An Overview of Innovative Technologies: Can They Provide Benefits to Florida Water Resource Recovery Facilities?

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For new water resource recovery facilities (WRRFs), at the time of major plant expansions or significant changes to discharge permit limits for existing facilities, the opportunity arises for utilities to re-evaluate the core technologies used to meet their treatment objectives.

Circumstances sometimes dictate that alternative technologies be adopted. This may occur when the technology in use lacks the ability to meet the new water quality limits or when there is insufficient space on an existing site. More progressive organizations may use these opportunities to advance higher-level goals, such as resource recovery or enhanced sustainability. At the highest level, utilities must meet minimum legal, service, and economic objectives, which in simple terms means meeting permit limits at the minimum cost.

Utility customers often lack an understanding of the systems that provide their wastewater service. As a result, customer expectations tend to focus on the basic services provided to them. Often, these expectations are that wastewater will be reliably removed from their property with no adverse aesthetic effects and at a low monthly charge.

The current regulatory system dictates technology, water quality, and antidegradation objectives. At a minimum, WRRFs must provide secondary treatment as defined by the U.S. Environmental Protection Agency (EPA) in Title 40, Part 33 of the U.S. Code of Federal Regulations (CFR). In addition, WRRFs typically must meet more stringent requirements established by the water quality requirements for the intended use of the reclaimed water, or by instream water quality criteria.

For many years, the challenges facing individual Florida utilities have included growing service area populations with concurrent higher demands on water resources and increasingly limited site space due to encroaching neighborhoods, which are compounded by the need for treatment to lower limits and greater demands for more aesthetically pleasing designs.

Conventional biological nutrient removal (BNR) processes, primarily the Modified Ludzak-Ettinger (MLE) and the Bardenpho processes, have served Florida utilities well in meeting these challenges since about 1980, with a majority of the nutrient removal facilities in the state employing these two processes in some fashion. While conventional BNR processes are a comfortable choice for plant expansions and upgrades, some of the innovative technologies that have been proven in full-scale use over the past decades may offer significant benefits over the tried and true. Some of the benefits offered by innovative and alternative technologies include:

- Improved economics in meeting specific water quality goals
- Smaller land requirements due to more compact facilities
- Greater recycling and reuse of water, nutrients, and energy

The challenge to utility owners and managers is to know when and where to implement innovative or alternative technologies to capture the benefits provided by them without incurring undue risk.

Innovations in Wastewater Treatment

The interest in innovative wastewater treatment technologies has ebbed and flowed over the past decades; however, an underlying interest in finding better methods of treating sewage has persisted. Over a period of one hundred years, wastewater treatment has evolved from intermittent filtration beds and Imhoff tanks, to BNR and membrane bioreactors (MBR). The evolution of technologies continues today, with new processes emerging into full-scale use.

While treatment technologies and their expected performance continue to evolve, the overall goals have remained remarkably similar over the years: simplicity, ease of operation, a small footprint, and low cost of ownership. Vendors of various technologies claim these and other benefits; however, the value of new processes relative to the activated sludge processes that now dominate the wastewater industry can be difficult to verify and challenging to realize through implementation.

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Overview of Selected Innovative and Alternative Technologies

The current crop of innovative technologies includes new processes, like granular activated sludge (GAS) and ballasted activated sludge (BAS), and improvements to older technologies, including integrated fixed-film activated sludge (IFAS) and biologically active filters (BAFs).

Conventional BNR processes are enhancements and extensions of the original post-anoxic process proposed by Karl Wuhrmann (Wuhrmann, 1968). The key concept of the MLE process is an anoxic-aerobic sequence with a recycle of nitrate from the aeration zone back to an initial anoxic zone. The MLE process improved upon Wuhrmann's post-anoxic process by taking advantage of the influent chemical oxygen demand (COD) for denitrification and recovering nearly half of the oxygen and alkalinity consumed during nitrification. Compared with newer processes, however, the MLE is not space-efficient nor capable of meeting very low nitrogen limits, and requires large mixed liquor recycle flows that are typically about three to four times higher than the influent flow. Over the last 40 years, the MLE process has become the standard workhorse of municipal wastewater treatment.

Table 1. Full-Scale Experience With Innovative Technologies at Municipal Scale

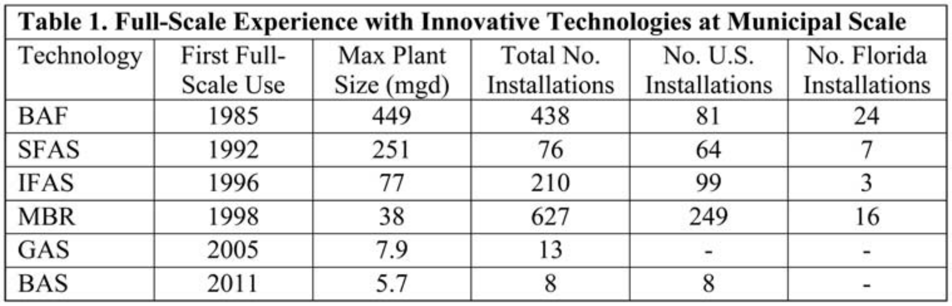

Table 1. Full-Scale Experience with Innovative Technologies at Municipal Scale

Technology	First Full-Scale Use	Max Plant Size (mgd)	Total No. Installations	No. U.S. Installations	No. Florida Installations
BAF	1985	449	438	81	24
SFAS	1992	251	76	64	7
IFAS	1996	77	210	99	3
MBR	1998	38	627	249	16
GAS	2005	7.9	13	-	-
BAS	2011	5.7	8	8	-

Like the MLE, the four- and five-stage Bardenpho processes came into use in the 1970s (Barnard, 1998). These processes are capable of meeting Florida advanced wastewater treatment (AWT) limits, but they require more space than MLE due to the need for two or three additional tanks. An anaerobic tank is required to obtain enhanced biological phosphorus removal, while second anoxic and reaeration zones are required to meet low total nitrogen (TN) limits. Bardenpho processes have similar advantages and disadvantages as the MLE process.

For the purpose of this article, the MLE and Bardenpho configurations using conventional activated sludge are referred to as CAS. An MLE configuration was used for one case study discussed where the plant has a 10-mg/L TN limit, while a Bardenpho configuration was used for the other two case studies where the plants have 3-mg/L TN limits.

Step-Feed Biological Nutrient Removal

Step-feed activated sludge (SFAS) processes were first exhibited at full scale at the 1939 World's Fair at the Tallman Island Water Pollution Control Plant (WPCP) in New York City (Buhr et al., 1984). Merging a BNR process, such as a MLE process, into a step-feed reactor was a later modification first evaluated in the 1970s (Miyaji et al., 1980) and put into practice in the 1990s (Schlegel, 1992; Fillos et al., 1996). In SFAS, influent is added at multiple points (typically three or four) along the length of the reactor. The mixed liquor suspended solids (MLSS) concentration is highest, equal to the return activated sludge (RAS) concentration, at the beginning of the reactor and drops at each feed point in proportion to the fraction of the feed added at that point. As a result, average MLSS concentrations for a step-feed tank are 20 to 35 percent higher than for a flow-through reactor; however, the effluent from a step-feed reactor has the same concentration as the conventional configuration. Consequently, the required clarifier size is the same for both flow configurations. Because of the reduced reactor volume, SFAS can have a significant footprint advantage compared to conventional plug-flow reactors.

Integrated Fixed-Film Activated Sludge

Like the step-feed BNR process, the IFAS process seeks to elevate the MLSS concentration in the biological treatment basin, which is achieved by the addition of an attached growth media. The suspended MLSS concentrations are kept about the same as is found within conventional processes; however, the biomass growing on the fixed media significantly increases the total biomass inventory compared to a conventional suspended growth process. Thus, a higher volumetric loading rate is possible for an IFAS tank than can be handled by a conventional one of the same size, while the solids loading rate to the clarifiers downstream stays the same. At least 210 IFAS plants worldwide have been documented; 99 of these are United States installations, with the largest rated at 77 mil gal per day (mgd), and Florida has three small IFAS plants with capacities ranging from 0.75 to 7.3 mgd. Important considerations for the IFAS process are the higher energy that's required for aeration, extra maintenance costs associated with accessing diffusers below the media, and additional capital costs for media and associated retention screens.

Ballasted Activated Sludge

Step-feed increases the MLSS concentration in upstream basins by stepwise dilution of the RAS with influent, IFAS achieves a higher biomass than conventional systems by the addition of fixed-film media, and BAS systems achieve higher biomass concentrations by increasing settling velocities by adding a ballast material. The ballast material is magnetite, which is a naturally magnetic, plentiful, dense, and inert iron oxide. A relatively new process, BAS has quickly gained a foothold in the 1- to 10-mgd market since the first installation in 2011. There are now a total of eight full-scale plants in operation, four in start-up and four in construction.

Like IFAS, BAS is especially well suited to retrofitting existing plants, but unlike IFAS, no structural alterations are required; however, covered space to house the magnetite feeding and recovery equipment is required with BAS. Magnetite is recovered from waste activated sludge (WAS) using a shear mill and a magnetic recovery drum. An approximately 1:1 mass ratio of magnetite to biomass is added to the mixed liquor, allowing for a total suspended solids (TSS) concentration of 10,000-12,000 mg/L.

Membrane Bioreactors

The MBRs can support high MLSS concentrations because they do not rely on gravity to perform a phase separation of the MLSS and water; rather, they use a semiporous membrane, typically in the microfiltration (MF) or the ultrafiltration (UF) range. Because MBRs do not require clarifiers or tertiary filters and can operate at high MLSS concentrations, they occupy a small footprint, at the cost of the energy to maintain the proper transmembrane pressure (TMP) to drive water through the membrane (5.0 to 20.0 ft) at the desired rate, plus the scouring energy to control fouling of the membranes. This energy requirement may be as much as double that of a comparably rated conventional process (WEF, 2009), although unit energy consumption is reported to have dropped as low as 0.20 kilowatt hour per cu meter (kWh/m3) in current designs. MBR installations up to 38 mgd have been built, but MBRs are typically found in small- to medium-sized facilities. The MBR processes are typically not economical when peak flows are greater than twice the average flow, unless a parallel system, where enhanced high-rate clarification is provided for physical-chemical treatment of flows, exceeds twice the average.

In a 2013 survey (Carollo, 2013), there were nearly 250 MBR installations in the U.S. greater than 0.25 mgd, 16 of which were in Florida, ranking it fifth out of 39 states for the number of total MBR installations.

Biological Active Filters

The BAFs predate activated sludge. When Ardern and Lockett announced their discovery of the activated sludge process in 1914, the title of their paper literally included the phrase "oxidation … without the aid of fil-

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ters." The current versions of BAFs, however, are derived from research done from the mid-1960s through 1980 (Hodkinson et al., 1999) with the first modern installations occurring in the 1980s (Mendoza-Espinosa & Stephenson, 1999). The BAFs can be applied for the oxidation of carbon and ammonia, and nitrogen removal, and BAFs for nitrification and nitrogen removal can be replacements for suspended growth BNR processes or tertiary installations following an activated sludge process.

The BAFs are an attractive option for any utility looking to construct a compact process. Step-feed BNR and BAFs are two of the few innovative technologies that have been proven in large-capacity installations. The survey done for this study identified 438 BAF installations around the world, ranging from small-capacity plants up to 450 mgd. The U.S. is home to 81 BAF installations, more than a quarter of which reside in Florida. Twenty-four facilities in Florida use BAF technology, with the largest having a design capacity of 96 mgd.

Granular Activated Sludge

Aerobic granular sludge has been defined as aggregates of microbial origin, which do not coagulate under reduced hydrodynamic shear and which subsequently settle significantly faster than activated sludge flocs (de Kreuk et al., 2005). The GAS is different from conventional activated sludge in that the granules will not flocculate and the five-minute and 30-minute sludge volume index (SVI) values are very similar. The granules (minimum of 0.20 millimeter) settle rapidly, allowing bioreactor operation at high MLSS concentrations (8,000-10,000 mg/L). The GAS operates on a simple feed, aerate, settle, and decant cycle that is similar to a conventional sequencing batch reactor (SBR) process and can perform carbon removal, nitrification, denitrification, and phosphorus removal in one bioreactor (Giesen et al., 2015).

The first full-scale plant using a GAS process was constructed in 2005. As of January 2015, 13 full-scale municipal installations were reported to be in operation (Naicker et al., 2015) with a number of others reported to be in various stages of design or construction. As of April 2016, there were no U.S. installations.

The largest plant is the Garmerwolde Sewage Treatment Plant in the Netherlands, with a design capacity of 7.9 mgd. Advantages claimed for GAS include significantly reduced footprint and power consumption. At the plant, the process was 75 percent smaller than a comparable A/B plant treating the same wastewater. The GAS appears to be well-suited to existing SBR plants looking to increase capacity without further tankage construction.

Full-Scale Experience

Table 1 contains a summary of the full-scale experience with the technologies evaluated in this study. With the exception of the two youngest technologies, BAS and GAS, a substantial amount of operating experience exists worldwide and within the U.S. With respect to facility size, large facilities are in operation for all but BAS and GAS. The significance is that there is ample opportunity available with which a given utility can evaluate these innovative technologies prior to making a decision on implementation.

Example Comparisons

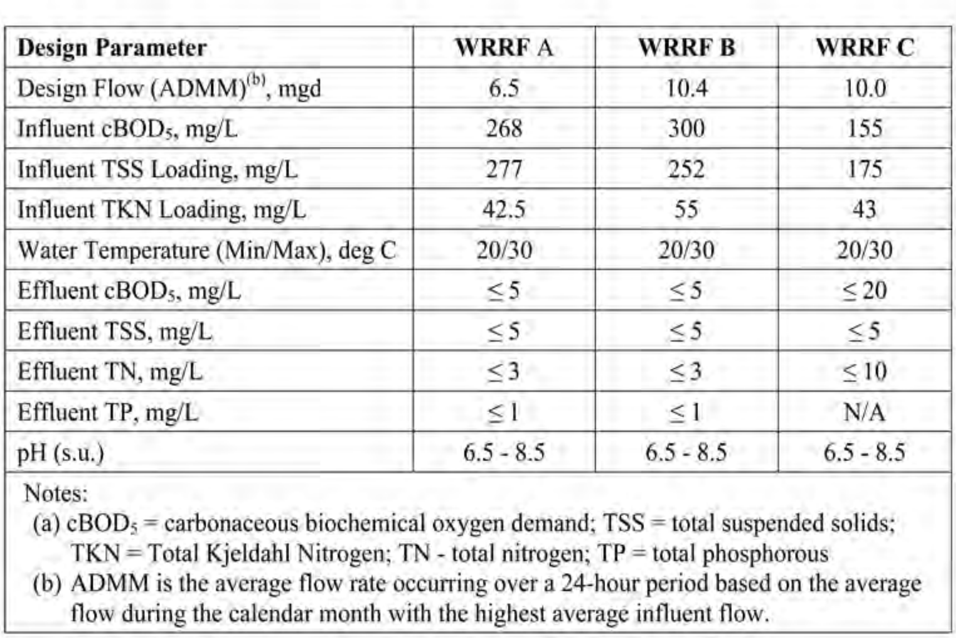
In the following sections, three case studies are presented for real-world technology evaluations for completed Florida WRRFs to select the primary liquid stream treatment technology. In all cases, maximum-month pollutant mass loadings were used to size the biological process reactors. Peak-hour flows were used to size the secondary clarifiers, tertiary filters, and other flow-dependent process elements. Aeration systems were sized to handle maximum-day demands.

The WRRF A is a completely new facility on a greenfield site designed to treat a flow of 5 mgd annual average daily flow (AADF). The influent wastewater was anticipated to be moderately strong. The effluent quality proposed was to meet Florida advanced wastewater treatment (AWT) with effluent disposal through public access reuse (PAR). Sludge management was anticipated to be aerobically held and then dewatered for further processing offsite.

The WRRF B is a retrofit of an existing facility to increase the design capacity in the face of increased influent loadings. The WRRF B currently operates as an MLE process with an existing capacity of 6 mgd AADF. The intent of the design is to increase capacity to 9 mgd AADF with influent wastewater strength being moderately strong. The effluent quality proposed for the upgrade is intended to meet Florida AWT with disposal through PAR. Sludge management was anticipated to be aerobically held and then dewatered for further processing offsite.

The WRRF C is a retrofit of an existing 8-mgd AADF secondary treatment plant using rotating biological contactors (RIBs). The intent of the design is to replace the rotating biological contactors (RBCs) and provide facilities that will produce effluent quality consistent with reuse through PAR. The influent wastewater quality is considered weak. Sludge management is anticipated to be aerobic sludge digestion, with dewatering for final disposal offsite.

Table 2. Specific Influent and Effluent Design Characteristics for Each Case Study(a)



Design Parameter	WRRF A	WRRF B	WRRF C
Design Flow (ADMM)(b), mgd	6.5	10.4	10.0
Influent cBOD_5, mg/L	268	300	155
Influent TSS Loading, mg/L	277	252	175
Influent TKN Loading, mg/L	42.5	55	43
Water Temperature (Min/Max), deg C	20/30	20/30	20/30
Effluent cBOD_5, mg/L	≤5	≤5	≤20
Effluent TSS, mg/L	≤5	≤5	≤5
Effluent TN, mg/L	≤3	≤3	≤10
Effluent TP, mg/L	≤1	≤1	N/A
pH (s.u.)	6.5 - 8.5	6.5 - 8.5	6.5 - 8.5

Notes:

(a) cBOD_5 = carbonaceous biochemical oxygen demand; TSS = total suspended solids; TKN = Total Kjeldahl Nitrogen; TN - total nitrogen; TP = total phosphorous

(b) ADMM is the average flow rate occurring over a 24-hour period based on the average flow during the calendar month with the highest average influent flow.

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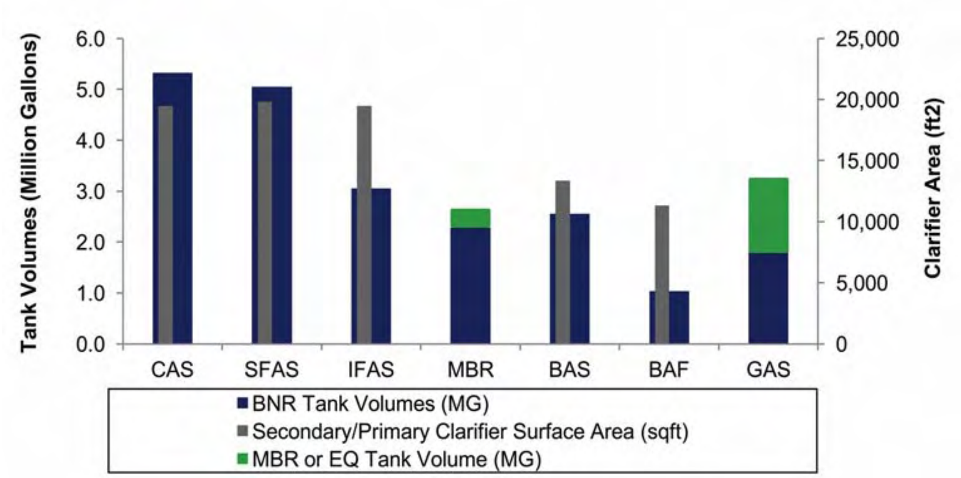

Figure 1. Estimated Treatment Volumes for Each Alternative for WRRF A

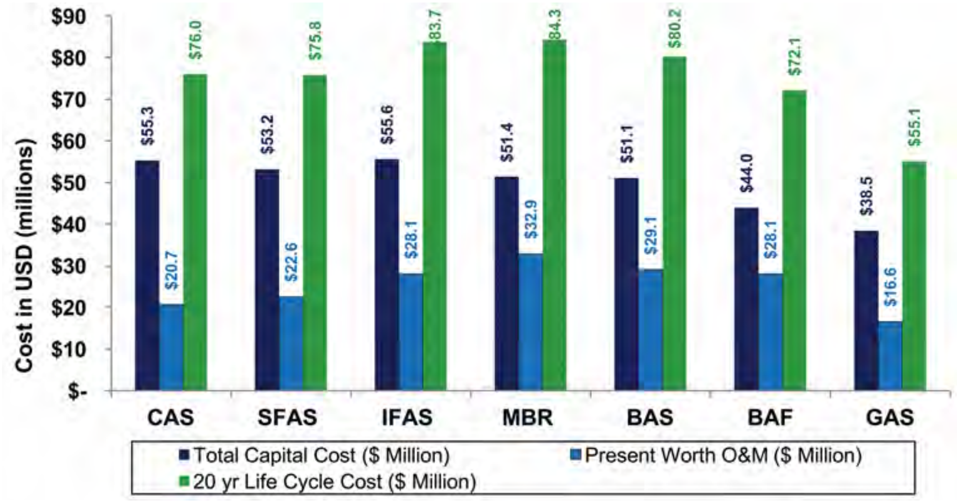

Figure 2. Estimated Capital Cost, Operation and Maintenance Costs, and 20-Year Life Cycle Cost for WRRF A

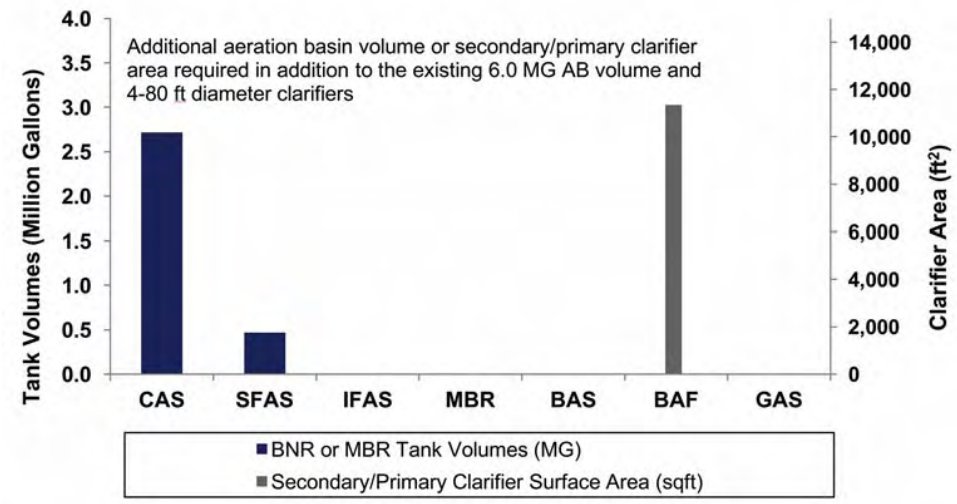

Figure 3. Estimated Treatment Volumes for Each Alternative for WRRF B

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Seven treatment processes were evaluated for each case study: 1) CAS, 2) SFAS, 3) IFAS, 4) MBR, 5) BAS, 6) BAF, and 7) GAS. Planning-level process sizing and estimates for capital, operations and maintenance, and present-worth costs were developed for each alternative. Due to the lower TN limits for WRRF A and WRRF B, a Bardenpho configuration was used as the CAS treatment system. An MLE configuration was evaluated for the higher TN criterion for WRRF C as the CAS treatment system. Table 2 shows the specific influent and effluent design criteria for each of the case studies.

The cost estimates were developed using cost information for the major components for each alternative; costs for both materials and installation were included. For major equipment items, budget-level quotes were obtained from vendors. To account for the lack of detailed design information, allowances were applied uniformly for miscellaneous piping and utilities, site work, electrical, and instrumentation for each of the three WRRFs. Present-worth costs assumed a uniform series compound factor of 13.7, an interest rate of 3.9 percent, and a design life of 20 years. Not all assumptions are presented here.

For the first case study, WRRF A required a high level of nutrient removal from the incoming wastewater, which was a major consideration for each of the alternative designs. Figure 1 shows the relative bioreactor volume and clarifier sizing for each of the alternatives for this case study. The CAS process (five-stage Bardenpho) design had the largest process volume requirement when compared to the other process alternatives, while the MBR process had the smallest overall volume.

The estimated costs for each of the alternatives for the WRRF A case study are displayed in Figure 2. Shown are:

- Individual capital costs of the liquid treatment system
- Present worth of the operation and maintenance costs
- Present worth of the total costs

As shown in Figure 2, the reduction in the process volume enabled by the use of the innovative technologies typically resulted in an increase in operational cost. The SFAS and BAS process designs assumed the addition of a chemical (aluminum sulfate) to reduce phosphorous. The IFAS and MBR required higher airflows compared to CAS, which increased power consumption, while the BAF required chemicals (methanol and alum) to reduce both nitrogen and phosphorous to the required levels; therefore, CAS had the lower operation and maintenance (O&M) costs when compared with these other alternatives. The exception to the inverse relationship between tank volume and operating costs, based on this case study, was GAS, which resulted in a reduced footprint and lower O&M costs. The GAS process design had a distinct advantage over the other facility designs for this situation.

The case study for WRRF B had the same effluent nutrients limits as WRRF A, but higher flow treatment capacity. This case study was different from the first one in that it evaluates the retrofitting of the different processes into an existing treatment system. The existing facilities at WRRF B were unique in that six MLE process tanks were constructed for a design flow of 9 mgd ADF, but only four tanks were equipped with aeration equipment. The process designs for the treatment process alternatives were similar to the WRRF A evaluation; Figure 3 shows the incremental increase in tank sizes required for each alternative beyond that in the existing facilities.

Both CAS and SFAS required additional volume beyond that in the existing facilities. The BAF process required significant modifications to the existing basins to incorporate this process. The IFAS, MBR, BAS, and GAS alternatives could be installed in the existing tank volume.

The estimated costs for each of the alternatives for the WRRF B case study are shown in Figure 4.

Similar to WRRF A, the CAS alternative required the largest overall tank volume, but had the least O&M costs of most of the alternatives. The existing facility had sufficient space available on the existing plant site for expansion; therefore, limitations on facility land space were not considered an issue. As mentioned, the BAF process design required additional retrofitting of the existing process, which increased the capital cost; the BAF also required significant chemical addition to reduce the phosphorous and nitrogen to the desired effluent quality. The SFAS process alone could not provide the required nitrogen removal due to the increased loadings; therefore, the existing deep-bed filters were retrofitted to be denitrification filters. This increased both capital and O&M costs.

Although, the IFAS, MBR, and BAS alternatives could be retrofitted within the basins, the overall life cycle costs were greater than the CAS and SFAS alternatives. The capital costs for these three alternatives were similar in magnitude to the CAS and SFAS alternatives, but the annual costs were significantly

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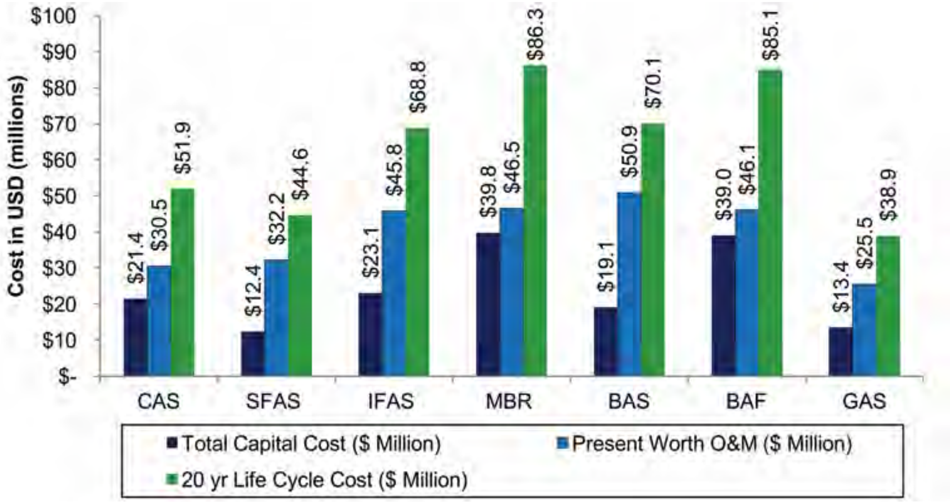

Figure 4. Estimated Capital Cost, Operation and Maintenance Costs, and 20-Year Life Cycle Cost for WRRF B

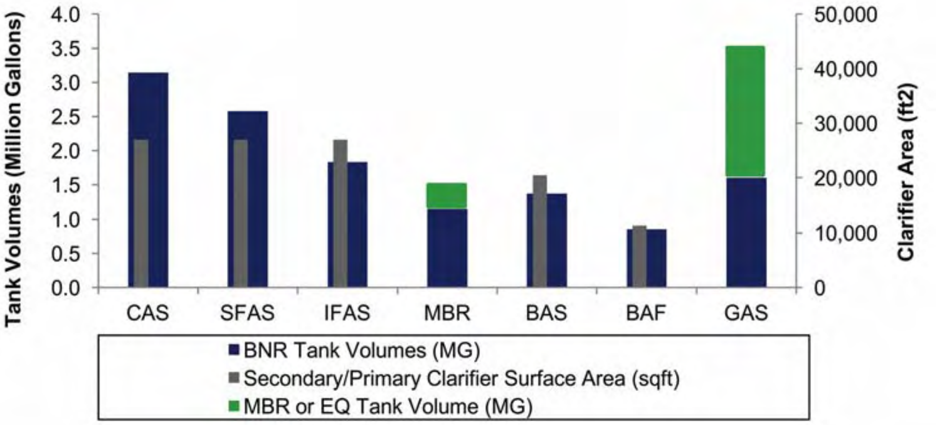

Figure 5. Estimated Treatment Volumes for Each Alternative for WRRF C

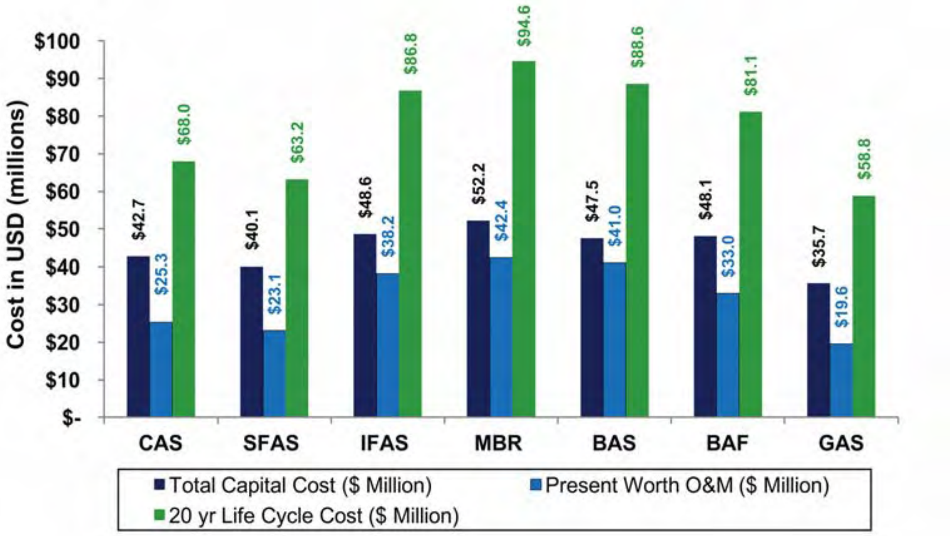

Figure 6. Estimated Capital Cost, Operation and Maintenance Costs, and 20-Year Life Cycle Cost for WRRF C

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higher. Both of these factors increased the 20-year life cycle costs for these alternatives and eliminated them from further consideration. The GAS design provided a small footprint, as well as lower O&M costs. The GAS alternative seemed to again provide a clear advantage over the other treatment designs for the WRRF B situation.

The WRRF C has a reduced nutrient removal requirement compared to both WRRF A and WRRF B. Similar to the prior studies, the CAS (MLE) process design volume for treatment was the largest. Figure 5 shows the design tank sizes for each of the alternatives for WRRF C; the estimated costs for each of the alternatives to upgrade WRRF C are shown in Figure 6.

Since phosphorus removal is not required for WRRF C and the TN limit is significantly higher (10 mg/L versus 3 mg/L), the estimated costs for chemical use for each alternative are significantly less than for the first two case studies; the BAF still required chemicals to provide the carbon for nitrogen removal. For WRRF C, the CAS had a lower annual cost over the IFAS, MBR, BAS, and BAF. The SFAS and GAC were the only options that had a lower O&M present-worth cost over CAS. As with the WRRF B case study, WRRF C site constraints did not affect the treatment options evaluation. Overall, the GAS alternative again presented a reduced footprint and reduced O&M cost, producing a clear cost advantage over the other treatment alternatives.

Figure 7 displays the life cycle costs for each alternative when compared to the CAS alternative for each case study, and illustrates the differences between each alternative for all three case studies. The GAS process seems to provide the more efficient and economical option for each of these situations.

Conclusions

The technologies considered have all successfully been implemented in full-scale treatment operations. The different alternatives that were compared are in operation throughout the world and many of them have been used in different-sized plants within the U.S. Most of the innovative alternatives considered are represented in wastewater treatment facilities over a wide range of treatment capacities and many of the process alternatives are in use in large facilities.

The relative costs of an alternative treatment process are dependent on several factors, such as influent wastewater quality, ability to reuse or repurpose existing facilities, effluent water quality requirements, cost of power and chemicals, availability of land, and aesthetic standards.

Based on the results of the different case studies within Florida, conventional technologies are often the best choice to meet the usual Florida requirements. Typically, the innovative technologies are a better fit for facilities that have limitations on land area, high effluent water quality requirements, or other special project constraints (i.e., constructability).

The GAS alternative for each case study seemed to provide a distinct cost advantage over the other alternatives and it has the potential to become the new standard for wastewater treatment in Florida.

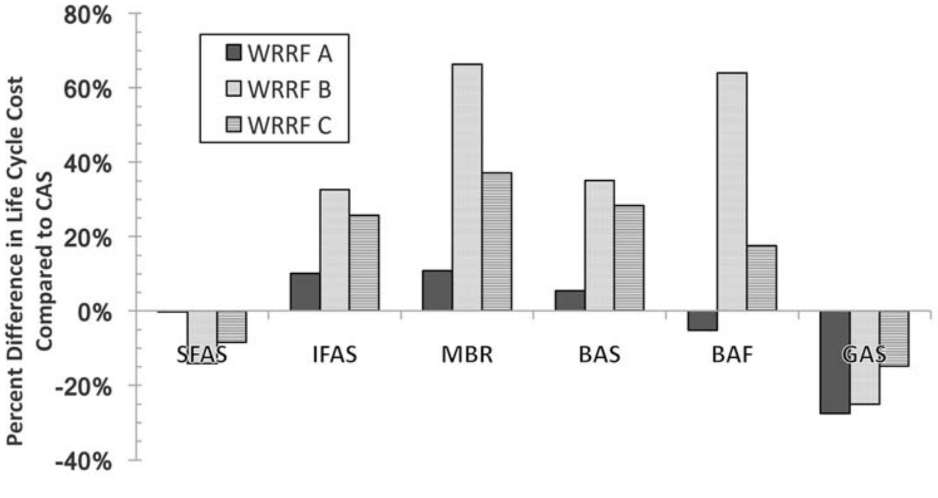

Figure 7. Twenty-Year Life Cycle Cost Comparison to the Conventional Activated Sludge Alternative for Each Case Study

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