A	1.5 GWh	N/A	N/A	[80, 81]
Average Flow Rate < 50 MGD										
Strass im Zillertal WWTP	Austria	6 MGD	Mixed BNR WAS + Trap grease + Crude glycerol + Food waste	N/A	Mesophilic	N/A	10 GWh	High-efficiency (38%) Cogenerator	100% Sale 20%	[59, 82]
Watsonville WWTP	CA, US	7 MGD	WAS (83333) + FOG (4500) = 88000 GPD	2 × 5700 m^3	Mesophilic	N/A	N/A	600 kW Cogenerator	N/A	[77, 83]
Boden WWTP	Sweden	10 MGD	Sludge (24000) + Food waste (1200) = 25200 GPD	1300 m^3	Thermophilic HRT 14-16 d	PSA	5.5 GWh	3.5 GWh/yr Plant heating 1.6 GWh/yr City heating network distribution 400 MWh Excess biogas upgraded to vehicle fuel	N/A	[84]
Viareggio WWTP	Italy	10 MGD	Sludge + OFMSW (1.21 kg VS /m^3/d) = 350 ton/d	1^{st}: 3000 m^3 2^{nd}: 1500 m^3	Mesophilic HRT 20 d	N/A	2.2 GWh	N/A	N/A	[80]
Gloversville-Johnstown Joint WWTP	NY, US	11 MGD	Sludge + HSW (yogurt/cheese whey wastewater)	1^{st}: 5700 m^3 2^{nd}: 4900 m^3	Two-Stage Mesophilic HRT 15 d	Activated carbon	28 GWh	6.6 GWh/year Electricity 9.0 GWh/year Heat	100%	[85]

Sheboygan Regional WWTP	WI, US	11 MGD	Sludge + FOG + HSW (dairy waste)	3 Primary 1 Secondary	Mesophilic	Condensation + Activated carbon	32 GWh	700 kW Microturbine 6 GWh/year Electricity 20 GBTU/year Heat	100%	[15, 86, 87]
Gresham WWTP	OR, US	13 MGD	Sludge (60000) + FOG (9000) = 69000 GPD	2 × 3800 m^3	Mesophilic HRT 18 d	N/A	17.2 GWh	2 × 400 kW Cogenerators 5 GWh/year Electricity 10.7 GWh/year Heat	100%	[74, 88]
Douglas L. Smith Middle Basin WWTP	KS, US	15 MGD	Sludge (6700 ton/yr) + FOG (3.23 MGY)	4 × 2000 m^3	Mesophilic	N/A	35 GWh	2 × 1.06 MW IC Engine 5.4 GWh/year Electricity	50%	[43, 89-91]
South Bayside System Authority Redwood City WWTP	CA, US	18 MGD	WAS (250000) + FOG (3500) = 253500 GPD	3 × 5700 m^3	Mesophilic	N/A	N/A	N/A	N/A	[77]
Baden-Baden WWTP	Germany	20 MGD	PS (15.9 MGD) + WAS (5.3 MGD) + Municipal biowaste (8.8 MGD) = 30 MGD	Hydrolyzer: 474 m^3 Digester: 2 × 3000 m^3	Hydrolysis: 42°C, HRT 23 h Digestion 37°C, HRT 14 h	N/A	28.3 GWh	N/A	N/A	[55]
Riverside Water Quality Control Plant (WQCP)	CA, US	30 MGD	PS (40000) + WAS (30000) + FOG (20000) = 90000 lb VS/d	N/A	Mesophilic	Iron sponge + rotary lobe blowers + gas chilling + activated carbon vessels	N/A	2.5 MW Cogenerator 1.2 MW Fuel cell	N/A	[92]
F. Wayne Hill WRC WWTP, Gwinnett County	GA, US	33 MGD	Sludge (204000) + FOG/HSW (23250) = 227250 GPD	5 × 3800 m^3 Egg-shaped	Mesophilic HRT 15 d	Iron sponge + activated carbon	46.2 GWh	2.15 MW Cogenerator 13 GWh/year Electricity	50%	[15, 45, 93]
South-Cross Bayou WRF, Pinellas County	FL, US	33 MGD	Sludge + FOG (2000-6000 dry lb/yr)	N/A	Mesophilic	N/A	N/A	1.4 MW Cogenerator	N/A	[15, 94, 95]
South Columbus WRF	GA, US	35 MGD	Sludge + FOG	1 CSTR 2 × 67 m^3 PFR 2 × 4500 m^3 Digesters	CSTR-Hydrolysis: 53 °C, HRT 6 d PFR-Hydrolysis: 53 °C, HRT 30min Digestion: 37 °C, HRT 15 d	PSA: Iron sponge + rotary lobe blowers + gas chilling + activated carbon vessels	40 GWh	2 × 1.75 MW IC Engine 11 GWh/year Electricity	40%	[7, 46, 57, 96, 97]
Prague Central WWTP	Czech Republic	42 MGD	Mixed PS+WAS (70 ton VS/yr)	12 × 4800 m^3	2-Stage Thermophilic HRT 25 d	N/A	115 GWh	3 × 1 MWe [15] + 2 × 1.2 MWe Cogenerators 37.6 GWh/year Electricity	94%	[62, 63, 98]
Inland Empire Utilities Agency (IEUA) Regional Plant	CA, US	44 MGD	Sludge + Dairy manure/Food waste (80/20) = 1.53~3.10 kg $VS/m^3/d$	N/A	3-Stage AG-MTM 1st Stage: 37 °C, HRT 3 d	PSA-water stripper	60 GWh	2.8 MW Fuel cell + 4.2 MBTU Heat recovery system	80%	[99, 100]

No. 1, Ontario					2nd Stage: 55 °C, HRT 10 d 3rd Stage: 37 °C, HRT 15 d					
Average Flow Rate < 100 MGD										
Des Moines MWRA WWTP	IA, US	59 MGD	Sludge + FOG + HSW = 0.5 MGD	6 × 10000 m^3	Mesophilic HRT 33 d	PSA	90 GWh	73 GWh/year Electricity 42 GWh/year Sale Cargill 9 GWh/year Heat	75%	[15, 43]
Zürich Werdhölzli WWTP	Switzer-land	67 MGD	Sludge (18000) + FOG (5000) = 23000 ton TS/yr	4 × 7250 m^3	Mesophilic	N/A	41.4 GWh	High-efficiency Cogenerator	100%	[101, 102]
East Bay Municipal Utility District WWTP, Oakland	CA, US	70 MGD	Sludge + FOG/Food waste/HSW	12 × 7500 m^3	Mesophilic HRT 18 d	Activated carbon	90 GWh	3 × 2.1 MW IC Engines + 4.6 MW Turbine =11 MW 55 GWh/year Electricity (10 GWh/year Sale)	100% Sale 20%	[103, 104]
Gryaab WWTP	Sweden	92 MGD	Sludge (430000) + FOG (5000) + HSW (4000) = 439000 ton/yr	2 × 11400 m^3	Mesophilic	Amine absorption (COOAP^{TM} Process)	60 GWh	Biogas sold to Goteborg Energi Co. for upgrading	N/A	[105]
Csepel WWTP	Hungary	93 MGD	Mixed PS+WAS from BNR Process (85 ton TS/yr)	Thermophilic: 17000 m^3 Mesophilic: 6300 m^3	1st Stage: 55 °C, HRT 12 d Exelys^{TM} Hydrolysis: 165 °C, HRT 30min 2nd Stage: 37 °C, HRT 15 d	N/A	95 GWh	39 GWh/year Electricity 20 GWh/year Heat	65%	[54]
Average Flow Rate < 500 MGD										
Village Creek WRF, Fort Worth	TX, US	110 MGD	Sludge + FOG + HSW (food processing waste, glycerin/organics acids from biodiesel facility)	14 × 4500 m^3	Mesophilic	N/A	62 GWh	2 × 5.2 MW Turbines 2 Steam-Turbines	75%	[106-109]
Annacis Island WWTP, Vancouver	Canada	130 MGD	Sludge (0.69) + FOG (0.07) = 0.76 MGD	4 × 12000 m^3	Thermophilic	N/A	132 GWh	IC Engines	50%	[83, 110, 111]
Point Loma WWTP	CA, US	175 MGD	Mixed PS+WAS (1 MGD)	8 × 13600 m^3	Mesophilic HRT 30 d	PSA	193 GWh	2 × 2.25 MW IC Engines 34.3 GWh/year Electricity 53.5 GWh/year Heat Excess biogas upgraded and sold to power off-site	100%	[46, 112, 113]

								4.5 MW fuel cells		
Davyhulme WWTW, Manchester	England	200 MGD	Mixed PS+WAS (91000 ton TS/yr)	2 × 7500 m^3	Cambi$^{\text{TM}}$ Hydrolysis: 165 °C, HRT 20 min Digestion: 40 °C, HRT 18-19 d	N/A	238 GWh	12 MWe IC Engines 87.6 GWh/year Electricity	96%	[114-116]
Joint Water Pollution Control Plant, Carson	CA, US	300 MGD	Sludge (91%) + Food waste (9%) = 4.84 MGD	24 × 14200 m^3	Mesophilic HRT 20 d	Venturi scrubbers + coalescing filter + cooling coils	484 GWh	3 × 10 MW Turbines 175 GWh/year Electricity Upgraded biogas injection to CNG fueling facility (300,000 GGE)	97%	[117, 118]
Blue Plains AWWTP, Washington DC	DC, US	375 MGD	Mixed PS + WAS	4 × 14200 m^3	Cambi$^{\text{TM}}$ Hydrolysis: 165 °C, HRT 20 min	N/A	360 GWh	3 × 4.6 MW Turbines 103 GWh/year Electricity	33%	[52, 76]

List of Figures

Abbreviations

AD: Anaerobic Digestion
AG-MTM: Acid-Methane Mesophilic-Thermophilic-Mesophilic Process
AWWTP: Advanced Wastewater Treatment Plant
CHP: Combined Heat and Power
COD: Chemical Oxygen Demand
CSTR: Continuous Stirred Tank Reactor
FOG: Fats, Oil and Grease
GHG: Greenhouse Gas
GPD: Gallons per Day
HRT: Hydraulic Retention Time
HSW: High-Strength Waste
IC: Internal Combustion
MBTU: Million British Thermal Unit
MGD: Million Gallons per Day (1 MGD = 3,785 m^3/day)
MGY: Million Gallons per Year
N/A: Not Available
OFMSW: Organic Fraction of Municipal Solid Waste
PFR: Plug Flow Reactor
PS: Primary Sludge
PSA: pressure swing adsorption
RFS2: the new Renewable Fuel Standard
RIN: Renewable Identification Numbers
scfm: standard cubic feet per minute
THP: Thermal Hydrolysis Process
TS: Total Solids
VS: Volatile Solids
WAS: Waste Activated Sludge
WWTP: Wastewater Treatment Plant
WWTW: Wastewater Treatment Work

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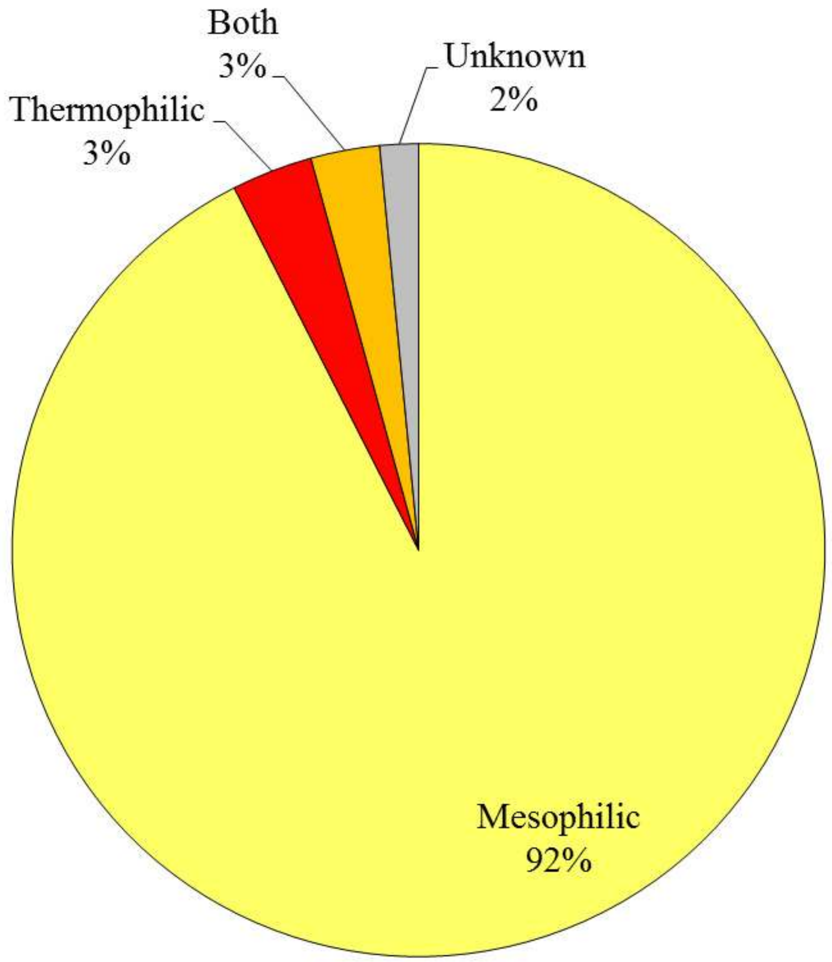

Figure 1. Summary of anaerobic digester operation and biogas utilization at WWTPs in the US: **(A)** AD system operating temperature

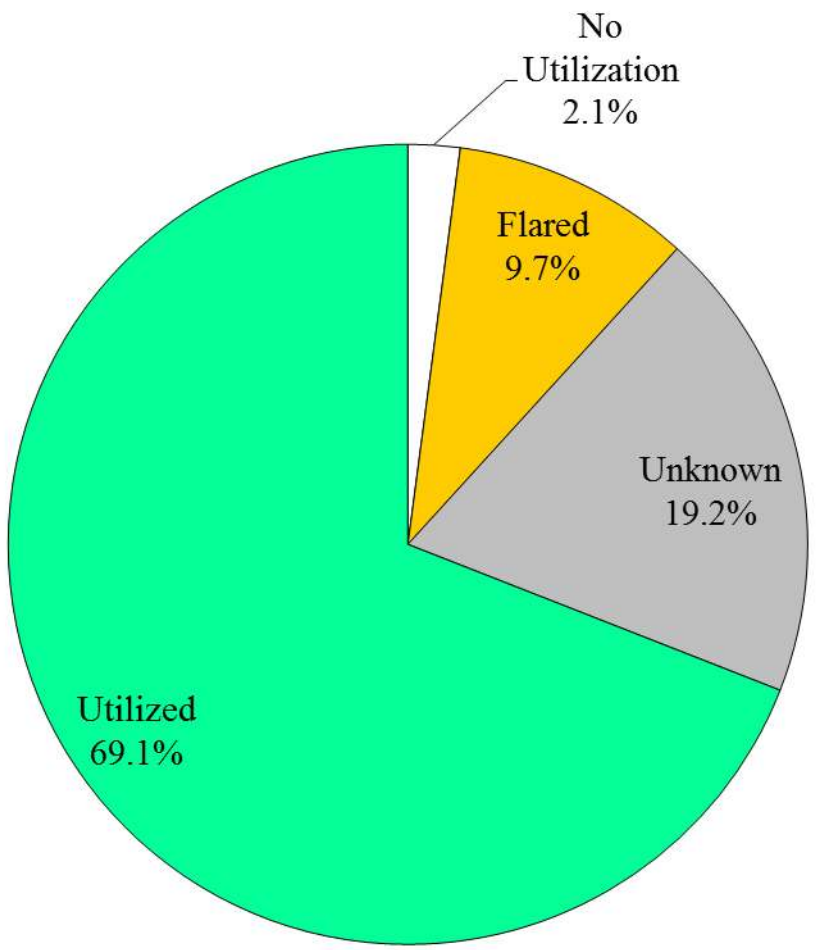

Figure 1. Summary of anaerobic digester operation and biogas utilization at WWTPs in the US: **(B)** Biogas utilization

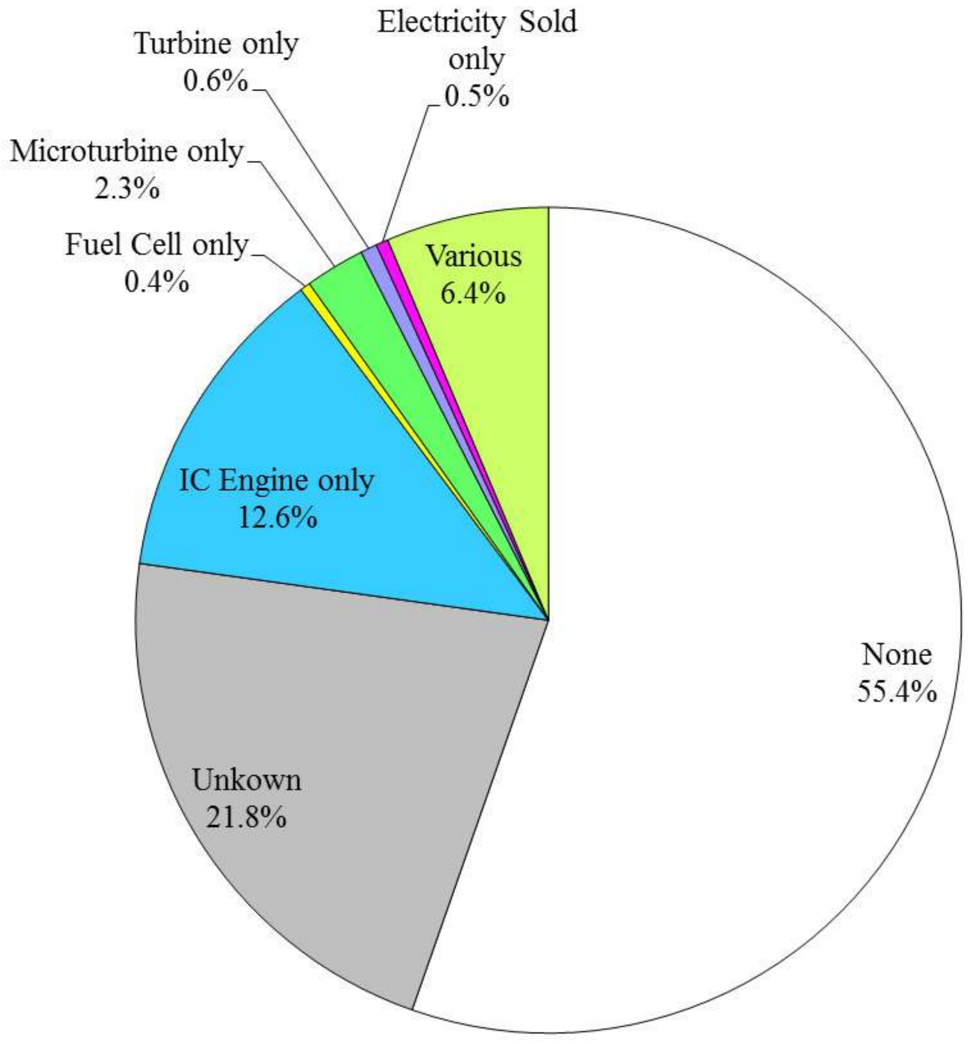

Figure 1. Summary of anaerobic digester operation and biogas utilization at WWTPs in the US: **(C)** CHP technologies for energy generation from biogas utilization

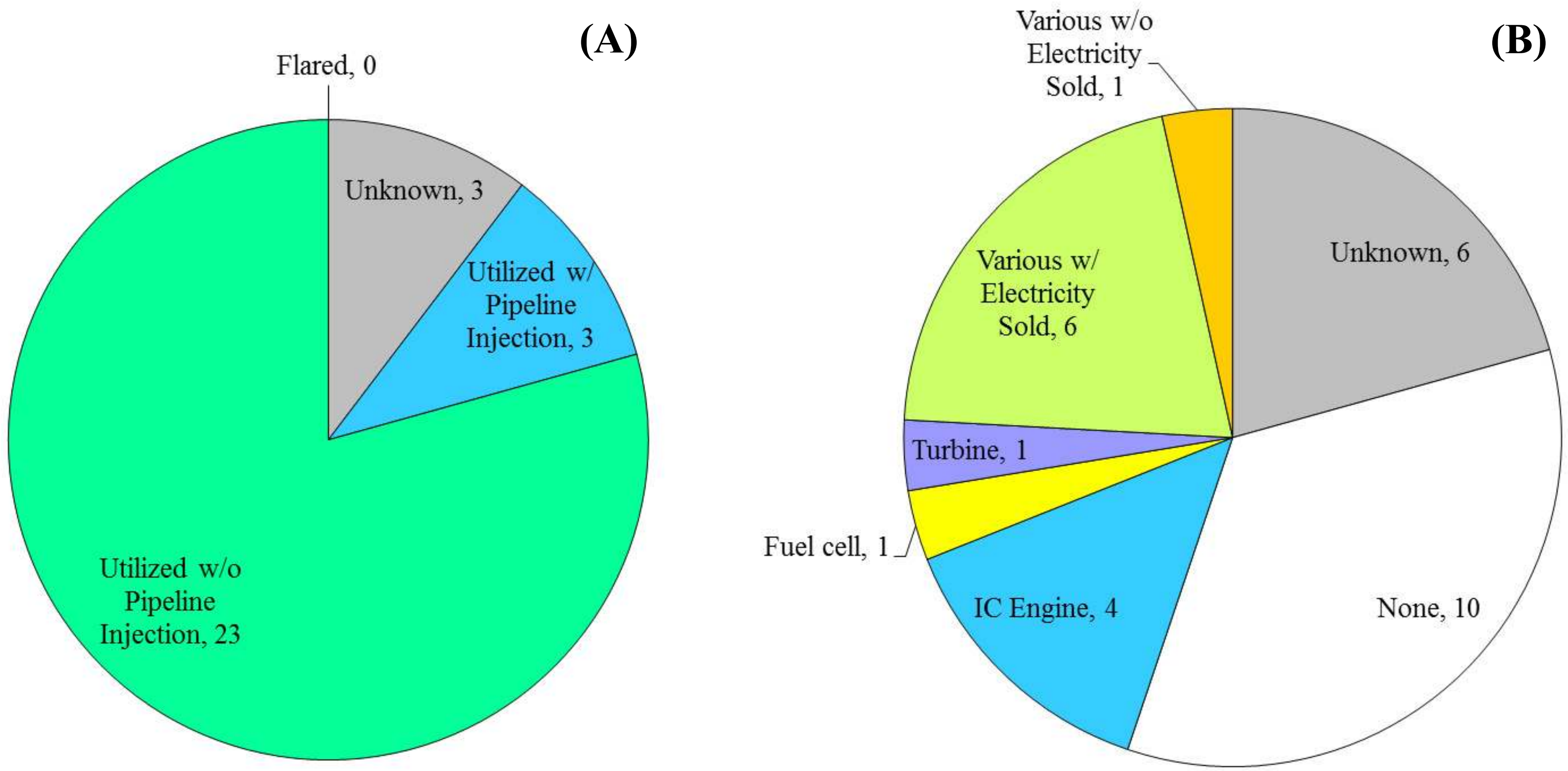

Figure 2. WWTPs in the US with average flow ranging from 100 to 1000 MGD: (A) Biogas utilization; (B) CHP technologies for energy generation from biogas utilization

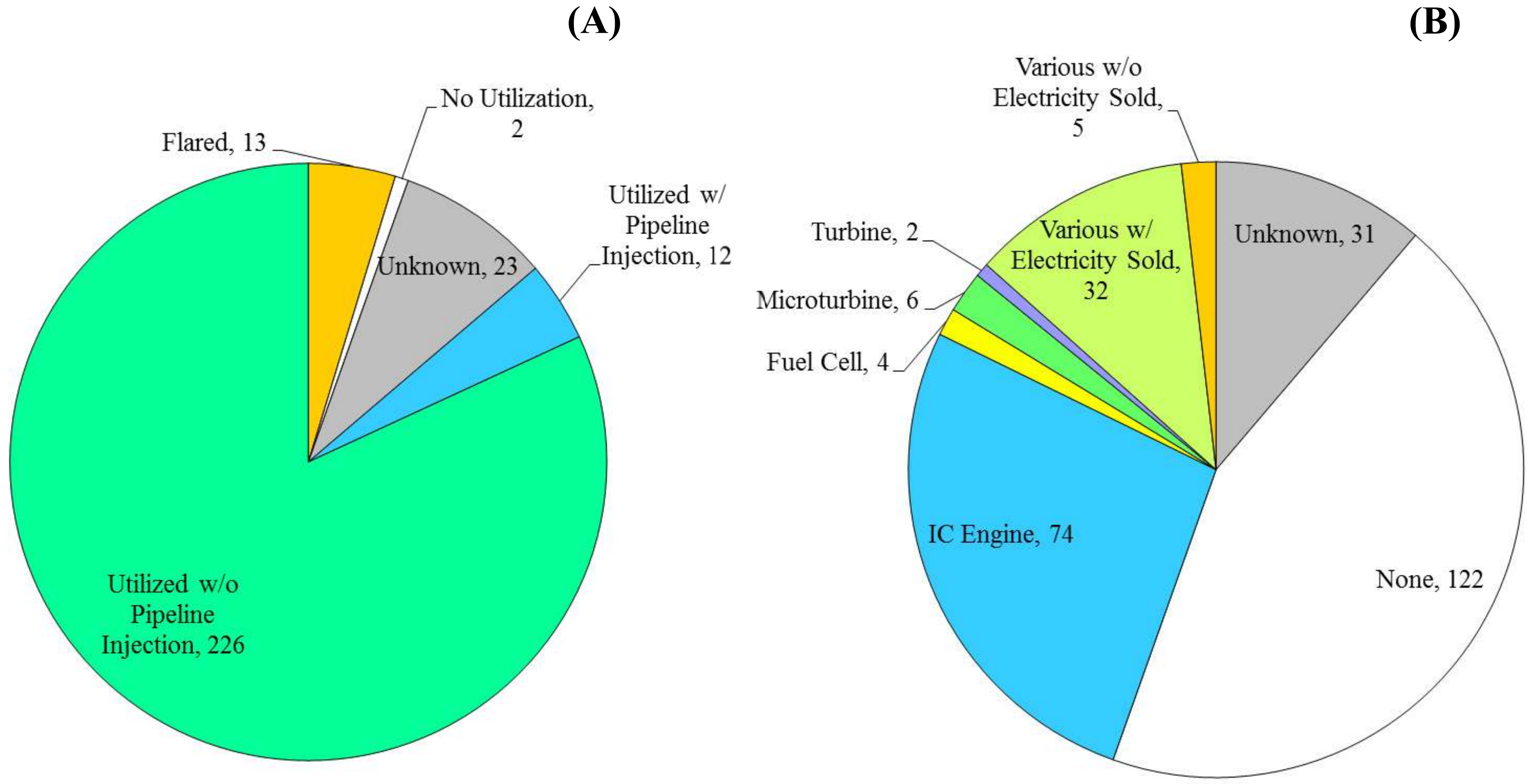

Figure 3. WWTPs in the US with average flow ranging from 10 to 100 MGD: (A) Biogas utilization; (B) CHP technologies for energy generation from biogas utilization

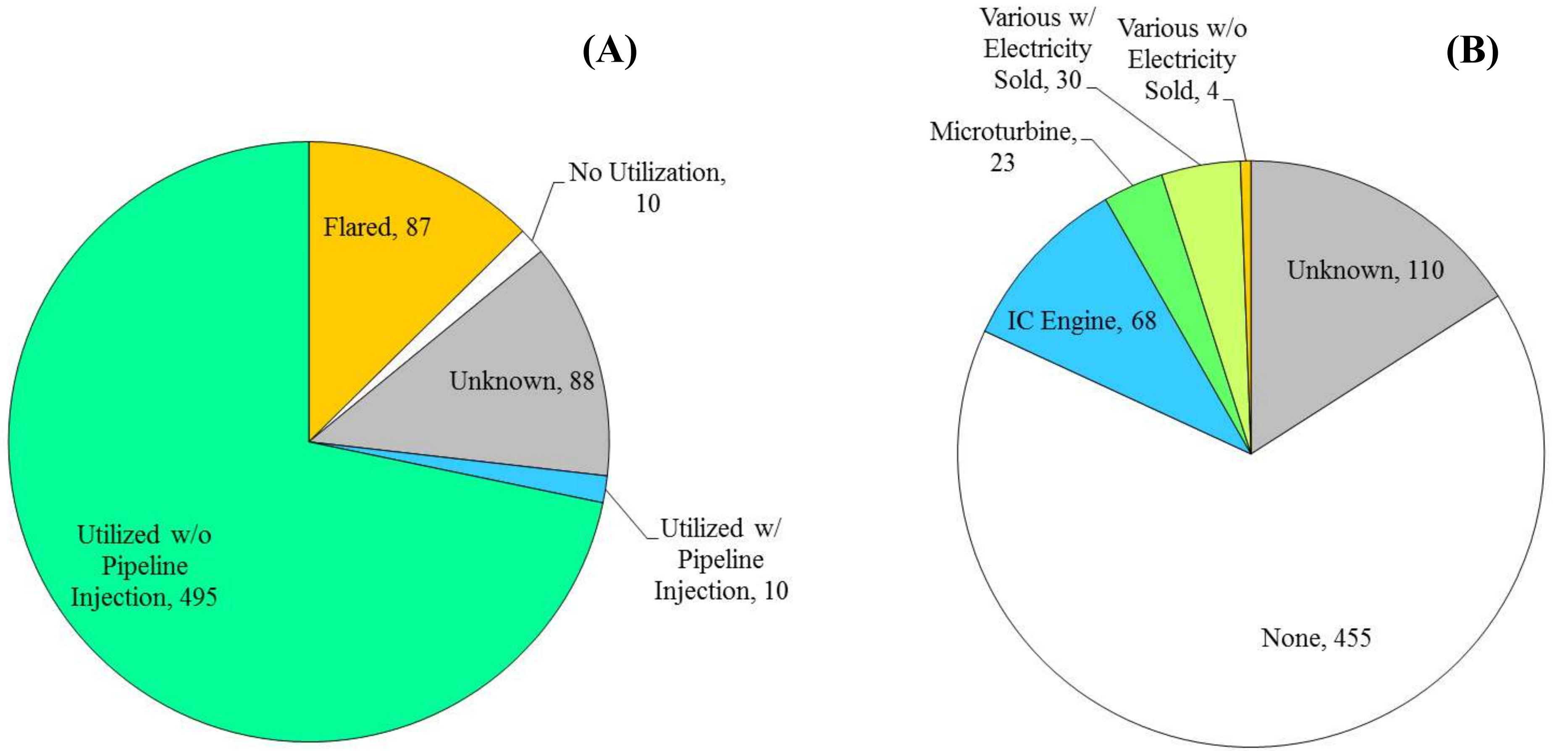

Figure 4. WWTPs in the US with average flow ranging from 1 to 10 MGD: (A) Biogas utilization; (B) CHP technologies for energy generation from biogas utilization

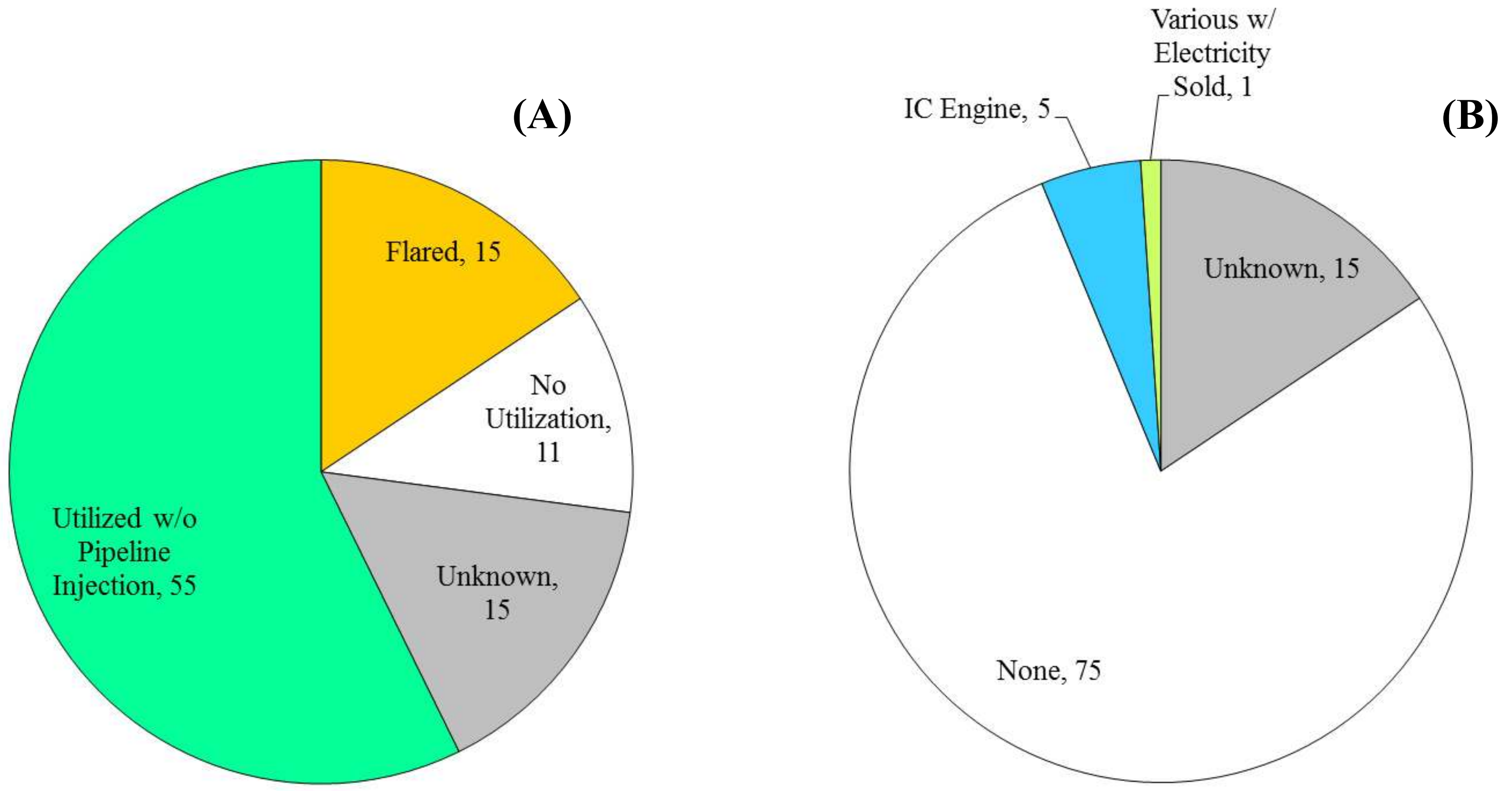

Figure 5. WWTPs in the US with average flow less than 1 MGD: (A) Biogas utilization; (B) CHP technologies for energy generation from biogas utilization

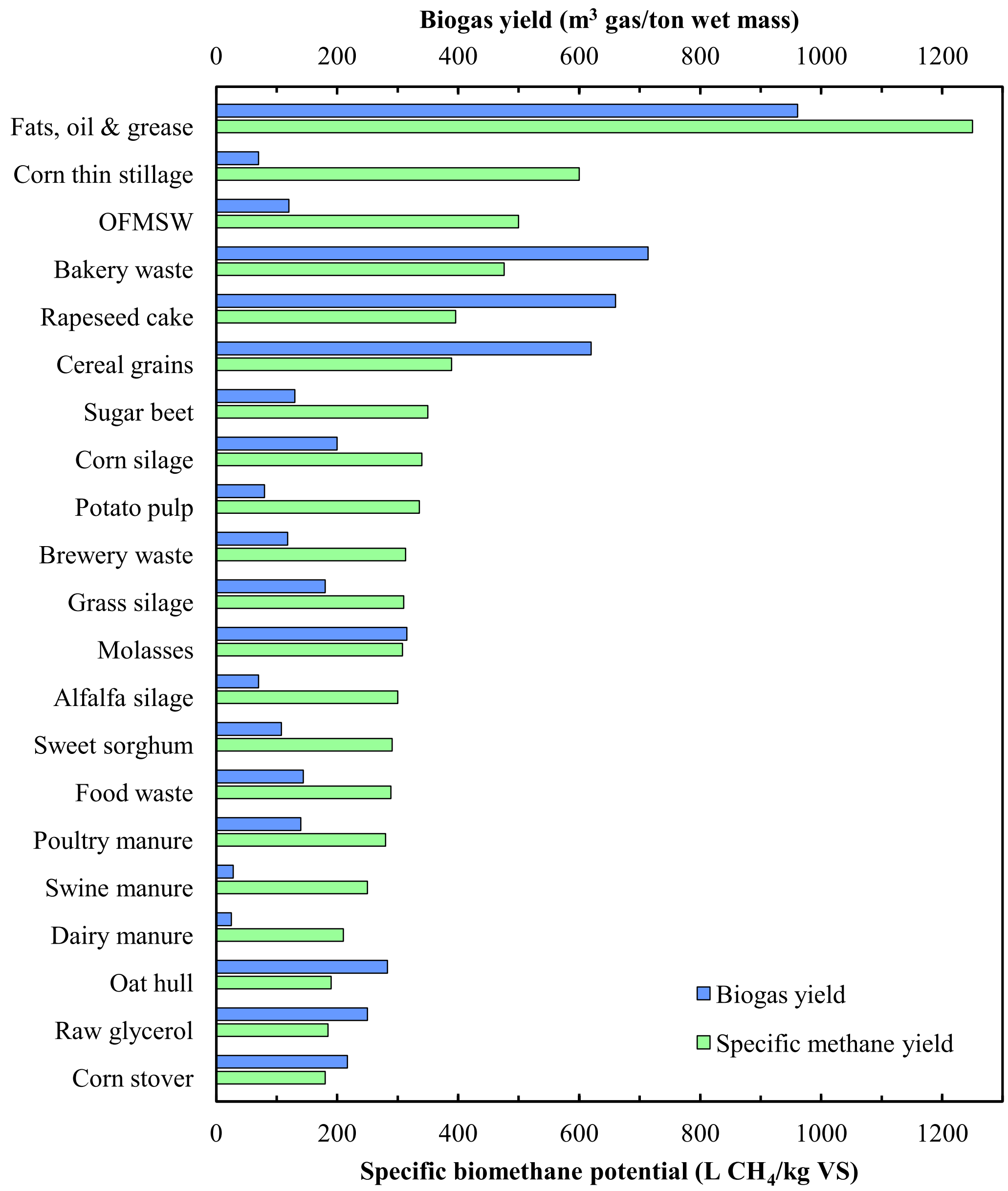

Figure 6. Biogas yield and specific biomethane potential of various feedstocks (Data source: [62-64])

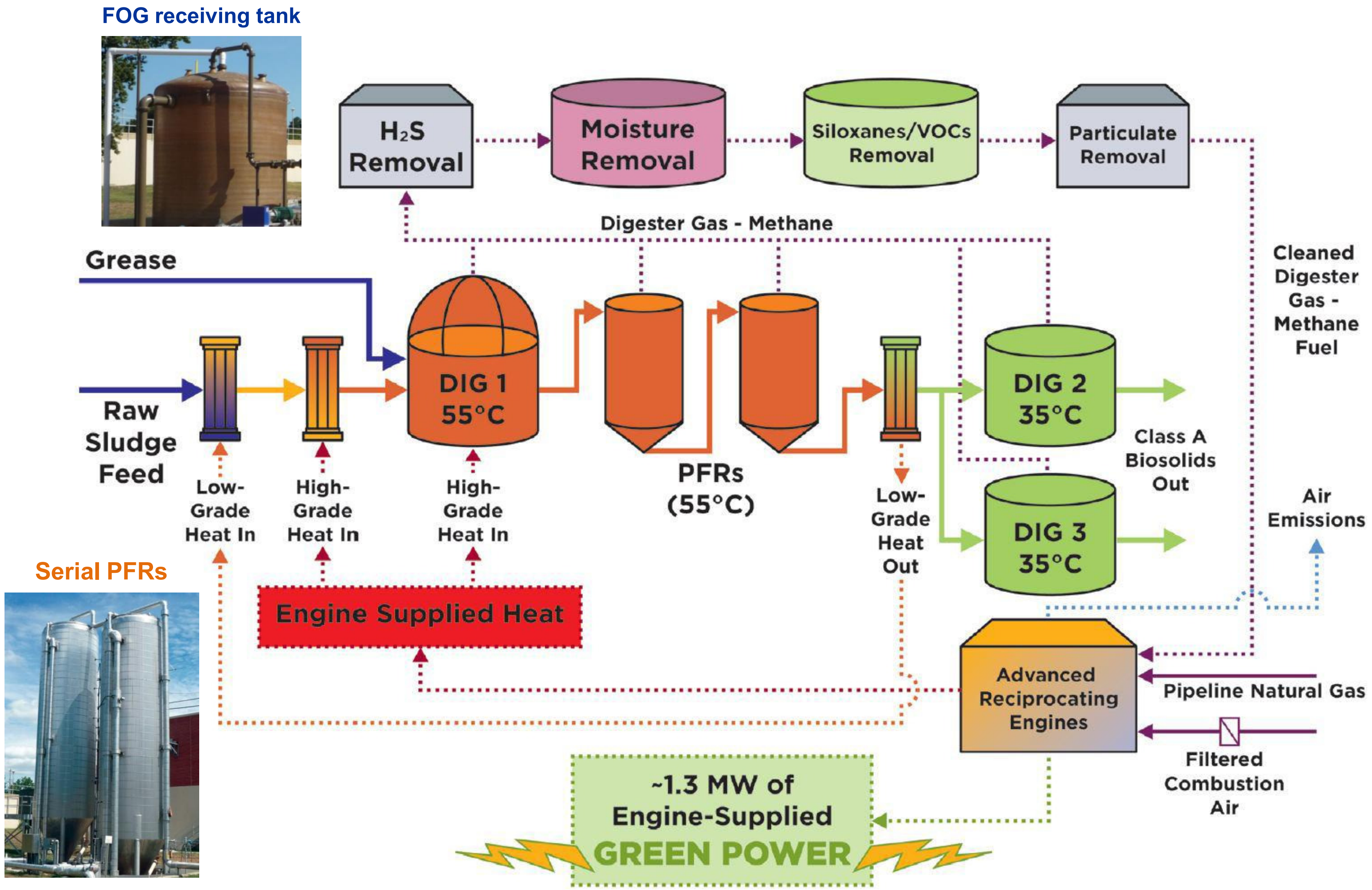

Figure 7. South Columbus WRF: schematic of CBFT^3 process conducting FOG co-digestion with sludge (adapted from [7])

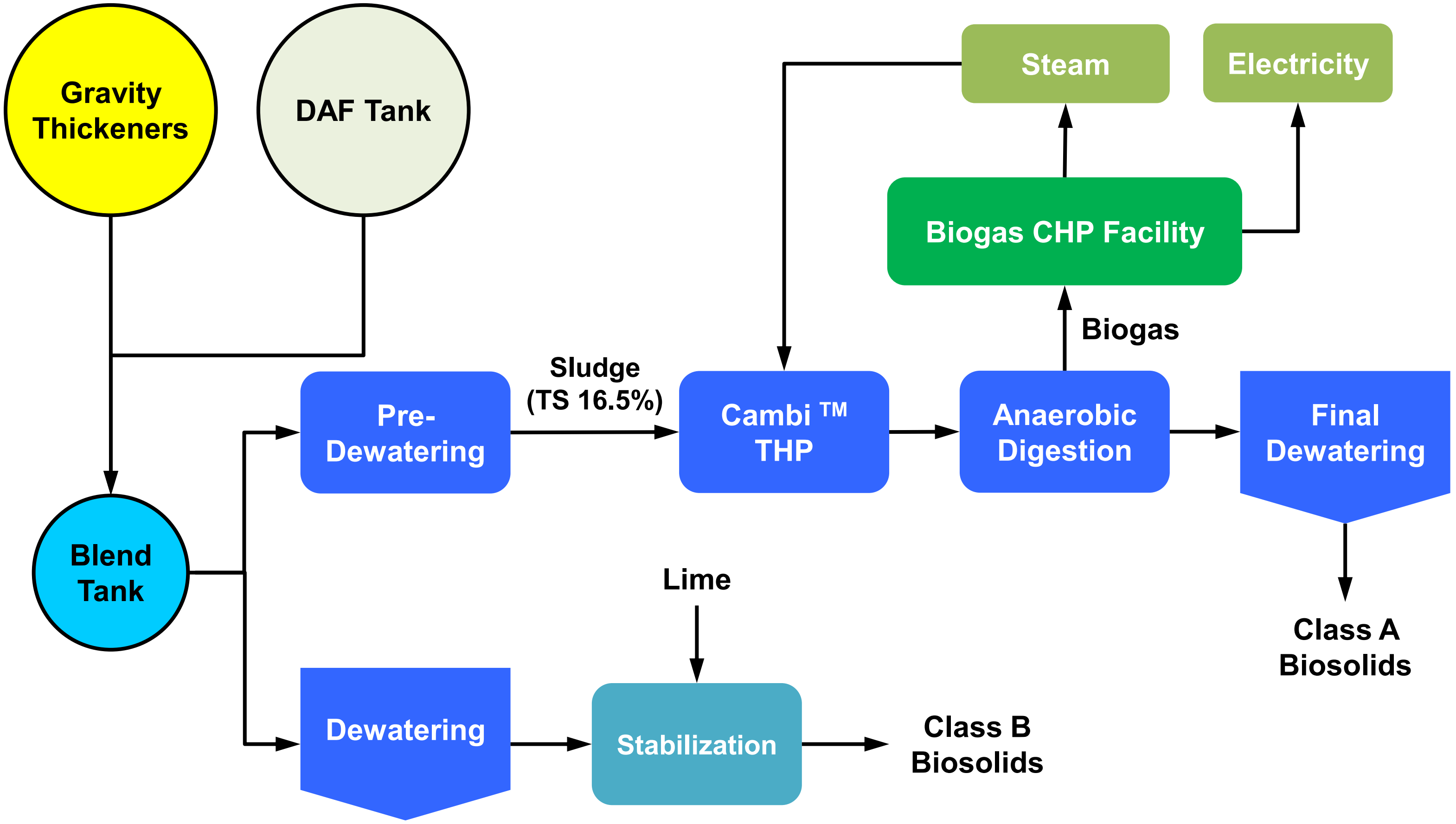

Figure 8. Blue Plains AWTP: schematic of the new Biosolids Management Plan (online in 2015, adapted from [116])

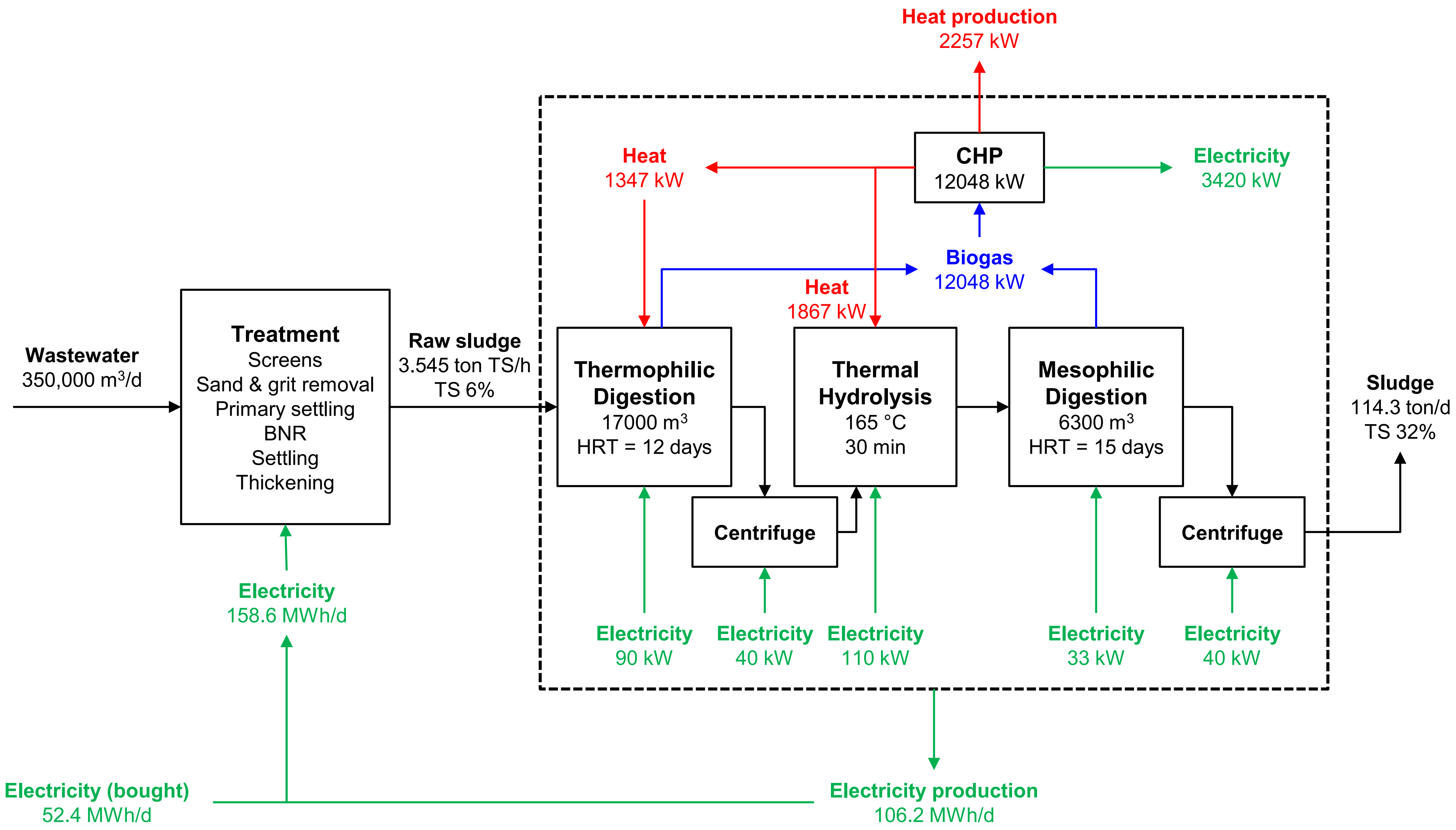

Figure 9. Csepel WWTP: schematic of Exley^{TM}-DLD process and flow of wastewater, sludge, thermal and electrical power (based on data reported in [52])

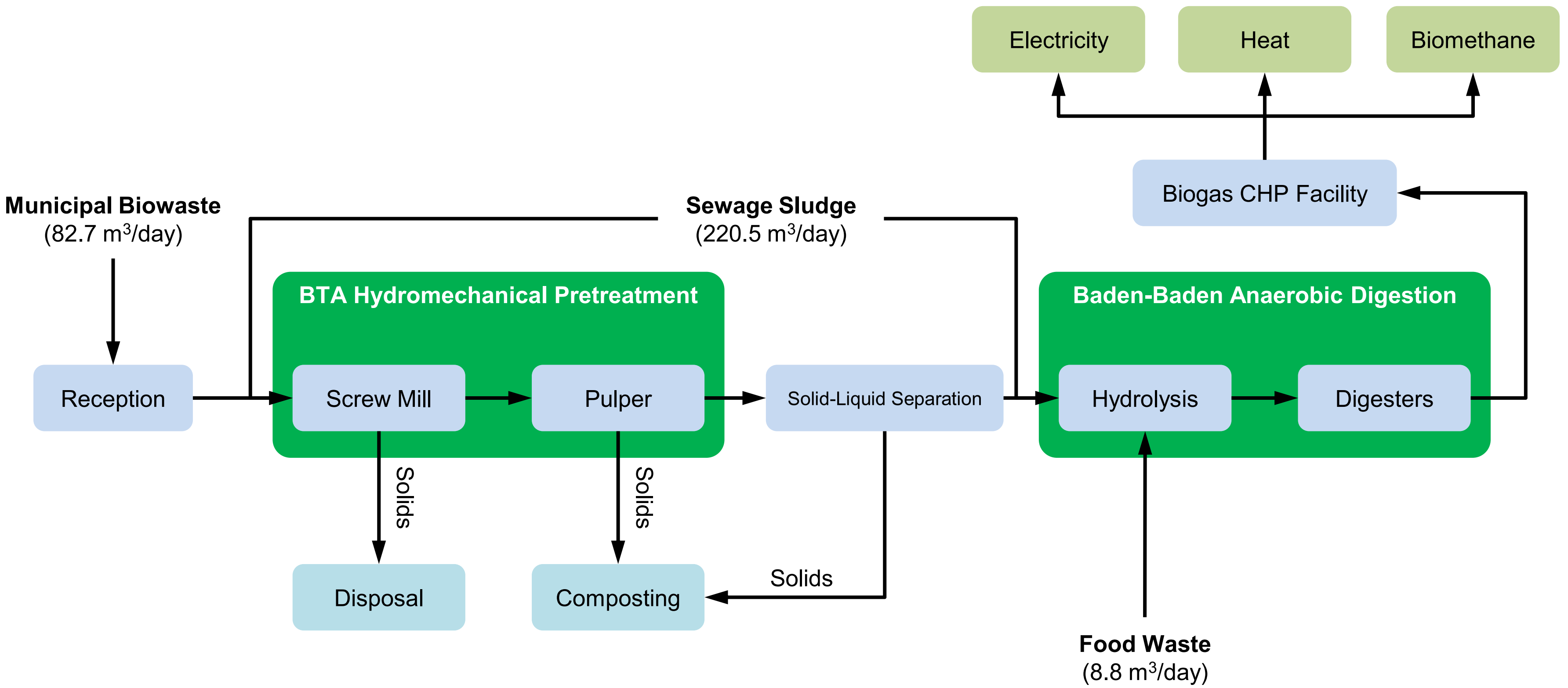

Figure 10. Baden-Baden WWTP: schematic of solid pretreatment process (BTA® Process), two-stage AD system (hydrolysis reactor and digesters) and biogas utilization system (based on data from [53])