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Escalating Water Demands for Energy Production and the Potential for Use of Treated Municipal Wastewater

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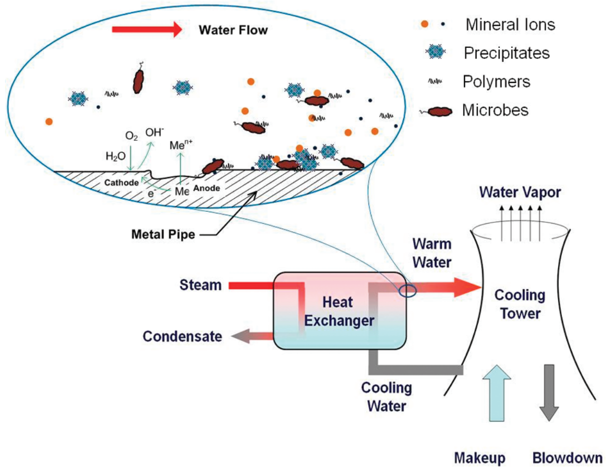

Population growth and economic development continue to increase the demand for electric power. The U.S. Energy Information Administration projects that demand for electricity in the United States will grow by 30% from 2008 to 2035.[1] According to the U.N. Environment Program, the global electric energy demand will increase by 49% from 2007 to 2035.[2] Despite growth in renewable energy sources, most of the electricity-generating capacity in the decades ahead will still be from coal, natural gas, and nuclear thermoelectric power plants.[1]

In most thermoelectric power production, water is used for cooling. About 43% of the existing power plants in the U.S. employ once-through cooling,[3] which will not be an option for many proposed new plants and may not be available for repermitted plants. Several cases have demonstrated that the lack of available freshwater for cooling can result in suspension of operations for existing power plants and permit denial for constructing new plants.[4,5] Meeting the freshwater demand of new power generation capacity will be very difficult in regions that already have limitations on available freshwater, e.g., in the west and southwest regions of the U.S.[6] Even in areas with relative abundance of freshwater, the water may already be fully allocated for maintenance of baseflow, aquatic ecosystem support, or other purposes.

Total freshwater withdrawal in the U.S. was 349 billion gal/d (BGD; 1.3 Gm^3/d) in 2005, of which thermoelectric power generation accounted for 41% while withdrawal for irrigation in agriculture was 37% of the total.[7] Although dry cooling technology exists for electric power production, water is desired for cooling as the capital infrastructure is lower cost and the use of water is associated with more efficient power plant operation.[8] The growth in demand for electricity in the U.S. and around the world means that new, reliable, abundant water sources for cooling will be needed to ensure sufficient electric power generation in the future.

Restrictions on available freshwater resources and difficulties in deciding water allocation priorities have led to increased interest in and use of alternative, nontraditional sources of cooling water. Indeed, the ability to use alternative water sources for cooling may provide a competitive advantage in terms of obtaining siting and construction permits for new power plants.[9]

Many types of nontraditional water sources can be considered for power plant cooling but their use may be restricted by varied availability and quality. For instance, abandoned coal mine drainage is abundant in Pennsylvania and West Virginia, while the most severe water constraints for cooling are more likely to occur in the western U.S.[10] Among various alternatives, treated municipal wastewater (MWW), or reclaimed water, is very promising owing to its ubiquitous availability and relatively uniform quality.[11]

A number of power plants have already blended MWW with freshwater as cooling system makeup[12,13] but the blend ratio varies significantly. Only a few power plants have operated their cooling towers with treated MWW as the dominant makeup water. A notable example is the Redhawk Power Plant in Arizona which uses MWW for over 90% of the cooling system makeup. The 6.46 million gal/d (MGD; 24.5 ML/d) of wastewater used at the facility is transported 40 miles (65 km) from a wastewater treatment plant in Phoenix.[11] The MWW received at the power plant is further treated before addition to the recirculating cooling system.

Although using treated MWW to replace freshwater for power plant cooling appears to be feasible based on its availability, use of this impaired water can pose several technical difficulties in cooling systems because of its lower quality compared to typical freshwater sources. The control of metal corrosion, mineral scaling, and biofouling in a cooling system is more challenging with use of a lower quality water such as secondary-treated MWW. In addition, legal and regulatory issues for wastewater reuse in power plant cooling need to be considered. Water ownership and right of use, for example, may complicate the use of treated MWW involving interstate or interbasin water transfer. Control of air emissions and proper management of blowdown (water removed for the control of salt concentration in the

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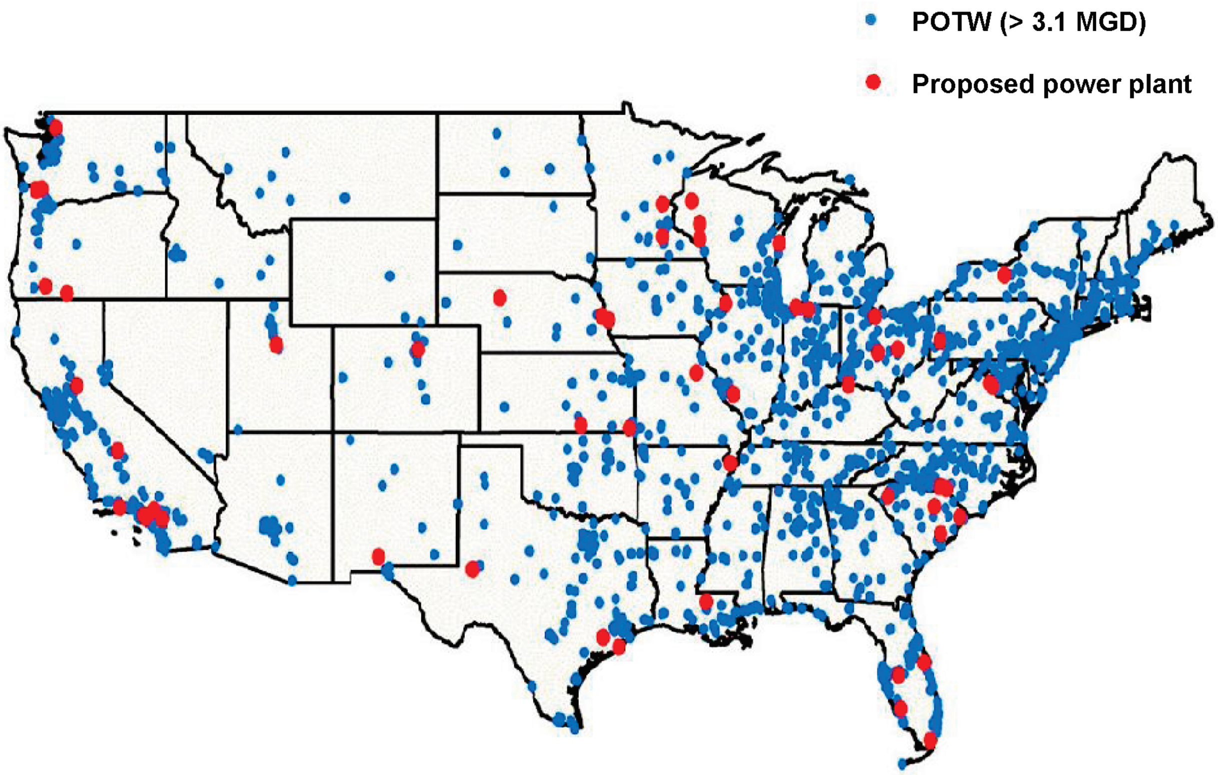

Figure 1. Locations of the proposed thermoelectric power plants (red dots) relative to the publicly owned treatment works (POTWs) that have flow rates greater than 3.1 MGD of treated MWW (blue dots) in the lower 48 states. A single red dot may represent multiple power plants if they are close to each other. The POTW locations were obtained from the U.S. EPA and the proposed power plant locations were obtained from the Energy Information Administration (2007).

system) in recirculating cooling systems using wastewater are public concerns that must be addressed.

The key technical, regulatory, and public acceptance challenges of using treated MWW as alternative cooling system makeup water in thermoelectric power plants are examined here. The existing U.S. regulations relevant to wastewater reuse for power plant cooling are first briefly reviewed followed by analysis of availability and accessibility of MWW for power plant cooling. Finally, the main technical challenges and potential solutions for MWW use in recirculating cooling systems are discussed.

RELEVANT REGULATIONS

Currently, the U.S. federal government does not directly regulate the practice of water reuse, including the reuse of treated MWW as power plant cooling water. The federal Environmental Protection Agency (EPA) has recommended guidelines for minimum treatment requirements and desired water quality for water discharge programs related to industrial cooling systems[13,14] (detailed review of regulations is available elsewhere[11]). The EPA guidelines specify that secondary-treated MWW effluent to be used as makeup water in recirculating cooling systems should at least meet the technology-based limits on BOD_5 (5-day Biochemical Oxygen Demand), TSS (Total Suspended Solids), and pH. BOD_5 and TSS are limited to a maximum of 30 mg/L on a weekly monitoring basis and pH should be maintained between 6 and 9. Fecal coliform bacteria are also restricted ($\leq$200 colony forming units/100 mL based on daily monitoring) with a minimum chlorine residual requirement (1 mg/L continuous) to limit the bacterial activity in the water aerosols leaving a cooling tower, which has the potential to enter the human respiratory system and cause health problems.

In addition to these EPA water reuse guidelines, several states have been developing regulations applicable to wastewater reuse in power plant cooling systems. The state regulations largely focus on the reduction of water aerosols emitted in cooling tower "drift," which may contain elevated concentrations of pollutants and microorganisms (*Legionella* is of particular concern) and pose a health risk to the public. Generally speaking, there are no major regulatory impediments for the use of treated MWW from publicly owned treatment works (POTWs) to meet the growing cooling water needs of thermoelectric power generation.

AVAILABILITY OF MWW FOR POWER PLANT COOLING

It is estimated that a total of 30−40 billion gal (110−150 GL) of MWW is treated per day in the U.S., with generation occurring in populated areas and with wide variation in effluent discharge rates.[15] For the analysis of MWW availability for power plant cooling, a comparison of the location and amount of wastewater generation and prospective water use in power generation was performed. The EPA maintains a database for National Pollutant Discharge Elimination System (NPDES) permits, and a review of this database revealed that 33,852 NPDES permitted discharges existed in 2007; 17,864 were POTWs in the lower 48 states.[15]

Depending on the particular cooling technology used in the power plant, the amount of water needed for cooling makeup can vary significantly. For once-through cooling, 20−50 gal of water (70−200 L) are used to generate 1 kWh of electricity.[16]

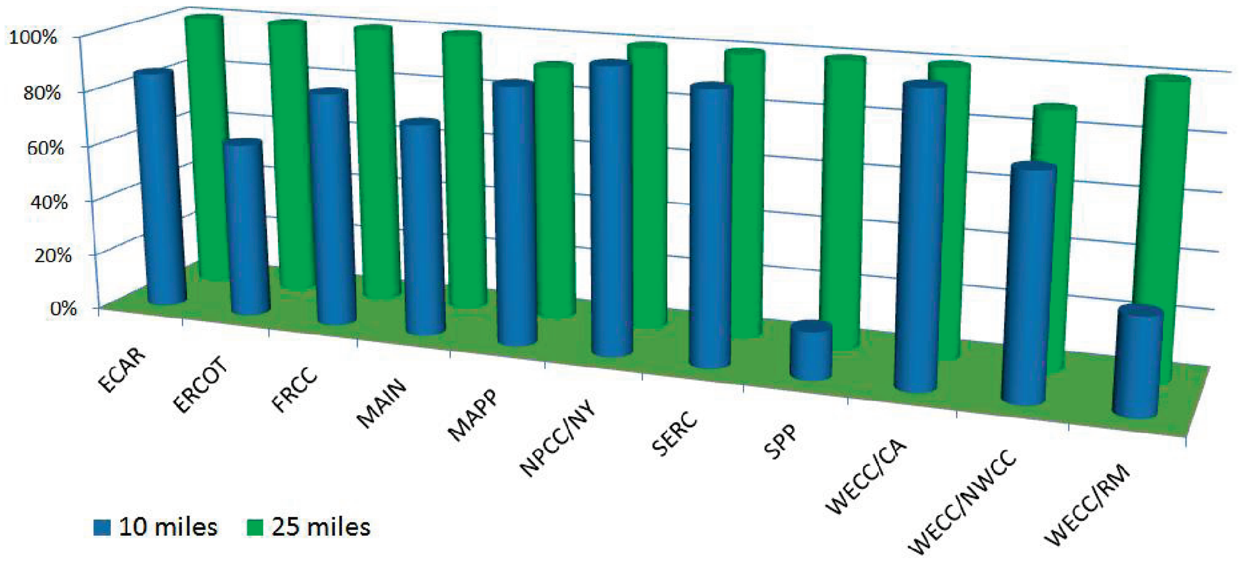

Figure 2. Fraction of the proposed thermoelectric power plants with sufficient amount of treated MWW available within the specified radius (10 miles and 25 miles). The power plants are categorized by NERC regions (NERC: North American Electric Reliability Council).

Alternatively, modern recirculating cooling towers only need 0.2–0.6 gal of water (0.8–2.3 L) to generate each kilowatt-hour of electricity.[9] Because the construction of new once-through cooling systems is discouraged under the Clean Water Act (Section 316(b)), the focus of our analysis was on recirculating cooling systems.

Among all thermoelectric power plants in the lower 48 states, 407 existing coal-fired power plants[17] were selected to represent potential users of treated MWW. It was assumed that the cooling systems in these 407 power plants are recirculating systems, regardless of their present actual configurations. A total of 110 proposed power plants, including renewal or new units as proposed in 2007 and to be constructed in the next five years,[18] were also selected to represent the potential new water users (Figure 1). The upper limit on cooling water demand was then estimated by using a conversion factor of 0.6 gal of water/kWh of electricity produced (2.3 L/kWh) for existing power plants and a higher conversion factor of 1.2 gal/kWh (4.5 L/kWh) for proposed plants.

The correlation between the water providers and users within a specified radius was determined in terms of the number of POTWs required to satisfy the cooling water needs of a power plant using geospatial analysis (ArcGIS version 9.2, ESRI, Redlands, CA).[19] Radii of 10 and 25 mi (16 and 40 km) around the power plant locations were examined as exemplary of reasonable transportation distances for treated MWW.

Nationwide, ~50% of existing power plants could obtain sufficient amount of cooling water from POTWs located within a 10 mi (16 km) radius, and an average of only 1.14 POTWs would be needed to supply enough water to meet their water demand. Furthermore, 76% of the power plants can have sufficient cooling water supply from an average of 1.46 POTWs if the radius is extended to 25 mi (40 km). As for proposed power plants, 81% would be able to obtain sufficient cooling water from POTWs located in a 10 mi (16 km) radius. With an increase to 25 mi (40 km), nearly all proposed power plants (97%) could operate with the supply of treated MWW (Figure 2). Thus, only 1 or 2 water conveyance pipes of reasonable length (<25 mi [<40 km]) would be required between a power plant and nearby POTWs to supply sufficient water for cooling. Of course, not all treated MWW will be available for use for power plant cooling, nevertheless the amount being produced and its widespread availability suggests that this potential source of cooling water merits investigation. The potential of MWW as an alternative cooling water source is particularly important to consider in the development of thermoelectric power plants in regions where freshwater is not readily available.

In addition to transportation issues, the actual quality of MWW and required cooling water quality will dictate treatment requirements in specific situations and will significantly influence the utility of MWW for cooling. Potential approaches for addressing these water quality and treatment challenges are discussed below.

■ TECHNICAL CHALLENGES

The major technical challenges for use of MWW in power plant cooling systems are exacerbated biofouling, scaling, and corrosion. These cooling system phenomena can be interconnected and antagonistically impact each other.

Biofouling. Although biodegradable organic material is largely removed in POTWs, treated MWW still contains appreciable amounts of phosphorus (P), nitrogen (N), and residual organic matter. The warm moist environment in recirculating cooling systems coupled with these constituents is conducive to biological growth.[20] Typical cooling tower operation at 35–45 °C and pH 6–9, with continuous aeration and exposure to sunlight, makes the cooling system a favorable habitat for bacteria, fungi, and algae.

The biological growth can quickly lead to biomass/slime accumulation on equipment surfaces, resulting in biofouling. The biofilm can bind with suspended solids, silt, corrosion products, and organic and inorganic deposits to exacerbate mineral scaling and corrosion problems.[21]

Control of biofouling can be achieved through chemical or physical methods. Application of chemical biocides is a widely adopted approach but often requires shock dosing (i.e., high dosages of the same or different biocide) or biocide alteration to ensure proper control.[21] Biocidal efficiency is affected by water temperature and chemistry, especially pH and redox state, and chemical species added for corrosion and scaling control.[22,23] A general guideline for acceptable biological growth in cooling towers is 10^4 CFU/mL (CFU: Colony Forming Unit) for planktonic bacteria or 10^4 CFU/cm^2 for sessile bacteria measured by the standard heterotrophic plate counts (HPC).[21]

Chlorination, usually with sodium hypochlorite (NaOCl), is the most common biocide used in cooling systems given its high efficiency and low cost.[20] Biofouling can be controlled by maintaining a total chlorine residual concentration of 1−2 ppm in the bulk water in laboratory experiments.[11] However, elevated organic content and ammonia (NH_3, though in near-neutral pH, significant concentrations of NH_4^+ are also present; herein "ammonia" will refer to this mixture) concentration in cooling systems using MWW can greatly increase the chlorine dose required to achieve breakpoint chlorination. Moreover, free chlorine tends to react with natural organic matter to form undesirable disinfection byproducts (DBPs), which are known to exhibit human toxicity.

Monochloramine (NH_2Cl) has been found as effective as free chlorine, with similar doses and contact times, in attacking preformed biofilms in cooling systems using seawater.[24] In preventing biofilm formation, NH_2Cl was more effective than free chlorine.[25] Although chloramination may require higher residual concentrations than chlorination (usually 1−3 ppm higher) to achieve similar biocidal efficacy, NH_2Cl is more stable than free chlorine.[26,27] Overall chemical consumption can be therefore potentially lower with chloramination.

Pilot-scale studies[11] indicated that NH_2Cl can be very effective in controlling biofouling in cooling systems using secondary-treated MWW operated at four cycles of concentration (CoC). Results from laboratory experiments did not indicate significant interference of carbonates (CO_3^{2-}/HCO_3^-), phosphates ($PO_4^{3-}/HPO_4^{2-}/H_2PO_4^-$), or sulfate ($SO_4^{2-}$) with the effectiveness of NH_2Cl while the organic matter slightly increased its decomposition rate. Pilot-scale tests indicated that in situ chloramine formation using ammonia present in the MWW and added NaOCl was unreliable.[11] To maintain total chlorine above 1 ppm (as Cl_2), preformed NH_2Cl had to be added to reliably control HPC in planktonic and sessile phases below the respective target criteria.

Inorganic Scaling. Given the relatively high levels of both dissolved and suspended solids, alkalinity, and water hardness (aqueous Group 2 metals expressed as calcium carbonate [mg $CaCO_3$/L water]) in secondary-treated MWW, a significant concern when using MWW in recirculating cooling system is the potential for severe mineral scaling. Scaling in cooling systems causes a multitude of operational problems, chief among which are the hindrance of heat transfer, the obstruction of flow in pipes, pump failures, and potential for cooling tower fill collapse due to excessive weight.[14]

The mineral precipitation and scaling in recirculating cooling systems is induced by the evaporative concentration of the recirculating water. Assuming there is no loss of the dissolved species to either evaporation or deposition, the CoC can be calculated using either the volume of evaporative water loss or the level of the salt concentration increase. With evaporative concentration, some salts eventually become supersaturated and precipitate to form scale. In this case, the volume-based CoC calculation is more appropriate. Besides evaporative concentration, the elevated temperature of the bulk water can exaggerate scaling, especially for common minerals such as $CaCO_3$ (which is reverse soluble—precipitation increases with temperature).

Power plant cooling with freshwater often involves only minor scaling problems, especially when the system is operated at low CoC. When MWW is used as makeup water, the cooling system performance could be significantly compromised by scaling and careful management of cooling water chemistry is needed. A better understanding of mineral deposition processes and control mechanisms is required before sound control technologies can be developed and implemented.

Antiscaling agents can prevent scaling in various ways.[28] Some can sequester or complex with scale forming cationic species, thereby raising the operational solubilities of the mineral ions and impeding the processes of clustering and nucleation. Others can work as crystal modifiers to alter the crystallization pathways and mitigate the growth of mineral particles. Many polymeric antiscalants, e.g., polymaleic acid, work as dispersants by providing an electrical and/or steric repellency of mineral particles, keeping them from aggregating. Finally, some chemicals, notably phosphorus-based agents such as tetra-potassium pyrophosphate (TKPP), can work as surface conditioners to render the surface unfavorable for scaling. A good antiscalant works through multiple mechanisms. Typical doses of the antiscalants used in cooling systems using freshwater are less than 10 mg/L. Most antiscalants that have been proven effective in freshwater may not, however, be as effective in treated MWW when similar doses are applied.[29]

A recent study shows that commonly used polymeric antiscalants can be effective to reduce scaling in recirculating cooling systems using treated MWW.[29] However, chlorine biocides reacted with the antiscaling polymers to decrease the polymer availability for scaling control. NH_2Cl was found to be better suited than free chlorine because of the reduced impact on antiscaling programs. This new understanding assists the development of scaling control strategies that are prerequisite for successful reuse of MWW for cooling.

Corrosion. Another challenge when using treated MWW in recirculating cooling water systems comes from corrosion of metal surfaces in heat exchangers or conveyance pipes. Corrosion may be exacerbated due to the degraded quality of the wastewater and the simultaneous occurrence of scaling and biofouling. Traditional corrosion control approaches in cooling systems have been developed based on the experience with freshwater and need to be re-evaluated.

Among the many water quality parameters influencing corrosion in cooling systems using MWW, phosphate and ammonia are of great concern: such concentrations can reach up to 50 and 70 mg/L, respectively, in secondary-treated MWW.[11] Ammonia is a strong complexing agent toward many metals and metal alloys.[30] It is recommended that it should not exceed 2 mg/L (as NH_3) in cooling systems.[31] Although the ammonia in the makeup water (MWW) can be high, several studies reported very low ammonia concentration in recirculating cooling water.[11,32−34] The phenomenon is most likely due to ammonia stripping and nitrification in cooling towers, where high water temperature (40−50 °C), high pH (8−9), and active aeration are all in favor of evaporative loss and/or oxidation of ammonia. A better understanding of ammonia stripping and nitrification in cooling towers is important for determining corrosion control strategies to overcome its aggressiveness.

Phosphate can adsorb onto the surface of metals and metal alloys to form a protective thin film against corrosion[35] and has been used as a corrosion inhibitor in cooling systems. $Ca_3(PO_4)_2$ has limited solubility and its precipitation and surface deposition help to mitigate corrosion. However, excessive phosphate precipitation causes scaling, and is particularly a concern when the water contains high hardness. Studies of the stability of phosphate and phosphate-based corrosion inhibitors show that these inhibitors tend to precipitate in treated MWW.[36]

Tolytriazole (TTA) is a commonly used copper corrosion inhibitor. It is capable of controlling corrosion of copper and cupronickel alloys to acceptable levels in tests with treated municipal wastewater.[37]

Acid addition is commonly practiced to control mineral precipitation, but decreased pH as a result of acid addition can raise the corrosivity of the cooling water. As such, pH-control-based scaling mitigation can potentially compromise the advantages of using mineral precipitation for corrosion inhibition. Studies on optimum acidification strategies that balance scaling and corrosion control are needed for particular cooling systems.

As noted previously, cooling systems using MWW can have high biofouling potential, which can cause microbiologically influenced corrosion. Traditional approaches of maintaining free chlorine residuals for biofouling control may cause higher corrosion rates due to the direct attack of free chlorine on metals and metal alloys. Free chlorine also degrades TTA. With respect to corrosion control, NH_2Cl has been found to be a more appropriate biocide than free chlorine for use in cooling systems using MWW.[37]

Chemical inhibitor addition for corrosion control is the most widely employed approach in recirculating cooling systems. When a cooling system switches its makeup water source from freshwater to an impaired water like treated MWW, traditionally proven corrosion control approaches may not work well and need to be re-evaluated by taking into account both the degraded water quality and the scaling and biofouling processes and associated control strategies.

POTENTIAL CHALLENGES AND OPPORTUNITIES

The complex water chemistry of MWW and the varying operating conditions of open recirculating cooling systems result in great challenges for the traditional approaches of using chemicals to control scaling, corrosion, and biofouling. New research is needed to identify technically sufficient, cost-effective control strategies to address these challenges. The feasibility of using chemical inhibitors in combination with advanced treatment to manage the cooling water quality needs to be examined to ensure successful use of MWW in cooling systems. Investigations employing both bench-scale systems and pilot-scale cooling towers are suited to explore optimum chemical treatment strategies before the most promising strategies can be tested in the field. Additional treatment of secondary-treated MWW, such as nitrification and/or filtration, can reduce suspended solids, bioactivity, organic matter, and alkalinity, but would require additional investment.

The most cost-effective approaches for managing MWW in cooling systems will depend on the quality of wastewater and are likely to involve a combination of onsite tertiary treatment of the MWW and chemical addition to the cooling tower. In addition, evolving regulatory issues, e.g., controls on interbasin transfers or concerns for contaminants in aerosols, will have to be considered, as well as environmental impacts of MWW transport and tertiary treatment. Integrated consideration of life cycle environmental impacts in addition to process costs will be needed for identification of the most sustainable approaches for use of treated MWW in meeting future electric power development needs.

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