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Cooling water use in thermoelectric power generation and its associated challenges for addressing water-energy nexus

Shu-Yuan Pan [a], Seth W. Snyder [b,*], Aaron I. Packman [c], Yupo J. Lin [d], Pen-Chi Chiang [a,e,*]

[a] Carbon Cycle Research Center, National Taiwan University, Taipei 10672, Taiwan, ROC
[b] Clean Energy and Transportation, Idaho National Laboratory, Idaho Falls, ID 83415, United States
[c] Department of Civil & Environmental Engineering, Northwestern University, IL 60208, United States
[d] Energy Systems Division, Argonne National Laboratory, IL 60439, United States
[e] Graduate Institute of Environmental Engineering, National Taiwan University, Taipei 10673, Taiwan, ROC

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ABSTRACT

Thermoelectric power plants traditionally have required huge volumes of water to condense steam from the turbine exhaust. The complex interdependency between water and energy poses new challenges for policy makers to achieve a safe, secure and sustainable supply of water and energy in the future. Cooling systems are the most water-intensive part of the thermoelectric generation process, presenting significant opportunities to reduce the withdrawal and consumptive use of fresh water. Reuse of impaired water for cooling can reduce freshwater withdrawal and decrease water contamination and withdrawal-related impacts on aquatic life and the environment. Here we focus on challenges and opportunities for improving water efficiency in the cooling systems of thermoelectric power plants. First, we present the types of cooling systems in a thermoelectric power plant. Then, we illustrate the key criteria for feed water quality for cooling systems. We use this information to determine appropriate design and operation guidelines for cooling systems. In order to facilitate the use of impaired water in cooling systems, we suggest the key technical issues and available water technologies for brackish water desalination.

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* Corresponding authors at: Carbon Cycle Research Center, National Taiwan University, Taipei 10672, Taiwan, ROC (P.C. Chiang).
E-mail addresses: seth.snyder@inl.gov (S.W. Snyder), pcchiang@ntu.edu.tw (P.-C. Chiang).

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1. Significance and importance

"Clean water and sanitation" and "affordable and clean energy" are two of the 17 Sustainable Development Goals suggested by the United Nations in 2016. Water and energy resources are inextricably entwined, because large amounts of energy are needed to pump, treat, transport, heat, cool, and recycle water, while water is used for generating power as steam to turn the turbines and the primary cooling fluid in thermal power plants. There are six interrelated aspects to water and energy management, as shown in Fig. 1: institutional, regulatory, technological, financial, social, and environmental aspects. From the technological point of view, the development of advanced water and energy technologies is of critical importance to achieve sustainable production and consumption of water and energy. The types of advanced water technologies may include green water infrastructure, energy-efficient water treatment, incorporation of information and communications technologies, and waste (e.g., brine) management. The development of advanced technologies also requires consideration of other components, such as sound regulation, institutional cooperation, environmental impact assessment, financial support, and community involvement.

Energy scenarios are usually developed based on forecasts of future energy demand and water constraints. Complex water-energy interdependencies pose new challenges for policy makers to achieve a safe, secure and sustainable supply of water and energy in the future. It requires systematically in-depth assessment on the impacts of energy and water production on one another. Dai et al. (2018) conducted an extensive literature review on the methodologies for water-energy nexus. They classified and assessed 35 comprehensive case studies based on both geographic scale (i.e., city-, regional-, national, and transboundary-level) and their nexus scope. The review revealed that research on the water-energy nexus has expanded in scale and scope over the past decade. For example, several assessments of water-energy use have shifted from the micro-level (e.g., industry and infrastructure) to the macro-level (e.g., city) to support resource management strategies at the regional level between countries (Dai et al., 2018).

Thermoelectric power generation is one of the most important areas of focus in the water-energy nexus because of its dependence on water resource availability for cooling. Cooling systems are the most water-intensive part of the thermoelectric generation process (Sovacool and Gilbert, 2014), presenting significant opportunities to reduce the fresh water use. This is especially critical in countries where thermoelectric power generation plays a dominant role in power production and regional water scarcity is a significant concern, such as the United States (UNESCO, 2014) and China (Zhang and Anadon, 2013; Zhang et al., 2014). In this review, we first

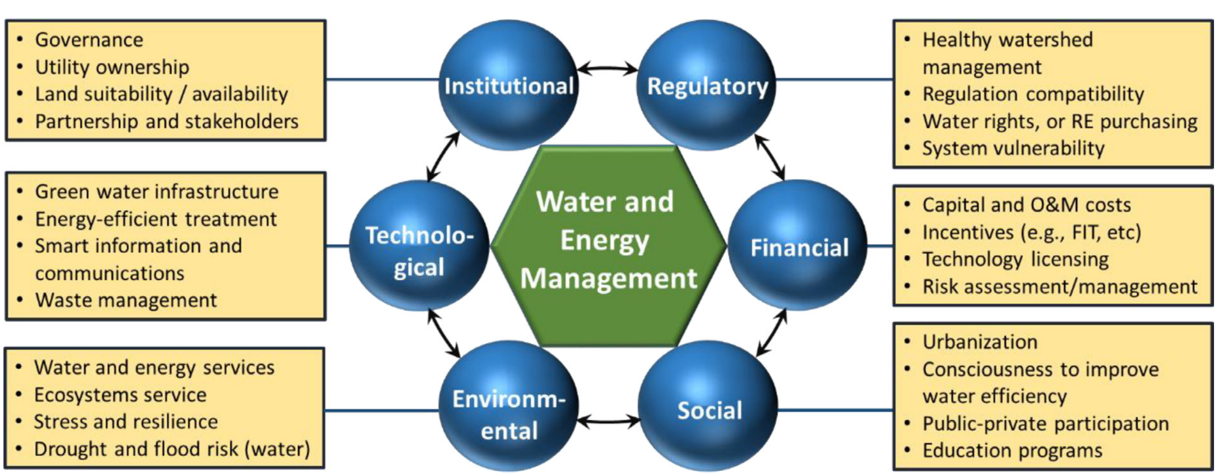

Fig. 1. Key components of water and energy management based on six interrelated aspects. Acronyms: RE (renewable energy), O&M (operation and maintenance), and FIT (feed-in tariff).

provide an overview of the water-energy nexus in thermoelectric power plants. Then, we focus on the general design and operations of water cooling systems in thermoelectric power plants. We summarize the average water requirements for several cooling systems in thermoelectric power generation, and identify the challenges of wet cooling systems in addressing the water-energy nexus. Two example challenges are compliance with zero liquid discharge and role of energy-efficient technology for water reuse. We also discuss and summarize the chemistry criteria of feed water quality for cooling systems to ensure the use of reclaimed water as makeup water in cooling systems. Finally, we suggest opportunities to maximize the efficiency of water and energy use for cooling systems in a thermoelectric power plant using a fit-for-purpose approach, retrofit cooling technologies, and green chemistry practices.

2. Water-energy nexus in thermoelectric power plants

Worldwide power generation including primary energy production accounts for ~10% and ~3% of total water withdrawals and consumption, respectively (IEA, 2016a). In the US and Western Europe, about 50% of water withdrawals are for energy production, primarily as cooling water (EEA, 2009). In China, almost 84% of total water withdrawals are for thermoelectric power generation, 99% of which is for coal-fired power plants (Qin et al., 2015). Taking into account impacts of climate change, there could be less inland freshwater available in many regions. The relation between future water use and thermoelectricity generation has been assessed in many regions, such as the southwest US (Talati et al., 2016), the UK (Murrant et al., 2017a) and South Africa (Thopil and Pouris, 2016). The scarcity of freshwater for cooling, as well as potentially in CO_2 capture units, in thermoelectric power plants can be expected in the near future (Murrant et al., 2017b). After use in the cooling system, cooling water effluent requires several treatment processes, which will consume additional energy, prior to discharge or further utilization. Extensive research has been carried out to examine the relationship between water and energy for thermoelectric power generation (Sanders, 2015; UNESCO, 2014). Several efforts have been underway to evaluate and optimize the efficiencies of energy and water use via various approaches, such as a series–parallel configuration of coolers (return temperature and flow rate) (Sun et al., 2015), a nonlinear uncertain systems algorithm (Salazar et al., 2011) and a sustainability risk index (Roy et al., 2012). In this section, we highlight the importance of water for energy and energy for water in thermoelectric power generation, as well as the strategies on mitigating the nexus trade-offs.

2.1. Water withdrawal and consumption for thermoelectric power generation

The options of source water for thermoelectric power plants include (i) natural surface water, (ii) underground water, (iii) reclaimed water, and (iv) treated potable water. As defined by the U.S. Geological Survey, 'water withdrawal' is water removed from a water source and most of which is returned to the source, while 'water consumption' refers to the portion of water removed that is lost to the system (e.g., by evaporation or incorporation into a plant or product) and unavailable to other users. Roughly 10% of the global water withdrawals is for energy production (IEA, 2016b), while over 80% of global electricity generation comes from thermoelectric power plants including fossil fuels and nuclear (IEA, 2017). Water is a particularly crucial element for the generation of thermoelectricity with respect to efficient and safe operation. In China, thermoelectric power generation accounts for about 10% of the total freshwater withdrawal (Zhang and Anadon, 2013). Similar in the US, the total water withdrawals in 2010 were dominated by agricultural irrigation (32%) and cooling water for thermoelectric power generation facilities (45%) (Maupin et al., 2014b). Over 90% of the electricity in the US is generated by thermoelectric power plants via nuclear and/or fossil fuels (USEIA, 2013). The performance of thermoelectric power generation largely relies on water cooling systems, and thermoelectric plants withdraw large quantities of water for cooling.

In addition to water withdrawals and consumption for cooling in thermoelectric generation, some water is used in extraction, processing, and transport for fuels in electricity generation. The extraction, processing, and transport of fuels in electricity generation could add as much as 10% to the life-cycle water consumption of coal-fired power plant (USDOE, 2014) and 20% to that of nuclear plants (Meldrum et al., 2013b) with wet cooling systems. Besides the fossil fuel-based and nuclear power plants, hydropower and other renewable energies such as solar cell and biopower (e.g., wood pellet) contribute a considerable amount to water consumption. Shaikh et al. (2017) developed an integrated framework for water and carbon footprint analysis to estimate the future trends of water consumption and withdrawal by electricity production sectors. Another study by Mekonnen et al. (2016) estimated the consumptive water footprint of electricity and heat sector in 2035 for five energy scenarios. They found that the consumptive water footprint of the electricity and heat sector to 2035 would increase if strong investments are not made in renewable energy including solar, wind and geothermal energy. Compared to fossil-based and hydropower energy, renewable energy (such as wind, solar photovoltaic and geothermal) has a relatively low water footprint per unit of electricity produced. It has been predicted that an increase of renewable energy contribution to 19.6% of total power production by 2035 would significantly decrease the water footprint of the global electricity and heat sector (Mekonnen et al., 2016).

Current post-combustion CO_2 capture systems (e.g., amine-based processes) associated with coal-fired power plants also require significant quantities of cooling water. The addition of an amine-based CO_2 capture process would double the water uses for a wet cooling system (Carter, 2010; Zhai et al., 2011). On average, a coal-fired power plant generates 1100 lb/MWh of CO_2 emissions. Talati et al. (2014) found that capture and storage of 90% of the CO_2 from such a plant would increase plant water use by 20–50%. Similarly, in the case of UK, pathways to the year of 2050 with high levels of CO_2 capture and storage would increase the water consumptive intensity by 30–69% over 2010 levels (Byers et al., 2014). Risks to the aquatic environment would also be intensified if thermoelectric power generation with CO_2 sequestration facilities is clustered.

2.2. Energy for cooling water supply and treatment

Energy is an imperative element for the conveyance, treatment, purification, distribution and disposal of water. The energy used for the water supply has rapidly grown due to the sharp increase in demands on water resources. It is expected that global water demand will increase by 55% by 2050 in comparison to 2000 levels (OECD, 2012). In 2010, global energy used for water abstraction, treatment, distribution, and post-use wastewater treatment and handling represented about 1.7–2.7% of total energy sales, corresponding to ~10.2 EJ of primary energy (Liu et al., 2016b). In 2014, however, the IEA's World Energy Outlook estimated about 4% of global electricity consumption was attributed to extraction, distribution and treatment of water and wastewater, along with 50 million tonnes of oil equivalent of thermal energy (IEA, 2016b). By 2040, the energy requirement in the water sector is

Table 1
Average energy intensity associated with water facilities (exclusive of end use consumption) around the World.

Water source	Scale	Item	Region	Average energy intensity (kWh/m^3)	References
Water	Network	Supply and treatment	-	~0.79	CEC (2006)
Water	Network	Supply and treatment	USA	0.42–0.55	Rao et al. (2017)
Water	Network	Supply and treatment	New York, USA	0.12–0.36	Rao et al. (2017)
Water	Network	Conventional treatment	Australia	0.01–0.20	Cammerman (2009)
Water	Network	Conventional treatment	Ontario, Canada	0.38–1.44	Maas (2010)
Water	Network	Conventional treatment	New Zealand	0.15–0.44	Kneppers et al. (2009)
Water	Network	Conventional treatment	USA	0.18–0.47	WEF (2010)
Water	Network	Conventional treatment	Taiwan	0.16–0.25	Cheng (2002)
Surface water	Network	Conveyance to agriculture uses	World	0.25–1.55[a]	Liu et al. (2016b)
Groundwater	Network	Conveyance to agriculture uses	World	0.20–0.55[a]	Liu et al. (2016b)
Wastewater	Network	Collection and conveyance	-	0.25–0.66	CEC (2006)
Wastewater	Network	Collection and treatment	-	~0.53	CEC (2006)
Wastewater	Network	Treatment and disposal	USA	0.2–0.8	Pabi (2013)
Wastewater	Facility	Aerobic and anaerobic digestion	-	~0.6	McCarty et al. (2011)
(Waste)water	Facility	Gravity filtration	-	0.005–0.014	Plappally and Lienhard (2012)
(Waste)water	Facility	Coagulation using polymers	-	0.4–0.7	Tripathi (2007)

[a] The range of the measures is between the 25th and 75th percentiles.

projected to more than double to ~16% of electricity consumption in the Middle East.

Table 1 presents the average energy intensity associated with water-related facilities around the world. The energy intensity of treatment for different water sources varies widely: from extremely low of relatively fresh surface waters (energy consumption mainly in pumping) to extremely high of seawater desalination (Plappally and Lienhard, 2012). It is noted that, in a typical municipal wastewater treatment plant, 52% of the energy is used for aeration, 30% for biosolid processing, and 15% for pumping (Pabi, 2013).

2.3. Strategies on mitigating nexus trade-offs

Opportunities to mitigate nexus trade-offs exist in improving both water and energy efficiency, especially at the point of end use (Rao et al., 2017; UNESCO, 2014). Different methodologies and tools, such as series–parallel cooler network (Ma et al., 2017b), have been proposed to reduce the amount of water use in cooling water system. Improving water efficiency in cooling systems can substantially reduce energy for treatment and supply within the entire water network, thereby reducing the amount of water needed by the power sector. Most cooling systems use water as the heat transfer fluid because of historically high availability and low cost, but require a large amount of energy to transport the cooling water, especially for coolers installed on high platforms. The cooling systems contain two subsystems, i.e., a cooler network and a pump network, which are usually optimized separately. Several strategies can be used to improve both water and energy efficiency in cooling operations, including increased water recycle and reuse, and energy recapture and reuse. Most of the required energy is lost due to friction and pressure drop or discharged as waste heat energy or concentrated brines. Novel materials and engineered surfaces to improve heat transfer and decrease friction can potentially improve energy efficiency by as much as 10% (Attinger et al., 2014; Chouquet et al., 2010; Zhang et al., 2017). Techniques such as hydro turbines (Ma et al., 2017a) can be applied to recover surplus potential energy (i.e., water pressure).

For cooling tower operations, the most straightforward way to decrease water use is to deploy cooling loops that reuse or recycle water, but ~40% of cooling plants in the US use once-through (OT) cooling and do not recycle cooling water (Gude, 2015; Tidwell et al., 2014). Water reuse strategies for cooling can employ very diverse approaches, from internal recycling of cooling water to use of municipal and industrial wastewater for cooling. Switching cooling to a wastewater source does not necessarily reduce total water use in the plant, but reduces withdrawals of cooling water from primary source water bodies, and thereby reserves high-quality freshwater supplies for direct consumptive uses. Internal water recycling generally involves evaporative cooling towers with an internal water loop for water recirculation in the facility. The limitation on water recycle in these systems is typically concentration of salts to a point that they cause mineral precipitation, scaling, and fouling of pipes and heat-exchange surfaces (Feeley et al., 2008). Antifouling strategies can be used to improve long-term heat-transfer performance and increase the water recycle factor (equal to the salt concentration factor) in the cooling system (Altman et al., 2012; Gill and Lin, 2010). Use of municipal and industrial wastewater for cooling typically provides a lower-cost alternative to other new sources of fresh water such as seawater desalination. The challenges in switching to wastewater for cooling involve the requirement of enhanced treatment processes for total organic carbon and biochemical oxygen demand, as well as subsequent demineralization (Hill et al., 2014; Walker et al., 2013). The quality of effluent from the polishing processes should meet the specifications for cooling tower influent that are consistent with the operation guidelines for biofouling and corrosion control.

Thermal power plants and water desalination facilities discharge large volumes of brine, providing a substantial opportunity for improved efficiency through recapture and reuse of water, energy, and solids (Elimelech and Phillip, 2011; Gude, 2015; Tidwell et al., 2014). Strategies of co-located desalination facilities with a power plant have been promoted not only because of the avoided cost of constructing and permitting a new intake of seawater but revealing environmental benefits of combining cooling water discharge with desalination brine. Advanced technologies such as pressure retarded osmosis (Prante et al., 2014), microbial fuel cells (Feng et al., 2017) and anaerobic membrane bioreactors (Hu et al., 2018) can be used to recover chemical energy from concentrated brine or wastewater. Improved dewatering or water recapture from brines can decrease the overall water needed for plant operations, or alternatively provide a recovered water stream that can be applied for other purposes (Löwenberg et al., 2015; Subramani and Jacangelo, 2014). Finally, recovery of purified salts can provide a value-added product that reduces the overall life-cycle water and energy use by producing these materials as a by-product instead of requiring additional water and energy to produce them in primary production facilities (Kim, 2011; Morillo et al., 2014; Perez-Gonzalez et al., 2012). Recapture and reuse options for water and energy are therefore being explored as strategies to reduce the overall water-energy nexus impact of cooling and desalination operations.

3. Cooling system in thermoelectric power plants

The bulk of water withdrawals and consumption for thermoelectric generation are for plant operations, especially for cooling. A cooling tower is a commonly used device that transfers excessive (residual) heat energy in a process system through introducing water streams with a lower temperature. Thermoelectric power generation requires huge quantities of water to condense steam from the turbine exhaust. For instance, a conventional 500 MW coal-fired power plant typically consumes roughly 26.5 m^3 of water per minute (Feeley, 2003). Approximately 90% of power plant water use is for cooling steam exiting the turbine (Tsou et al., 2013). As a result, water reuse and recycling from other processes in the plant or the use of cooling tower blowdown for supplying water to other plant processes can reduce the total plant water usage. In this section, we illustrate and discuss the types of cooling systems, operation indexes, and evaluation of source water for cooling systems.

3.1. Types of cooling system

Cooling towers can be classified by the approaches: (i) the type of air induction into the tower such as natural draft (air moves up naturally without the use of fans), mechanical draft (air is forced through the structure by a fan), or fan-assisted natural draft; (ii) the direction of airflow such as cross-flow or counter-flow; and (iii) the type of air–water contact such as direct (open circuit) and indirect (closed circuit). In general, four types of cooling systems are employed when generating electricity.

3.1.1. Dry cooling

Dry cooling relies on air, rather than water, as the primary coolant medium to transfer heat through a surface that separates the circulating cooling fluid from ambient air. Since it utilizes the principle of convective heat transfer (not using evaporation), the needs for water withdrawal and consumption are eliminated. However, the efficiency of dry cooling is significantly affected by ambient temperatures and humidity. It is most desirable to apply a dry cooling system in regions with tropical and dry climates. Moreover, the capital cost of dry cooling is approximately ten times higher than that of once-through cooling (i.e., ~180 USD per kW) (EPRI, 2007).

3.1.2. Once-through systems

Once-through (OT) systems withdraw water from a source (e.g., ocean, river, lake or cooling pond) as the cooling fluid and then returns it to the surface water body. Seawater is widely used for OT cooling in coastal coal-fired and/or nuclear power plants (Zhang et al., 2016). Since the cooling water passes through heat exchanger only once, the composition of cooling water does not change significantly while passing through equipment (Nalco, 2009). The OT systems do not normally consume water within the plant, but do indirectly consume water in freshwater systems through increased evaporation resulting from reservoirs and increased water temperature (Gude, 2015). This is especially important for the life-cycle cost analyses of water handling, where several studies on its global analysis have been conducted (Destouni et al., 2012; Jaramillo and Destouni, 2015).

3.1.3. Wet cooling towers (or open recirculating)

Wet cooling towers operate on the principle of evaporating cooling for heat rejection. Open recirculating system withdraws water and then circulates it within the system rather than discharge it, while air is forced to pass through circulating water. Since a fraction of the cooling water leaves the tower by evaporation and drift during recirculation, the concentrations of minerals and contaminants in circulating water increase over time. To maintain the appropriate concentration, a fraction of cooling water is removed as 'blowdown', while 'makeup' water is introduced to cooling systems to compensate for water losses due to evaporation, drift and blowdown. The amount of makeup water required directly depends on the extent to which water can be reused within the plant, and the salt concentration factor is equivalent to the water recycle factor. Practically, the extent of water recycle depends on the maximum salt concentration that can be used in cooling operations, and is typically limited by mineral precipitation, scaling, and fouling on pipes and heat exchange surfaces that degrades system performance.

3.1.4. Hybrid cooling (or closed circuit cooling)

Hybrid cooling incorporates elements of both wet and dry cooling systems separately or simultaneously. A hybrid system exhibits similar performance of heat transfer to a wet cooling system, while providing the advantage of a dry cooling tower (i.e., protection of working fluids from environmental exposure and contamination). In a closed recirculating system, the circulating water is ideally filled once, completely enclosed, and shut off from the atmosphere, and therefore, minimal water is lost from the system. The composition of cooling water remains fairly constant (Nalco, 2009).

3.2. Water use for cooling systems

The intensity of water consumption for electricity generation varies by region significantly since the power generation mixes and the adopted cooling technology would largely influence water consumption at a facility level (Lee et al., 2017). The specific selection of cooling technologies determines the water withdrawal and consumption for electricity generation in a country. Table 2 summarizes the average water requirements for cooling systems with respect to types of energy/fuels and generators for thermoelectric power generation. Water-efficient cooling technology is essential for thermoelectric plants, especially for concentrated solar power plants located in arid regions with high solar flux. Concentrated solar power plants are frequently located in water stressed regions (Sun et al., 2017). Dry cooling is considered the most important water conservation approach for thermoelectric power plants. As shown in Table 2, the total water withdrawal and consumption of dry cooling were only 0.02–0.60 m^3/MWh. Zhai et al. (2011) also found that water consumption and withdrawal of dry cooling system can be reduced by more than 75% compared with wet recirculating cooling towers. In fact, the withdrawal water use in wet cooling system is typically five times higher than that in dry cooling (Zhang et al., 2014). The average consumptive and withdrawal water using wet cooling system is roughly 0.5–2.6 and 1–132 m^3/MWh, respectively, depending on the unit size of power plants. When comparing the same cooling systems, combined-cycle gas turbines exhibit relatively low water withdrawals and consumption among other generator technologies.

For selection of cooling technologies, there is a trade-off between water withdrawal and consumption, depending upon regional water availability. For instance, at existing U.S. thermoelectric power plants, OT cooling and recirculating cooling towers account for 43% and 53% of the total cooling systems, respectively (USEIA, 2014). In India, OT cooling and recirculating cooling towers account for 32% and 67% of the total cooling systems in coal-fired power plants, respectively (IEA, 2015). As shown in Table 2, OT cooling results in significant water withdrawal but negligible water consumption, while wet recirculating cooling exhibits higher water consumption but significantly less water withdrawal. The vast majority of water withdrawn for power generation is passed through an OT cooling system and then returned to the original source. In this case, the water is rapidly "used" for the cooling process rather than "consumed". However, the OT cooling

Table 2
Average water requirements for cooling systems in thermoelectric power generation.

Cooling system	Fuel type[a]	Generator technology[b]	Capacity (MW)	Cooling water requirement (m^3/MWh)[c]		References
				Consumption	Withdrawal	
Dry (air) cooling	Coal	ST	100–250	–	0.59	Zhang et al. (2016)
	Coal	SC	300–1000	–	0.31–0.37	Zhang et al. (2016)
	Natural gas	CC	231–241	0.38	0.38	Sanders et al. (2014)
	Natural gas	CC	–	0.00–0.02 (0.01[d])	0.00–0.02 (0.01[d])	King et al. (2013)
Once–through cooling	Coal	Generic	–	0.4–1.2 (1.0[d])	76–189 (138[d])	Maupin et al. (2014a)
	Coal	ST	443–811	1.41	110.5	Sanders et al. (2014)
	Coal	ST	–	2.0	143.8	Scanlon et al. (2013)
	Coal	SC	300–1000	–	82.8–103.1	Zhang et al. (2016)
	Natural gas	ST	20–742	0.05	4.6	Sanders et al. (2014)
	Natural gas	ST	1179–1363	3.23	454.3	Sanders et al. (2014)
	Natural gas	ST	–	1.7	533.7	Scanlon et al. (2013)
	Natural gas	CC	186–706	0.14	24.8	Sanders et al. (2014)
	Natural gas	CC	–	0.08–0.38 (0.38[d])	28.4–75.7 (43.1[d])	King et al. (2013)
	Natural gas	CC	–	0.5	223.3	Scanlon et al. (2013)
	Nuclear	ST	–	1.7	136.3	Scanlon et al. (2013)
Wet cooling (open recirculating)	Coal	Generic	–	1.8–4.2 (2.6[d])	1.9–4.5 (3.8[d])	Maupin et al. (2014a)
	Coal	ST	–	2.1	2.4	Scanlon et al. (2013)
	Coal	ST	157–854	2.13	2.85	Sanders et al. (2014)
	Coal	ST	–	0.53	132.5	Meldrum et al. (2013a)
	Coal	SC	550	1.5	1.9	Zhai et al. (2011)
	Coal	SC	300–1000	–	2.1–2.4	Zhang et al. (2016)
	Coal	SC	–	0.38	87.1	Meldrum et al. (2013a)
	Coal	IGCC	–	0.76	0.95	USDOE (2006)
	Natural gas	ST	–	2.6	2.7	Scanlon et al. (2013)
	Natural gas	ST	–	2.5–4.4 (3.1[d])	3.6–5.5 (4.6[d])	King et al. (2013)
	Natural gas	CC	–	0.68	0.87	USDOE (2006)
	Natural gas	CC	–	0.9	1.0	Scanlon et al. (2013)
Cooling pond	Coal	Generic	–	1.1–2.7 (2.1[d])	1.1–90.9 (46.3[d])	King et al. (2013)
	Coal	ST	–	2.8	37.9	Meldrum et al. (2013a)
	Coal	SC	–	0.2	56.8	Meldrum et al. (2013a)
	Fossil/biomass	–	–	~1.82	1.89–2.27	USDOE (2006)
	Nuclear	Generic	–	2.1–2.7 (2.3[d])	1.9–49.2 (26.7[d])	King et al. (2013)
	Nuclear	–	–	~2.73	3.03–4.16	USDOE (2006)
Hybrid system	CSP	Power tower	–	0.4–1.1 (0.6[d])	0.4–1.1 (0.6[d])	King et al. (2013)
	CSP	Trough	–	0.4–1.5 (1.3[d])	0.4–1.5 (1.3[d])	Diehl and Harris (2010)
	Geothermal	Binary	–	0.8–2.7 (1.8[d])	0.8–2.7 (1.8[d])	King et al. (2013)

[a] Concentrated solar power (CSP).
[b] Steam turbines (ST); combined cycle (CC); supercritical (SC); integrated gasification combined cycle (IGCC).
[c] Per megawatt hour (MWh) net electricity output.
[d] Median value.

may not be an environmentally-friendly option for modern thermoelectric power plants due to the large intake of water and thermal discharge to the water environment. This would disturb and affect aquatic ecosystems considerably. Therefore, a gradual shift has occurred in the thermoelectric power generating sector away from OT cooling to wet-recirculating (evaporative) towers and dry cooling systems. At present, the number of power plants utilizing wet (evaporative) cooling system with an open recirculating cooling tower has rapidly increased in many regions (Peer and Sanders, 2017). In California, the use of OT cooling is banned and thus all cooling system must be replaced with recirculating towers or dry cooling systems (Rao et al., 2017).

4. Challenges in wet cooling to addressing water-energy nexus

For a thermoelectric power plant, water-related challenges are primarily pertinent to scarcity, quality and the allocation of water (Wehn and Montalvo, 2017). In this section, we discuss the potential challenges in a wet cooling system including zero liquid discharge and controlling chemistry.

4.1. Compliance with zero liquid discharge (ZLD) scheme

Sound management of blowdown water from thermoelectric plants is a key issue for wet recirculating cooling systems. The blowdown stream contains elevated levels of hardness and total dissolved solids but little organics. Improper management of blowdown could have an adverse impact on the aquatic environment, soil and groundwater. Management options depend on water quality, local discharge regulations, location of the discharge plant, and capabilities of treatment processes (Feng, 2010). Typically, four options for blowdown management can be considered (Muftah, 2011): (i) direct discharge to surface waters, (ii) discharge to wastewater treatment facilities, (iii) deposition in land disposals, and (iv) injection in deep wells. Although blowdown reuse after proper treatment processes can be beneficial to water conservation, the overall process system would still result in a concentrated brine discharge with extremely high levels of total dissolved solids (TDS) and/or contaminants. These higher levels of concentration present significant problems in sewage treatment plants, or to further recycle for non-potable uses in buildings.

The goal of zero liquid discharge (ZLD), or "zero blowdown", is to eliminate liquid waste leaving the facility. In other words, all wastewater should be converted to dry form for ultimate disposal (EPRI, 2012). In the cooling systems, the goal to achieve ZLD is through the deployment of treatment technologies to manage high TDS levels, low blowdown rates, and thus, high cycles of concentration. In general, ZLD involves three stages: pretreatment (generate sludge), pre-concentration (produce reclaimed water), and evaporation/crystallization (produce distillate and solid salts). In the pre-concentration stage, cost-effective membrane processes are usually applied to push the water recovery ratio to 90–95% (Xiong and Wei, 2017), and to ensure that effluent characteristics avoid corrosion and temperature issues (Ahirrao, 2014). The energy and costs per unit of water recovery increase exponentially as the concentration of brine and other components increase. Therefore, at a transition point in terms of% recovery, the value of the water does no longer justify further recovery. Prior to the pre-concentration stage, a pretreatment stage is typically required to protect the membranes from fouling and scaling by removing potentially problematic constituents such as suspended particles and hardness. The evaporation/crystallization stage is regarded as the final step to eliminate the concentrated liquid waste through phase change with the input of energy (e.g., thermal methods). However, high energy consumption for ZLD, i.e., typically from membrane-based or thermal processes, remains a major issue that limits the deployment of ZLD (Tsai et al., 2017).

4.2. Operation and maintenance

In the cooling system, common technical issues of operation and maintenance include scale deposition, corrosion, and (bio)-fouling. To mitigate the scale depositions, corrosion and microbiological contamination, makeup water for cooling systems is subjected to standard treatment protocols (Nall and Sedlak, 2013). In the following section, these important technical issues in the cooling system are discussed.

4.2.1. Scale deposition

Scale is a dense coating of inorganic compounds formed from the precipitation of partially water-soluble constituents (Nalco, 2009). It may be attributed to the presence of calcium, magnesium, sulfate, alkalinity, phosphate, silica, and fluoride in cooling water. Minerals, such as calcium carbonate ($CaCO_3$), calcium phosphate (e.g., $Ca(H_2PO_4)_2$, $Ca_2P_2O_7$, etc) and magnesium silicate ($MgO{\cdot}xSiO_2$), are relatively insoluble in water. These minerals would precipitate out of the water to form scale in cooling systems. The deposition of mineral scales on the surface of heat exchanger in cooling systems will reduce the heat transfer efficiency from the process fluid to cooling water. Although increasing cycles of concentration can save water, as levels of dissolved minerals increase with higher cycles of concentration, the potential for scaling and corrosion increases. An increase in pH or alkalinity drives the formation of $CaCO_3$ scale. If the pH is greater than 10.3, the dominant species is carbonate (CO_3^{2-}) ion, which provides a favorable environment for the formation of $CaCO_3$ precipitates (Pan et al., 2012; Stumm and Morgan, 2012). In contrast, some minerals such as SiO_2 are less soluble at lower alkalinity.

To predict the tendency of $CaCO_3$ scale forming in cooling systems, three indicators, i.e., Langelier Saturation Index (LSI), Ryznar Stability Index (RSI), and Puckorus Stability Index (PSI), are typically employed. These three indexes depend on the calcium hardness, alkalinity, temperature and TDS of the cooling water by defining a "$p\mathrm{H_s}$" value (i.e., the saturation pH for $CaCO_3$), as shown in Eq. (1):

$$p\mathrm{H_s} = (p\mathrm{K_2} - p\mathrm{K_s}) + p\mathrm{Ca} + p\mathrm{Alk} \tag{1}$$

where $p\mathrm{K_2}$ and $p\mathrm{K_s}$ are the second dissociation constant and the solubility product constant of $CaCO_3$, respectively. pCa and pAlk are the negative logarithms of the calcium and alkalinity concentrations (as in pH with respect of hydrogen ions), respectively. Then the LSI, RSI and PSI are defined as Eqs. (2), (3) and (4), respectively:

$$\mathrm{LSI} = p\mathrm{H_{actual}} - p\mathrm{H_s} \tag{2}$$

$$\mathrm{RSI} = 2p\mathrm{H_s} - p\mathrm{H_{actual}} \tag{3}$$

$$\mathrm{PSI} = 2p\mathrm{H_s} - p\mathrm{H_c} \tag{4}$$

where $p\mathrm{H_{actual}}$ is the pH of cooling water, and $p\mathrm{H_c}$ is the equilibrium pH based on total alkalinity. The three indexes reveal different criteria for $CaCO_3$ scaling. For the LSI, a positive value signifies a tendency for $CaCO_3$ scaling, while a negative value indicates a corrosion tendency by the cooling water. For the RSI, the ideal range is 6–7 (i.e., represents no scaling or corrosion in the system), while values higher than 7 indicate a corrosion tendency and values lower than 6 indicate a scaling tendency. Similarly, to consider the effect of actual water alkalinity, the PSI system modifies the RSI one by calculating the system equilibrium pH instead of the actual pH.

4.2.2. Corrosion

In a cooling system, corrosion is attributed to the oxidation of metals (e.g., steel) through electrochemical or biochemical reactions. Corrosion is a great concern with the common materials in cooling systems, such as mild steel. For copper, aluminum alloys and stainless steel, although they generally corrode more slowly than mild steel, these materials may be subject to severe localized attack (or pitting). In any case, corrosion will cause loss of metal thickness, even penetration through tube walls and then leakage of process fluids. The most important factors affecting corrosion include dissolved and suspended solids, oxygen and other dissolved gases, pH, alkalinity, superficial velocity of water (or fluid), temperature, and microbial activity.

Compatibility with materials of construction (e.g., piping) should also be a critical concern. Chemical constituents of concern include, but are not limited to, chloride (Cl^-), ammonia (NH_3), sulfides (H_2S), and TDS (Tsou et al., 2013). Materials to focus on include metal alloys and concrete, where metals are of primary concern due to the potential for corrosion and stress cracking. When temperatures exceed 150–160 °F, excessive chloride concentration in water is a problem in auxiliary heat exchangers. High conductivity attributed to chloride and/or sulfate ions also may result in severe corrosion by increasing concentrations of species that precipitate to form scale. If the TDS of the water is above 10 g/L, copper bearing alloys should be used as the main condenser (EPRI, 2003). Sodium silicate corrosion inhibitor chemistry (Duke and Yang, 2009) and Azole corrosion inhibition chemistry (Hsieh et al., 2010) can protect metallic surfaces and copper/bronze surfaces, respectively.

4.2.3. Fouling and biofouling

Fouling, including chemical fouling and biofouling, is the deposition and accumulation of suspended materials in heat exchange equipment. It severely decreases the heat transfer efficiency and reduces the lifetime of cooling tower systems. In general, foulants could come from external sources such as dust, dirt, sand and natural organics around a cooling tower, or internal sources such as corrosion products, aluminum phosphates, and iron phosphate (Nalco, 2009). Numerous microorganisms, e.g., algae and bacteria, can grow in a cooling tower system under advantageous conditions. For instance, constituents such as formaldehyde, carbonate, sulfate, phosphate and organic compounds in cooling water can serve as nutrients for the growth of microorganisms (Al-Bloushi et al., 2017b). The presence of ammonia or nitrate also changes the water chemistry of the system considerably, and contributes to the metabolic activity (Venkateswarlu, 1996). Ammonia also impacts the ability of certain biocides to adequately inactivate microorganisms. In general, an open recirculating cooling system provides a favorable environment for triggering biofouling, compared to a closed system. Nutrients and substrates that contribute to microbial growth and biofouling include suspended particles, dissolved organic matter and minerals, which readily accumulate in the cooling system through intake and concentration of makeup water (Kusnetsov et al., 1993; Meesters et al., 2003). If biological growth is not controlled, severe biofouling and accelerated corrosion can occur.

4.3. Incorporation of water-energy flow analysis with water reuse

Adequate treatment can provide the required water purity for reliability, safety, efficiency, and economic performance. In Fig. 2, we present the concept of water reuse and recycle for wet recirculating cooling towers in power plants. Proper management and treatment of makeup and feed water is necessary to mitigate scale depositions and corrosion in cooling systems. Successful operations require consideration of the mass balance on energy and water parameters for the plants. The steady-state concentration of water quality parameters, such as salinity, can be evaluated and provide an estimate of the energy requirements for water treatment of the makeup water.

In a wet cooling system, a water mass balance including makeup, blowdown, evaporation and drift can be established via Eq. (5):

$$Q_M = Q_B + (Q_E + Q_D) \tag{5}$$

where Q_M is the flow rate of makeup water, Q_B is the flow rate of blowdown, Q_E is the flow rate of evaporation, and Q_D is the flow rate of drift. The makeup water rate (Q_M) is typically 166% of the evaporation rate (Q_E) (EPRI, 2003). The Q_E is mainly related to the flow rate of circulating water (Q_C) based on a heat balance in Eq. (6):

$$Q_E = (Q_C \times \Delta T \times C_p)/H_v \tag{6}$$

where H_V is latent heat of vaporization of water (i.e., ~1000 Btu/pound), ΔT (°F) is water temperature difference from tower top to tower bottom, and C_p is specific heat of water (i.e., 1 Btu/pound/°F).

Drift should be tightly controlled to protect exterior structures from the staining and corrosive effects of the cooling tower water. The flow rate of drift (Q_D) also can be estimated based on the value of Q_C, as described by Eq. (7):

$$Q_D = f \times Q_C \tag{7}$$

where the term f is a constant: (i) <0.001 if the cooling tower has windage drift eliminators; (ii) 0.001–0.003 for an induced draft cooling tower; and (iii) 0.003–0.010 for a natural draft cooling tower. Typically, the f value of 0.008 should be a reasonable estimate for a new tower in good mechanical condition.

After determining the flow rates of both evaporation and drift, one can obtain a relationship between flow rates of makeup (Q_M) and blowdown (Q_B), so-called cycles of concentration (*COC*), by Eq. (8).

$$COC = Q_M/Q_B \tag{8}$$

Typical values of *COC* in cooling towers range between 3 and 10 (EDF, 2013). Increasing *COC* reduces the volume of makeup water and decreases the overall water use. *COC* is a universal measure that defines the maximum concentration for a limiting chemical constituent, such as salinity and silica. We can also estimate the value of *COC* using other chemical compositions by Eq. (9):

$$COC = C_B/C_M \tag{9}$$

where C_B and C_M are the chemical composition of a certain constituent (e.g., magnesium hardness, chloride or sulfate) in blowdown and makeup, respectively. For ion pair limits, such as magnesium and silica, the value of *COC* can be determined via Eq. (10):

$$\mathrm{COC} = \sqrt{\frac{C_{B,ij}}{C_{M,i}C_{M,j}}} \tag{10}$$

Calcium hardness is not always a dependable indicator of *COC*. Based on the calculation for each of the constituents of concern, the constituent or constituent pair with the lowest calculated *COC* value represents the limiting parameter for that source of water or blend of source waters.

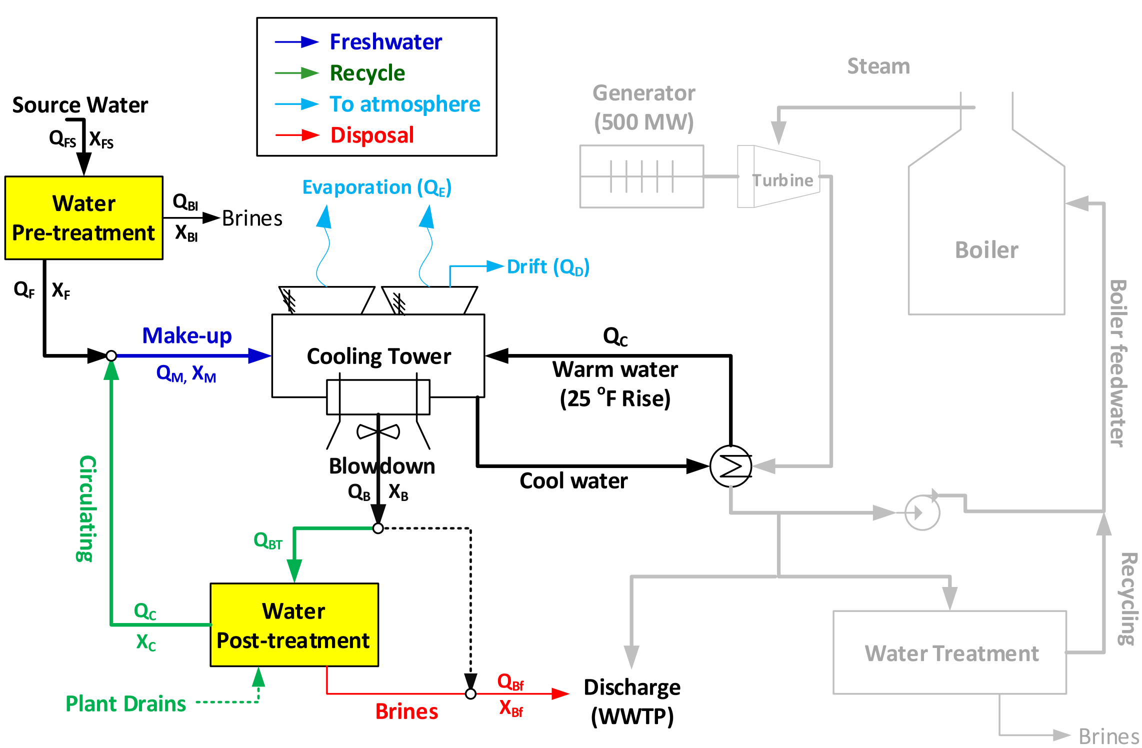

Fig. 2. Water reuse scheme for an open recirculating wet cooling tower in a power plant.

4.4. Lack of On-Line monitoring and control programs

Monitoring is an integral part of water treatment systems to determine the treatment efficiency and effectiveness and guide cost-effective usage of energy, water and chemicals. In fact, monitoring for scale control, corrosion and microbial growth during system operation is essential to minimize the total cost of operation. For instance, corrosion monitoring, as a diagnostic tool, is a standard practice in the treatment system to predict equipment life, as well as to identify key factors responsible for corrosion issues and assure implementation of solutions (Nalco, 2009). While there are several monitoring techniques, no one technique provides all the necessary data to evaluate treatment efficacy. Therefore, more than one technique may be necessary to monitor a particular treatment system (Nalco, 2009).

The performance of cooling systems can be optimized through the implementation of on-line control for cooling system parameters. Water quality typically varies based on seasonal factors, such as summer/winter conditions (salt and snow melt), rains (introducing suspended solids) and droughts. Continuously maintaining and improving the critical measurements of cooling water quality (e.g., conductivity, pH, TDS, dissolved oxygen and sodium ion concentration) are important to improve system life, plant integrity, and overall efficiency (Honeywell, 2012). Normally, the conductivity, pH and ORP in cooling water treatment systems are measured to minimize scale formation, corrosion and biological growth.

4.5. Uncertainty of climate change and temperature variations

Water availability plays a critical role on the future of the water and energy nexus. During dry summers, cooling water scarcity and higher water temperatures reduce plant efficiency and lead to reduced power output at several thermal power plants (both nuclear and fossil fuel) in Europe and the South-East US. Increased temperatures also generally increase electricity demand for air conditioning. This increased stress from the power sector correlates with increased water consumption for agricultural crops and domestic use (USDOE, 2014). These changes and variations pose significant challenges for resilience of energy infrastructure. The climate and weather conditions should be critically considered in the design of cooling tower systems. Changes in heat budget of the cooling water may impact the capacity and efficiency of thermoelectric power plants to generate electricity (Quijano et al., 2016). Martín and Martín (2017) found that hotter climates require twice as much heat transfer area and consume 5% more water while colder climates need larger towers, around 50% larger diameter and height.

5. Criteria for using reclaimed water in cooling systems

In a power plant, the steam condenser has the largest cooling requirement (heat rejection). With limited water availability, source water treatment and supply may affect project development, such as site selection, treatment systems, and waste discharge.

5.1. Suitability of source water as makeup water

The suitability of source water as makeup water for cooling towers in power plants should be systematically evaluated. Generally, the evaluation of source water includes six steps (EPRI, 2003): (i) identification and characterization of water sources, (ii) evaluation of constituents of concern such as cooling tower chemistry criteria and environmental concerns, (iii) identification of design and operating impacts, (iv) screening of source water, (v) requirement of pre- or post-treatment, and (vi) evaluation of disposal options. It is necessary to obtain reliable water quality information from available resources, such as state/local water quality sources. However, the water databases are usually lack of future water trend estimates. They are also lack of criteria specific for cooling tower operations. Therefore, the design phase requires supplemental sampling and analyses for typical cations and anions (e.g., scale forming ions), metals, and other contaminants (GE, 2009).

The quality of the makeup water should be assessed as part of the risk assessment for the cooling systems. Table 3 presents a summary of technical issues based on water source. Natural surface water such as lakes, rivers, and streams can be used for cooling tower makeup in thermoelectric generation if the distance and elevation differences are economically viable for conveyance. Using natural surface water for cooling, the pre-treatment of raw water consists of (i) biofouling control, typically by chlorination, and (ii) removal of suspended solids (Venkateswarlu, 1996).

Reclaimed water includes rain (or storm) water, municipally treated wastewater (or wastewater treatment plant effluent), industrial process water, and agricultural return water. Reclaimed water can vary widely in constituents such as conductivity, ammonia, phosphate, nitrates, organic carbon, and micro-organism. For instance, rain/storm water collected from a roof can be harvested

Table 3
Technical issues based on water source as a cooling fluid.

Types of water	Water sources	Seasonal variations	Suspended debris	General Minerals[a]	Biological related[b]	Organics[c]	Metals[d]	Others[e]
Natural surface water	Rivers and streams	O	O	O				
	Lakes	O	O	O	O			O
Underground	Well water			O				
	Contaminated groundwater			O		O	O	O
Reclaimed water	Rain/storm water	O		O				
	Industrial process			O	O	O	O	O
	Municipally treated wastewater							
	Wastewater treatment plant effluent							
	Agricultural return			O	O	O	O	O
	Dairy or feed-in runoff			O	O	O		O
	Cooling tower blowdown			O			O	O
Potable water	Drinking water							

[a] General minerals (Na, K, Ca, Mg, HCO_3, CO_3, Cl, SO_4 and SiO_2).
[b] Biological (BOD, COD, NH_3, PO_4, etc).
[c] Organics (Organics Volatile, non-volatile or pesticide compounds).
[d] Metals (Ba, Sr, Fe, Mn, Cu, Zn, Se, As, Cr, Hg, etc).
[e] Others (NO_3, PO_4, ClO_4, S, F, etc.). Relevant information was gathered from the literature (EPRI, 2003).

for cooling tower makeup because of its relative lack of contamination. The low salinity levels of these types of reclaimed waters reduce challenges and costs, especially compared to seawater desalination. Industrial process water may contain a high level of salinity, which requires additional desalination treatment technologies to 'upgrade' the quality of water. Veolia has successfully applied a Hydrotech Discfilter process to reclaim sewage plant effluent for cooling tower makeup in a 1200 MW natural gas power plant since 2016. The maximum treatment capacity for the sewage plant effluent is designed to be 2725 m^3/h (Veolia, 2017).

Displacing a fraction of fresh water consumption with reclaimed water could have a major impact (Gellings and Goldstein, 2008). Peer and Sanders (2017) investigated the shifts of cooling water usage in thermoelectric power generation in the US between 2008 and 2014. The authors noted a trend of transitions from traditional fresh and/or saline surface water to reclaimed water sources in the US power sector. Similarly, Stillwell and Webber (2014) developed a retrofit analysis tool to evaluate the geographic, technologic, and economic feasibility of using reclaimed water from wastewater treatment plants as an alternative cooling source for thermoelectric power plants. The results indicate that using reclaimed water as cooling water at thermoelectric power plants in Texas reduces water withdrawals by at least 300 million gallons per day of freshwater at the 92 power plants (representing about 50% of the total power generation).

5.2. Cycle chemistry of makeup water to cooling systems

Reuse of impaired water can reduce freshwater withdrawal and decrease water contamination and withdrawal related impacts on aquatic life. Proper management and treatment of makeup water is necessary to prevent scale, corrosion, and other deposits in the cooling system. The water quality will impact the efficiency of the cooling system operation, and the system's ability to meet the required cooling demand. The cycle chemistry of a cooling tower is a critical part of a plant's efficiency, although it is often misunderstood or neglected. In a cooling water system, the cycle chemistry is determined by the makeup water and the materials of construction. A good cycle chemistry treatment will minimize makeup water intake and blowdown. Since the chemical constituent of makeup water can affect the performance of cooling system, the maximum allowable concentration of each water quality parameters should be critically evaluated, as aforementioned in Eq. (9). Typically, the major constituents in water can be categorized into:

- Suspended solids: such as clay, silica, and organic matter.
- Dissolved impurities: such as Ca^{2+}, Mg^{2+}, Na^+, NH^{4+}, HCO_3^-, Cl^-, CO_3^{2-}, SO_4^{2-}, NO_3^-, SiO_2, and soluble organic matter (e.g., humic substances).
- Nutrients: such as phosphates and nitrates.
- Microorganisms: such as algae, bacteria (sulfate reducers, iron bacteria, etc.) and fungi.
- Dissolved gas: such as O_2, CO_2, NH_3, and H_2S.

A primary consideration for the operation of cooling systems is the water quality, and therefore treatment technology of the makeup stream. The impurities affecting water quality can include turbidity, oil and grease, harmful microorganism, heavy metals, nutrients, organics, dissolved inorganics, endocrine disrupters, odor and taste, and engineered nanomaterials. Cooling tower makeup water typically contains soluble minerals, low concentrations of organic compounds, and suspended solids (EPRI, 2003). In this section, we discuss several key water quality parameters, including salinity, silica and microbiological activity.

5.2.1. Salinity

Salinity or TDS is a measure of the total ionic concentration of dissolved salts in water. Salinity is usually derived from the conductivity measurement, known as practical salinity, by a factor dependent upon the level and type of impurities. The most common chemical constituents of salinity in municipal water supplies include calcium, sodium, potassium, phosphate, nitrates, carbonates, and chlorides (Nall and Sedlak, 2013). In contrast, the definition of TDS is the sum of all ion particles that are smaller than 2 μm. In wastewater, TDS may include organic constituents such as urea and hydrocarbons in addition to the salt ions (salinity).

Levels of salinity or TDS often pose significant challenges for end-uses such as cooling tower makeup water or irrigation. For cooling tower users, high salinity can lead to corrosion, scale and fouling. Water consumption in a cooling tower is affected by the salinity level in the makeup water. Conventional limits for salinity in the basin water range from 1.0 to 1.5 g/L, consistent with a conductivity of ~2400 μS/cm (Nall and Sedlak, 2013). In contrast, the salinity of potable water is generally less than 0.5 g/L (Nall and Sedlak, 2013).

5.2.2. Silica

The build-up of scaling from both dissolved and colloidal silica is an issue in cooling towers and evaporation systems for thermoelectric power generating facilities. Polymerization of silica strongly depends on water chemistry and governed by system operating conditions (e.g., pH, temperature, impurities). In evaporative cooling systems, the concentration of silica in feed water must maintain below ~0.18 g/L in absence of silica/silicate control agents, to avoid silica-based deposits (Amjad and Zuhl, 2010). Silica's glass-like morphology and abrasive particles may damage membranes in processes such as reverse osmosis.

The concentrations of silica in surface waters and groundwater are usually <0.020 and <0.045 g/L, respectively, while typically exceeding 1.0 g/L in brackish waters or brines. Excess silica in water is undesirable for several industries since it will be deposited on the high-pressure steam-turbine blades. It is difficult to remove silica and silicate scale completely from equipment surfaces. Considerable effort and expense to mitigate silica scale deposition (Arar et al., 2013) or reduce silica concentration in feed water (Amjad and Zuhl, 2010) have exhibited some success. The most common methods for removing silica from a waste stream include electrocoagulation (Den and Wang, 2008; Wang et al., 2009), lime softening (Al-Mutaz and Al-Anezi, 2004), and ion exchange (Salvador Cob et al., 2014; Wang et al., 2011). In some cases, maintaining the pH of basin water above 9.0 can effectively avoid the occurrence of ammonium ions in water minimizing silicate scale (Morgan and Stumm, 1981).

5.2.3. Microbiological activity

Nutrients and substrates for microbial growth in cooling systems are mainly derived from suspended particles, dissolved organic matter, and minerals (Kusnetsov et al., 1993). Side stream filters can be deployed in closed-cycle cooling systems to reduce turbidity in cooling water (Basu and Debnath, 2015). A variety of biocides are used in cooling water systems for biofouling control. Chlorine dosing (e.g., chlorine, chloramine, or chlorine dioxide) is the most common method to inhibit microbiological growth in cooling water systems (Frayne, 1999). However, there are tradeoffs between the effectiveness of chlorine-based disinfection and corrosion of pipe and reservoir materials from this strong oxidant. Very high free chlorine concentrations, 30–50 mg/L, are effective in killing suspended cells and surface-attached biofilms as long as these concentrations are achieved throughout the system (Carducci et al., 2010; Iervolino et al., 2017; Lin et al., 2011), but cause substantial corrosion damage to metallic materials in the water loop (Ludensky, 2005). Conversely, low chlorine concentrations at levels typically used as water residuals, 1–5 mg/L, kill suspended cells but not biofilms in cooling systems. Therefore, chlorination should be complemented by dosing with other chemical oxidants (e.g., ozone and sulfuric acid) and non-oxidizing biocides to prevent biofouling (Lin et al., 2011; Liu et al., 2011).

Efficacy of many anti-microbial compounds is highly dependent on ionic charge, which controls the ability of the compound to penetrate microbial cells and biofilms (Abdallah et al., 2014; Tseng et al., 2013). As a result, pH control is important to the performance of biofouling control, e.g., the suitable pH range for chlorine (an oxidizing biocide) is 5–8, while triazine (a non-oxidizing biocide) is 6–9. Additional chemicals such as polyphosphonates are also typically added with oxidizing biocides to protect metal surfaces and prevent scaling and corrosion (Amjad and Demadis, 2015). Scale deposits also affect the performance of chemical disinfectants, while biofilm growth can exacerbate scaling and corrosion, making it important to co-manage biofouling, scaling, and corrosion to maintain long-term system performance (Li et al., 2016; Ludensky, 2005).

Because bio-available nitrogen and phosphorous also can contribute to microbial growth in cooling towers, pretreatment for nutrient removal can help reduce biofouling (GE, 2009). Secondary-treated effluent is the water after secondary wastewater treatment (primarily aim to remove dissolved and colloid compounds measured as biochemical oxygen demand) and typically contains certain levels of nutrients. Using secondary-treated effluent as cooling tower makeup, its phosphorous levels (lower cooling tower cycles) must be reduced to avoid biofouling. Otherwise, a cooling tower treatment program designed to handle more than 10–20 mg/L of phosphorous (as P) should be utilized.

5.3. Improving energy efficiency of treatment technologies

While water reuse from impaired water is a sustainable solution to water scarcity, consideration must be placed on the energy consumption for treatment technologies for removing salts and other minerals from saline water. The energy consumption for treatment technologies largely depends on the quality of the source water and the targeted treatment efficiency (e.g., salt removal ratio). Water treatment technologies are commonly used to upgrade the source water, and to maintain conventional upper limits of each constituent of concern (e.g., TDS) for cooling tower makeup. In general, the water technologies can be divided into three categories (EPRI, 2003): (i) pre-treatment for treating source water to meet the chemical criteria; (ii) pre- and side-stream treatment for treating water to prevent fouling and scaling; and (iii) post-treatment for minimizing or eliminating blowdown.

In Fig. 3, we present common issues of water quality and their associated treatment technologies. For instance, pH control is a critical task for cooling water treatment since it directly impacts scale formation, corrosion, and microbial growth, as well as the effectiveness of biocides and disinfectants (e.g., chlorine). Scale formation increases with increasing pH, while corrosion of most metals increases with decreasing pH (Nalco, 2009). These water treatment techniques can be used in various combinations of configurations for enabling on-site reclamation of cooling water. If reclaimed water is used for makeup water, a multi-point biocide program and side-stream filtering may be required (EPRI, 2003). In an RO system, the membrane and micron-filter maintenance and replacement as a result of biofouling and fouling by solids are important, which should be frequently executed. Also, deploying high-efficient softening technologies can minimize both carbonate and silicate scaling on the surfaces of cooling towers (Nall and Sedlak, 2013).

Water technologies, including reverse osmosis (RO), electrodialysis (ED), electrodeionization (EDI), and capacitive deionization (CDI), remove salinity from impaired water. RO is a cost-effective approach for seawater desalination, and is commonly used in power plants to provide high-purity water for boiler and steam cycle. RO is less economical for brackish water desalination due to the per ion energy consumption (Amy et al., 2017; Pan et al., 2017). For brackish water desalination, Table 4 compiles the technological data for electrokinetic processes, including operating conditions, treatment capacity, energy consumption and water recovery. The process energy consumption should be closely related to treatment capacity of processes, where a larger scale of processes would typically have a lower energy consumption. Electrokinetic processes use an electromotive driving force to separate ions rather than a pressure-driven, size selective process. The methods, such as ED (Burn et al., 2015), are cost-effective for low salinity feeds (<3.0 g/L). These electrokinetic processes typically exhibit a high recovery ratio (>85%) with low operating and maintenance costs (Malek et al., 2016). For example, ED requires 30% less energy than RO at a feed salinity of 3 g/L (Wright and Winter, 2014). As shown in Table 4, the energy consumption for brackish water (a feed salinity of 5.0 g/L) desalination was only 0.8 kWh/m^3 at a productivity of 45 L/m^2/h (Lopez et al., 2017). Cui et al. (2017) also developed a continuous electrochemical modulus for brackish water treatment, and revealed that the specific energy consumption of the ED process (a feed salinity of 4.5 g/L) for a 99.5% removal ratio was about 0.89 kWh/m^3.

To enhance the ionic migration, EDI combines ionic conductive materials, such as resin beads (Tanaka, 2015) or resin wafers (Arora et al., 2007; Pan et al., 2018b), within the dilute compartments (where ions are moved out by the electromotive force) of conventional ED. Multivalent ions exhibit stronger electromotive force in comparison to monovalent ions, and preferential bind to the resin phase. For strong acid and strong base resins, the selectivity for the ions commonly present in water is $Fe^{3+} > Ca^{2+} > Mg^{2+} > Na^{+}$, and $SO_4^{2-} > Cl^{-} > HCO_3^{-}$. Enhancing EDI is a significant opportunity for cost-effective and energy-efficient brackish water reuse (Gellings and Goldstein, 2008). Lopez et al. (2017) evaluated the performance of resin wafer EDI, and observed that a specific energy consumption between 0.48 and 1.01 kWh/m^3 can be achieved at a productivity between 13 and 40 L/m^2/h for a feed salinity of 5 g/L. Similarly, CDI technology can be used for ion removal, such as sodium/chloride (Liu et al., 2016a) and arsenic (Fan et al., 2017), in the water solution. With CDI, sodium and chloride ions in brackish water are electrosorbed within electric double layers under an applied electric field (typically at 1.0–1.6 V). When treating an artificial brackish water with a salinity of 5.5 g/L, CDI with carbon aerogel electrodes required about 0.95 kWh/m^3 to recover $\sim$30% of the water at a permeate concentration of 0.5 g/L (Xu et al., 2008).

The brine concentrate management is an important issue to avoid potential environmental impacts. Electrokinetic water treatment technologies typically produce a smaller volume of but more concentrated waste stream. With respect to brine concentrate management, electrical energy can be recovered from the brine concentrate using such as reverse electrodialysis (RED) and pressure retarded osmosis (PRO). Tufa et al. (2015) developed an integrated membrane distillation–RED system for simultaneous production of desalted water and electrical energy toward a near-ZLD paradigm. Similarly, Prante et al. (2014) applied PRO to recover energy from RO brine and observed that the net specific energy consumption of a seawater RO could be reduced by 40% with respect to state-of-art values.

5.4. Good engineering practices to achieve ZLD with water reuse

To achieve ZLD requires interdependent and synergistic strategies for water treatment technologies, and system operation and controls. The design factors for planning a zero discharge system

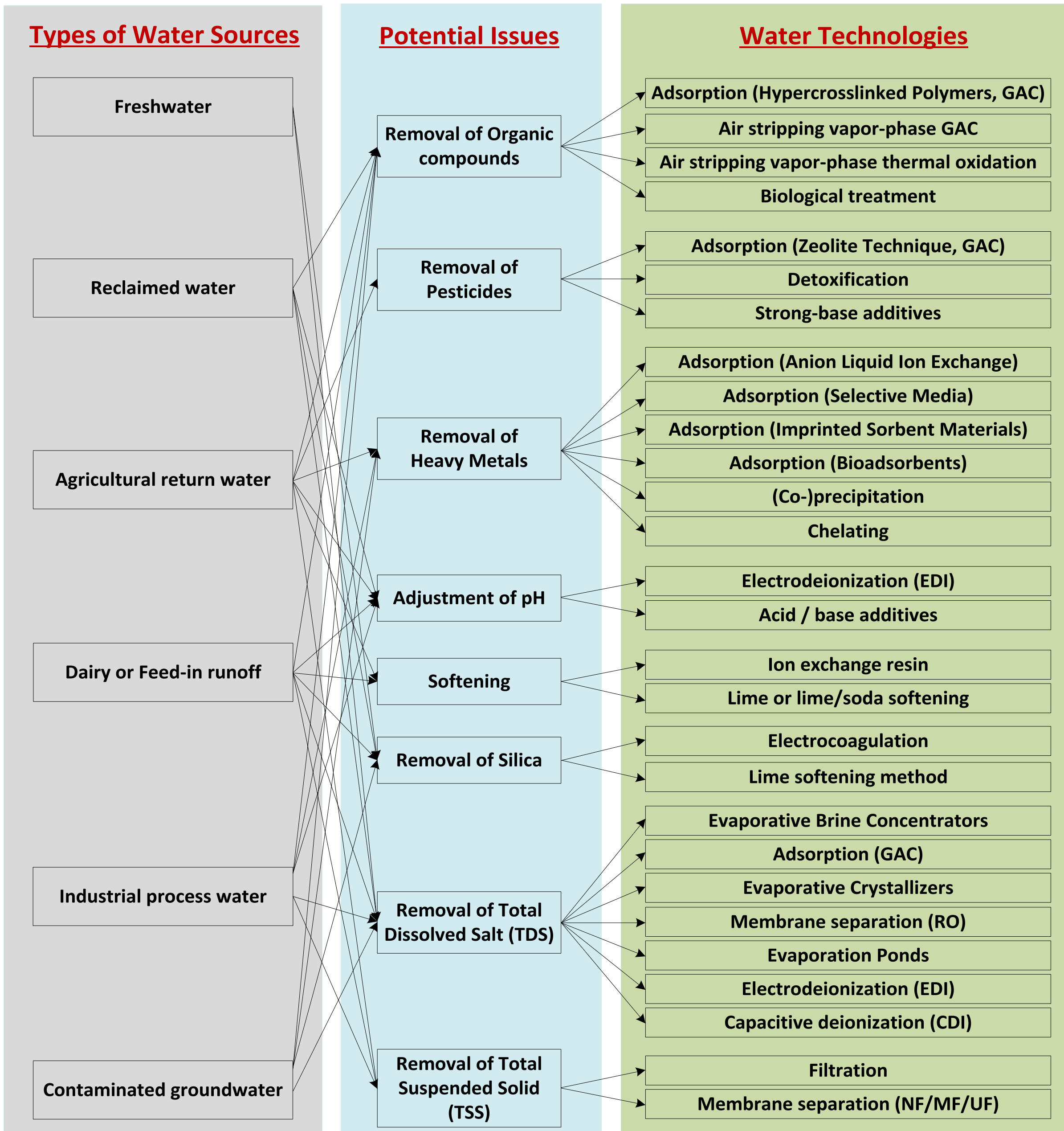

Fig. 3. Water technologies for cooling water reuse in thermoelectric power plants. Acronyms: GAC (granular activated carbon).

include temperature, salt concentration, organic load, and crystallization methodology (Ahirrao, 2014). Since the thermal evaporation and crystallization processes are typically capital and energy intensive, it is beneficial to apply other energy-efficient technologies. There are more energy-efficient processes for pre-concentration, such as membrane or electrokinetic separations, to recover water and reduce the liquid waste volume. Though ZLD may be the target, not all power plants can achieve this goal. Even with 90% water recovery, a brine stream still remains. As post-treatment options, potential brine disposal solutions for waste minimization include evaporation ponds (Ahmed et al., 2000), deep well injection (Wolthek et al., 2013), membrane distillation (Drioli et al., 2015), reverse electrodialysis (Amy et al., 2017), or a combination. For evaporation ponds, since water is evaporated from brine by the sun, they are suitably applied in arid regions because of availability of land and high solar intensity. For membrane distillation, it utilizes a vapor pressure gradient across the membrane to dewater concentrated brine, which is coupled with solar thermal, geothermal, or residual process heat. Reverse electrodialysis utilizes concentrate (salinity) gradient between a brine stream and a low salinity stream to generate electricity.

Analytical tools, such as water auditing, that evaluate the quantity and quality of water flows within a predefined boundary can be applied to identify potential water conservation strategies toward ZLD. Water auditing is conducted to close water cycles within a system, minimizing water input via the 'Reduction-Reuse-Recycle-Reclamation-Recovery-Redesign' (6R) principles. Barrington and Ho (2014) conducted a water audit on a sodium cyanide plant, and found that the water conservation techniques could reduce overall water inputs and outputs by up to 40%. Water auditing can provide suggestions for implementation strategies on conservation technologies either through retrofitting existing plants, or via contributing to the design of new plants. Water auditing can also be applied in conjunction with other analytical tools,

Table 4
Performance evaluation of electrokinetic processes for brackish water desalination.

Process[a]	Capacity (m^3/d)	C_i (mg/L)[b]	η (%)[b]	Cell Voltage (V)	Water recovery (%)	Productivity ($L/m^2/h$)	SEC (kWh/m^3)[b]	References
ED	0.014	5000	>90	2.8–3.8	–	45	0.8–1.5	Lopez et al. (2017)
ED (/wind)	10.1	5000	>88	–	–	84–150	2.52–4.15	Al-Karaghouli and Kazmerski (2013)
ED	6.0	4500	99.5	0.5	–	–	0.89	Cui et al. (2017)
ED	–	1100	70	1.6–1.9	82	43.5	0.60	Goodman et al. (2013)
EDR	200,000	1470	–	–	–	–	0.60	Burn et al. (2015)
EDR	5,000	1720	>70	–	–	–	1.55	Martinez et al. (2009)
EDIR	~0.15	2000	90.7	2.75	75	–	1.04	Sun et al. (2016)
EDI (RW)	0.002	5000	90	2.8–3.8	–	13–40	0.48–1.01	Lopez et al. (2017)
EDI (RW)	1.2	5000	90	1.4–3.5	–	20–41	0.35–0.66	Pan et al. (2017)
CDI	0.014	58.4	22.0	1.2	–		0.04	Hou et al. (2014)
CDI	0.36	5520	90.9	1.3	25–33	–	0.95	Xu et al. (2008)
CDI	37.85	2500	88–89	1.0–1.6	80		1.06	AQWATEC (2015)
CDI	3.785	1000	99.0	–	–		0.36	Farmer (2000)
MCDI	1.44	500	90.6	–	–		0.20	Dlugolecki and van der Wal (2013)
MCDI	0.054	400	–	3.5	–		0.62	Zhao et al. (2013b)
MCDI	0.043	4650	89.2	–	50		3.45	Zhao et al. (2013a)
MCDI	0.043	1100	54.5	–	50		0.17	Zhao et al. (2013a)

[a] ED: electrodialysis; EDR: electrodialysis reversal; EDIR: electrodeionization reversal; EDI: electrodeionization; RW: resin wafer technique; CDI: capacitive deionization; MCDI: membrane capacitive deionization.
[b] C_i: feed salinity (mg/L); η: removal efficiency (%); SEC: specific energy consumption (kWh/m^3).

such as water minimization hierarchy (Wan Alwi et al., 2008), to determine appropriate water conservation measures. The optimal operation scheme and guidance of the cooling system could be obtained through the analysis with the integrated models, thereby reducing the consumption of resources and energy as well as the operating costs. Zhu et al. (2017) developed a superstructure-based integrated model to describe the performance of a circulating cooling water system by considering the operation principle and the diversity of actual pipe network.

Process control and automation are another key component to maximize water and energy efficiency. Automation systems can monitor and control the blowdown rate (via blowdown controllers) and manipulate water quality parameters, such as conductivity, salinity and pH (by real-time chemical monitoring and dosing). The benefits of proper process control and automation include (1) control of chemical residuals and treatment dosing, (ii) mitigation of scaling and corrosive conditions, and (iii) elimination of excessive blowdown and water use.

6. Prospectives and prospects

The increasing demands on both water and energy pose a growing threat to national sustainable strategies on developing gray and green infrastructures. The opportunity to address trade-offs in the water-energy nexus is to improve both water and energy efficiency. In this section, we suggest three opportunities for optimizing the water and energy use in a thermoelectric power plant cooling system.

6.1. Fit-for-purpose approach to improving energy efficiency

For using reclaimed water, water treatment program must be specific to the targeted water quality from the demand side (e.g., as makeup water or other applications). For cooling makeup water, the reclaimed water should be fit for the intended purpose within the cooling water system, including the operational characteristics and the materials used in the construction of the components of the system. "Fit-for-purpose" implies that the water is treated to the quality requirements for the specific use, not over-treated for all uses. Fit-for-purpose can enhance energy efficiency and chemical usage, and decrease operating costs. As an example, with brackish water desalination, electrokinetic processes such as EDI and CDI can provide water at a targeted salinity that is fit-for-purpose (Pan et al., 2018a). Electrokinetic processes can be adjusted to changes in feed stream salinity without compromising product water quality, reducing impacts on operations. However, electrokinetic processes only remove ionized or ionizable species and are not useful for removing organics or biological species.

6.2. Advanced cooling technologies for improving water efficiency

Improving water efficiency by retrofit of existing cooling systems and promotion of advanced water-efficient technologies can save energy for treatment and supply and reduce the amount of water needed by the power sector. To optimize the performance of recirculating cooling system, integrated modeling approaches based on system mechanism analysis and superstructure should be applied. Scanlon et al. (2013) suggest that the use of wet cooling systems instead of OT cooling ponds is an effective strategy for decreasing water withdrawal rates. Adding air coolers to cooling water system is an effective approach to reducing heat load and water use, as well as preventing system fouling (Ma et al., 2017c). Similarly, Taghian Dehaghani and Ahmadikia (2017) proposed a high-precision airflow control method by taking advantage of fans with variable frequency drive to regulate airflow and retrofit an existing wet cooling system. This accurate airflow control can effectively prevent sudden fluctuations in requisite fan power. The results reveal that using the proposed approach can result in 64.6% and 9.4% decreases in fan power and water consumption, respectively.

6.3. Implementations of green chemistry practices

Cooling water systems require proper chemical treatment and preventive maintenance for reliability, stability, and efficiency. In practice, comprehensive cooling water treatment programs, including sophisticated engineering analysis, advanced water technology and diligent maintenance, should incorporate water conservation strategies. Implementation of green chemistry practices can reduce the environmental impacts of chemical treatment, raising public acceptance of the facility. Although they don't directly improve energy (thermal) and water efficiency, green chemistry practices may increase environmental compliance and reduce discharge of harmful substances (USDOE, 2011). Green chemistry practices, such as using mechanical energy or electromotive force to displace added chemicals, can be implemented as point treatments to control scaling, corrosion or microbiological activity. Their mechanisms perturb the characteristics of water by hydrodynamic or electromagnetic principles to disrupt surface adhesion. Overall, green chemistry practices may decrease costs. Other green chemistry practices include polyaspartic acid dispersants for corrosion inhibition (Migahed et al., 2016), and ozone (Al-Bloushi et al., 2017a) or ultraviolet (Wang et al., 2016) as biocide systems for biofouling control.

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