Utilization of Municipal Wastewater for Cooling in Thermoelectric Power Plants: Evaluation of the Combined Cost of Makeup Water Treatment and Increased Condenser Fouling

Michael E. Walker[1], Ranjani B. Theregowda[2], Iman Safari[1], Javad Abbasian[1],*

Hamid Arastoopour[1], David A. Dzombak[2], Ming-Kai Hsieh[3] and David C. Miller[4]

1 – Illinois Institute of Technology, Department of Chemical and Biological Engineering, 10 W. 33rd St RM 127 PH Chicago, IL 60616

2 – Carnegie Mellon University, Department of Civil and Environmental Engineering, 5000 Forbes Ave, PH 119, Pittsburgh, PA 15213

3 – Tamkang University, Water Resources Management and Policy Research Center, 151 Yingzhuan Rd, Danshui Dist., New Taipei City 251, Taiwan

4 – U.S. Department of Energy, National Energy Technology Laboratory, 3610 Collins Ferry Rd PO Box 880, Morgantown, WV

Corresponding Author: Michael E. Walker, mwalker9@hawk.iit.edu

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Abstract

A methodology is presented to calculate the total combined cost (TCC) of water sourcing, water treatment and condenser fouling in the recirculating cooling systems of thermoelectric power plants. The methodology is employed to evaluate the economic viability of using treated municipal wastewater (MWW) to replace the use of freshwater as makeup water to power plant cooling systems. Cost analyses are presented for a reference power plant and five different tertiary treatment scenarios to reduce the scaling tendencies of MWW. Results indicate that a 550 MW sub-critical coal fired power plant with a makeup water requirement of 29.3 ML/day has a TCC of $3.0 - 3.2 million/yr associated with the use of treated MWW for cooling. (All costs USD 2009). This translates to a freshwater conservation cost of $0.29/kL, which is considerably lower than that of dry air cooling technology, $1.5/kL, as well as the 2020 conservation cost target set by the U.S. Department of Energy, $0.74/kL. Results also show that if the available price of freshwater exceeds that of secondary-treated MWW by more than $0.13-0.14/kL, it can be economically advantageous to purchase secondary MWW and treat it for utilization in the recirculating cooling system of a thermoelectric power plant.

Keywords

power; electricity; fouling; water treatment; wastewater; freshwater conservation

List of Symbols and Acronyms

A	Condenser heat transfer area	NCF	Total negative cost impact of fouling
CCM	Cooling-water costing model	NCF_i	Negative cost impact of fouling, component i
CNCF	Annual cumulative negative cost impact of fouling	$Q_{condenser}$	Condenser heat load
COC	Cycles of concentration	Q_{loss}	Heat loss due to fouling
DACT	Dry air cooling technology	R_f	Condenser tube fouling factor
F_o	Condenser overdesign factor	RPOE	Retail market price of electricity
F_t	Condenser performance factor	RW	River water
FW	Freshwater	$t_{95\%}$	Time required for fouling level to reach 95% of final value
HHV	Coal higher heating value	TCC	Total combined cost of degraded water use
(H-T)	Enthalpy-Temperature	T_{in}	Cooling water inlet temperature
LCOE	Levelized cost of producing electricity	T_{out}	Cooling water outlet temperature
Load	Plant production load	T_{shell}	Shell-side steam temperature
MCA	Monochloramine	TTA	Tolytriazole
m_{cw}	Mass flow rate of cooling water through condenser	U	Overall heat transfer coefficient
m_s	Mass flow rate of steam through condenser / turbine	USD	United States dollars
MWW	Municipal waste water	W_{loss}	Power production loss due to fouling

1. Introduction

The United States relies on thermoelectric power plants to generate approximately 90% of its electricity demand [1]. These plants utilize heat produced from nuclear reactions or the burning of carbonaceous fuel, such as coal, natural gas (methane), or biomass, to raise high pressure, high temperature steam in a boiler system. This steam is subsequently expanded to low temperature and pressure within a turbine generator which utilizes the energy contained in the steam to turn a turbine shaft and produce electricity. The low pressure, low temperature steam that exits the turbine must be condensed back into the liquid state and pumped to high pressure before being reintroduced to the boiler, thus completing the power cycle. To perform this condensation step, large amounts of cooling water are passed through the tubes of a steam surface condenser to remove the latent energy contained in the low pressure steam.

The cooling water requirement for thermoelectric power generation places a large demand on freshwater resources. In the U.S. alone, over 1287 GL/day of freshwater are withdrawn from lakes and rivers to satisfy this cooling requirement [2]. About 43% of U.S. thermoelectric plants utilize once-through cooling configurations (Figure 1a) [3]. In these plants, the heated cooling water is returned to the source body after passing through the condenser system. Alternatively, a plant may be fitted with a recirculating cooling system, as shown in Figure 1b [4]. In this configuration, heated cooling water is routed to an evaporative cooling tower where the heat contained in the recirculating water stream is removed through contact with air. Because the water is recycled, less water is withdrawn compared to a once-through system; however, much more water is consumed because a significant amount of water is lost through evaporation in the cooling tower (e.g., in the range of 1% of the recirculating water flow rate) [5]. This loss of water causes non-volatile species within the cooling loop to become concentrated and it is therefore necessary to remove a portion of the recirculating water, also known as "blowdown" [5]. Water that is lost to evaporation, liquid aerosols that escape from the top of the cooling tower (drift), and blowdown is replaced with makeup water.

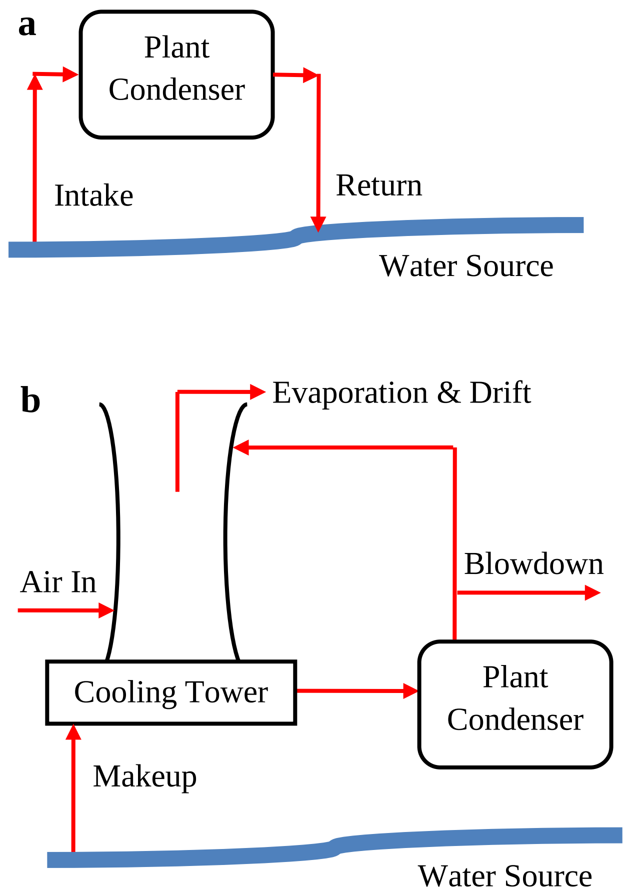

Figure 1.a. Once-Through Cooling System in Thermoelectric Power Generation, **b.** Recirculating Cooling System in Thermoelectric Power Generation

In a recirculating system the buildup of non-volatile species within the cooling water is problematic because the increased concentration of non-volatile species leads to the precipitation of mineral salts [6]. Increased concentrations are a particular concern in the case of salts with inverse solubility (i.e. lower solubility at higher temperatures) such as calcite ($CaCO_3$). When the recirculating cooling water is heated within the tubes of the power plant condenser, these salts fall out of solution and form deposits on the inner surfaces of the condenser tubes. This phenomenon, known as mineral scaling, decreases the heat transfer efficiency of the condenser tubes and leads to a loss in power plant performance [7].

Mineral scaling is one of four major categories of condenser tube fouling. Particulate fouling, biofouling and corrosion comprise the remaining three categories. Particulate fouling involves the settling or adhesion of particles present in the cooling water to heat exchange surfaces; biofouling refers to the buildup of organic materials; and corrosion refers to the degradation of the condenser tube metal as a result of processes such as oxidation [8].

The study presented in this work builds on the investigations by Vidic and Dzombak [9] and Dzombak et al. [10] which focus on the evaluation of different strategies for physical-chemical treatment to prevent fouling in recirculating cooling loops utilizing effluent from municipal wastewater treatment facilities in lieu of freshwater. These investigations have determined that treated municipal wastewater (MWW) is a widely available water source and that the fouling tendencies of secondary treated MWW can be controlled with additional treatment for recirculating systems operating between 4-6 cycles of concentration (COC) [9,10]. The relationship between extent of additional, tertiary treatment and effects on cooling system performance was also studied.

In this work, results from Dzombak et al. [10], and in particular the evaluation of alternative tertiary treatment options to reduce the scaling tendencies of MWW as described in Liu et al [11], were integrated with cooling system process modeling to evaluate combined costs of tertiary treatment of MWW and condenser operation with different levels of water quality. The combined cost modeling incorporated the costs associated with the tertiary treatment of MWW for scaling prevention, costs associated with management of condenser tube scaling, and effects of condenser tube scaling on power plant economics. Theregowda et al. [12] developed a life cycle conceptual cost model (LC^3) to account for the costs of tertiary treatment unit construction, operation, maintenance and chemicals. Walker et al. [13] developed a methodology to evaluate the economic impact of condenser fouling in thermoelectric power plants.

Similar work utilizing mathematical models to study the design and economics of heat exchanger systems have been reported previously in the literature. The methodology developed by Walker et al. [13] and utilized herein is built upon work presented by Putman [14] which addresses the fundamentals of condenser-turbine performance interrelationships. Other related work includes an investigation of the optimization of cleaning schedules in a crude oil preheat train by Sheikh et al. [15], and work by Georgiadis et al. [16] on the optimization of cleaning schedules in heat exchangers under fouling conditions. Similarly, Zubair et al. [17] present a probabilistic approach to characterize fouling processes and their influence on heat exchanger maintenance. In addition, Caputo et al. [18] consider the design and scheduling of maintenance as a joint optimization problem to minimize the life cycle cost of heat exchanger equipment.

This paper presents a broader evaluation of the combined treatment and fouling costs associated with the use of tertiary-treated MWW in the recirculating cooling systems of thermoelectric power plants. This evaluation is necessary to assess the economic viability of utilizing tertiary-treated MWW for power plant cooling because the scaling tendency of this degraded water is high, the use of recirculating cooling systems results in the concentration of scaling species (thus leading to even higher scaling tendency), and the use of anti-scaling agents alone has been shown to be inadequate for systems employing MWW [9].

The specific objectives of this study were (1) to evaluate the combined treatment and fouling costs of MWW use in cooling systems for five tertiary treatment scenarios against a baseline scenario of freshwater (i.e., river water) use; (2) to determine the breakeven differential cost of tertiary-treated MWW use compared to river water use in terms of $/kL; and (3) to compare the freshwater conservation cost associated with utilizing tertiary-treated MWW to that of dry air cooling technology (DACT), $1.5/kL [19], and the U.S. Department of Energy - National Energy Technology Laboratory (NETL) 2020 freshwater conservation cost target, $0.74/kL [19].

2. Methodology

This manuscript presents a novel methodology for the determination of the total combined cost of utilizing degraded water for cooling in thermoelectric power plants. This methodology incorporates elements of life cycle costing, thermo-economic evaluation and lab-scale experimentation into a unique hybrid evaluation strategy. As a vehicle for this methodology, a combined Cooling-water Costing Model (CCM) was developed by integrating the Theregowda et al. LC^3 model for treatment system life cycle costing [12] with the condenser fouling cost model presented by Walker et al. [13]. The CCM is an Excel-based analysis tool that operates with a user friendly front end graphical user interface. It was developed to provide researchers, students and plant personnel with a detailed, tractable resource that allows for the same type of evaluations presented in this paper. The CCM is publicly available at http://mypages.iit.edu/~abbasian/CCM. A flowsheet overview of the model structure and basic functionality is presented in Figure 2, which highlights the interrelationship of the CCM information flow and calculation routines.

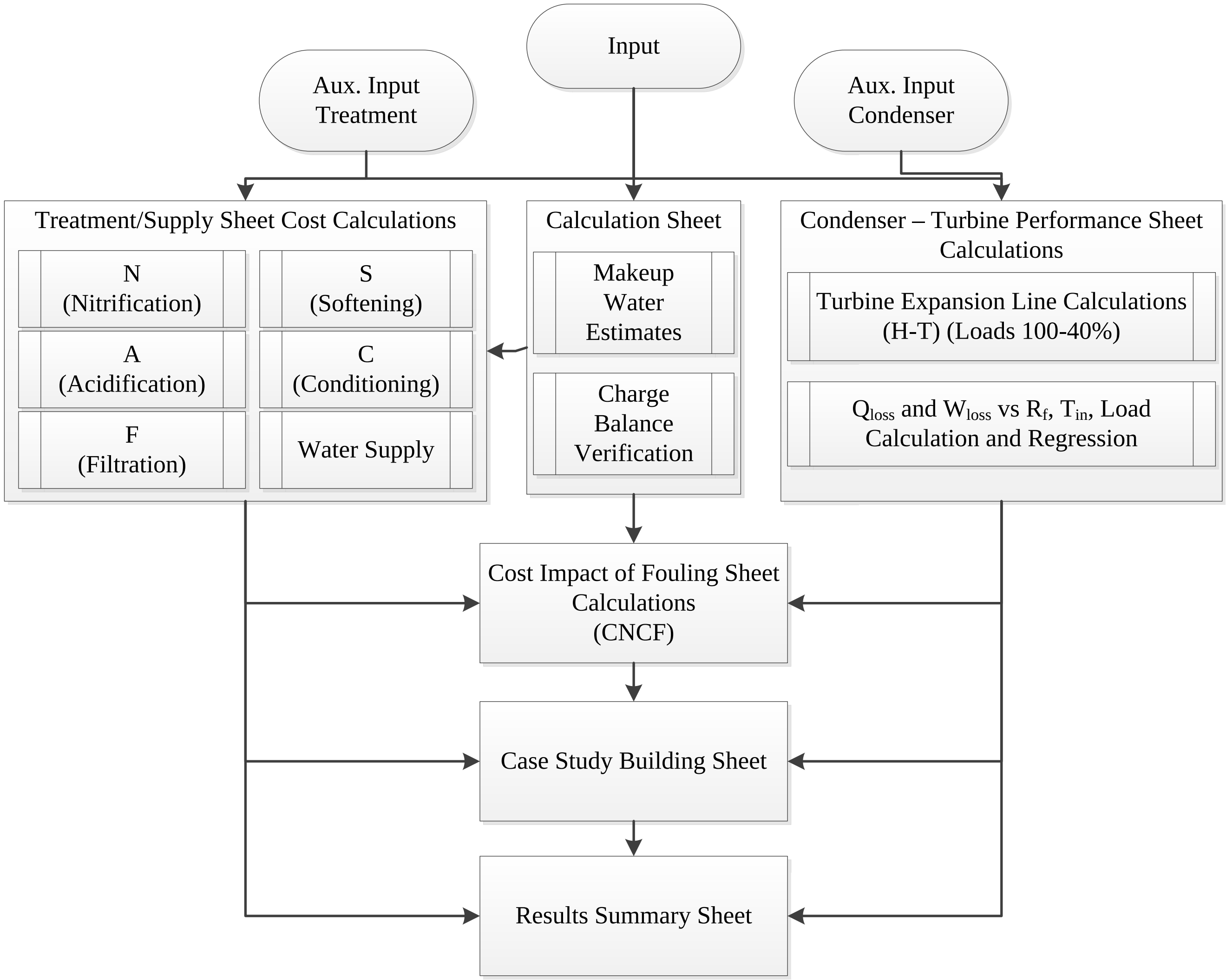

Figure 2. Information and Calculation Flow Diagram: Combined Costing Model (CCM)

The water treatment costing portion of the CCM, adopted from Theregowda et al. [12], estimates construction and operational costs for a number of treatment units including: filtration, softening, nitrification, acidification and chemical conditioning (biocide and corrosion inhibitors). This portion of the CCM also integrates water supply and piping costs. The calculation structure for each water treatment unit, as well as water supply, is outlined in Figure 3. As shown in Figure 3, the CCM calculates the fixed levelized costs of treatment separately from the variable costs of treatment. These costs are then integrated into the overall cost of degraded water use. As shown in Figure 4, the variable water treatment cost information interfaces with water usage data to determine an estimate of this portion of water treatment costs. Note that all costs calculated or presented in this paper are in 2009 USD.

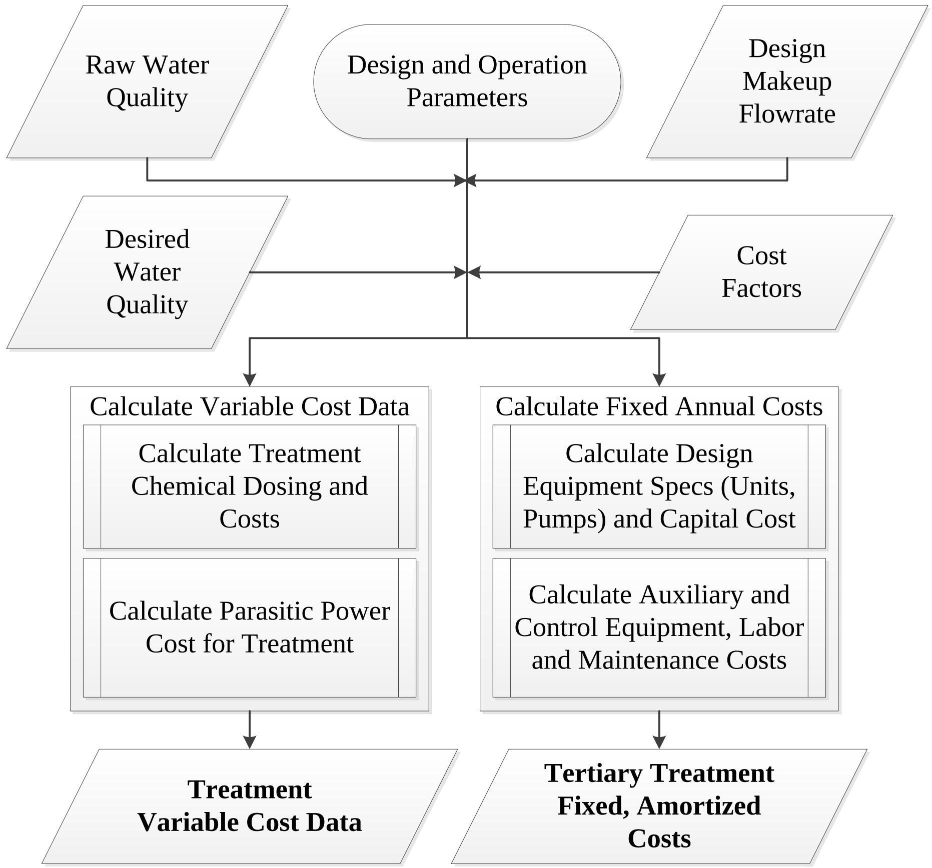

Figure 3. Overview of CCM Water Treatment Cost Calculation Algorithm

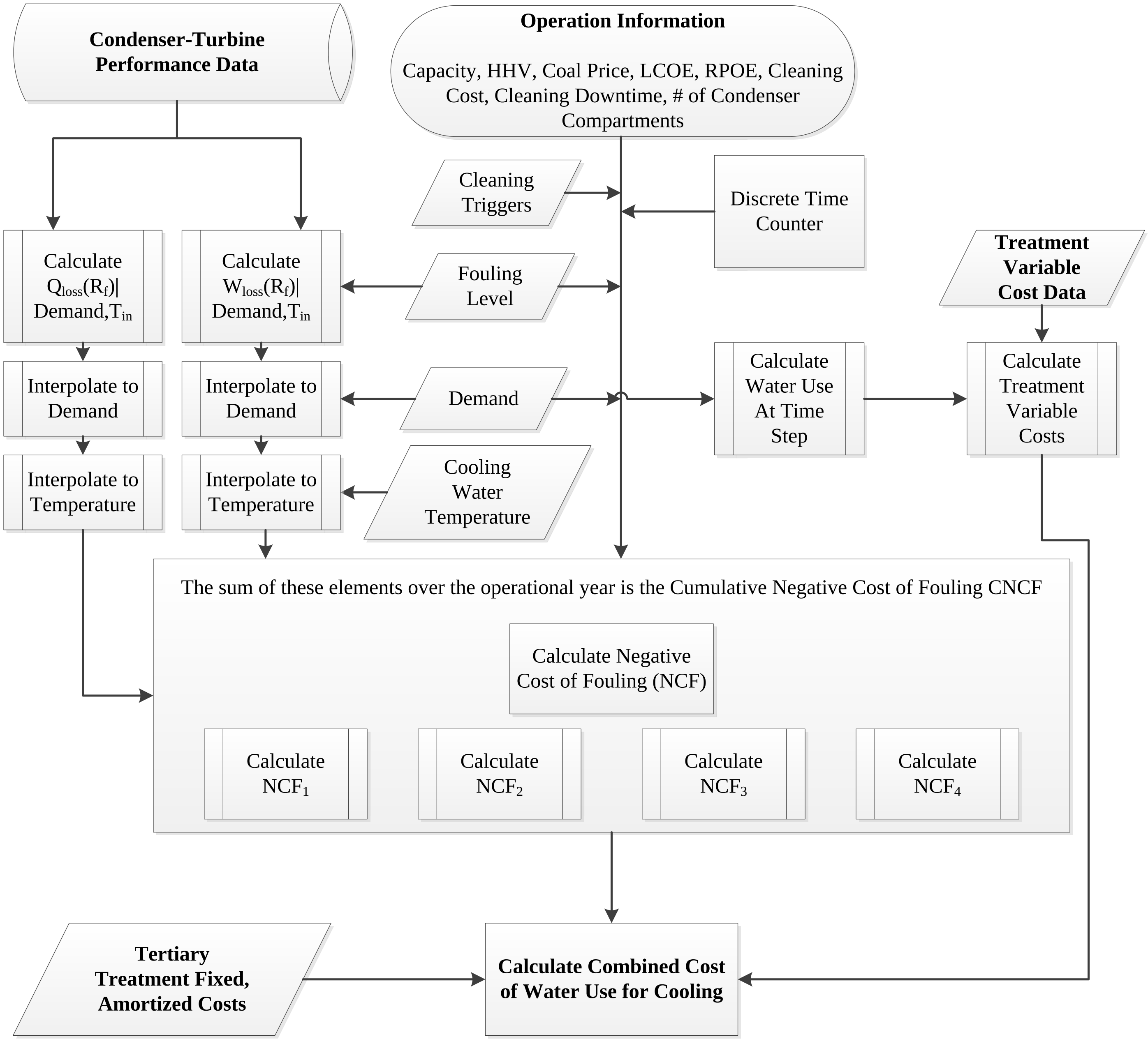

Figure 4. Combined Cost of Water Use for Cooling: Calculation Algorithm Overview

The condenser fouling cost portion of the CCM, adopted from Walker et al. [13], estimates the cumulative negative cost of condenser fouling, CNCF, by calculating its four contributing cost factors for every 12-hour period of operation. The first, NCF_1, is the cost of additional fuel required to maintain the power output for the power plant when fouling degrades plant performance. The second, NCF_2, is the cost of lost production when performance losses due to fouling prohibit the plant from producing the desired level of power. The third, NCF_3, is the cost of carrying out a cleaning event to remove fouling material from the condenser. Finally, NCF_4 is the cost of production lost when powering down during a cleaning event. The basic information flow used by the CCM to calculate these factors and integrate them with treatment cost estimates is provided in Figure 4. Detailed information on the calculation of these cost parameters is described in the literature [13].

The primary application of the CCM is the determination of combined treatment and fouling costs associated with the use of a particular type of water in a recirculating cooling system. As shown in Figure 4, the CCM performs these estimates via a hybrid LCC/thermo-economic analysis. It is the application of this hybrid approach that allows the CCM to account for the relevant externalities associated with these evaluations. Specifically, the LCC model integrates detailed treatment unit and water supply costing that includes considerations for such externalities as treatment chemical preparation, sludge handling and landfilling, delivery pipeline excavation, pump costs and electricity usage costs [12]. Furthermore, the condenser fouling portion of the model is an engineering-based calculation tool that allows specification of fouling curve information to determine additional fuel requirements and lost revenue due to downtime. This portion of the model accounts for such externalities as: plant size, efficiency, makeup water demand, makeup water temperature, condenser design and cooling loop operation [13].

The analyses in this study were performed for a 550 MW sub-critical coal fired power plant with a cooling water makeup requirement of 29.3 ML/day. Plant design and operation parameters are listed in Table 1. These parameters describe the plant size, efficiency, condenser design and cooling water operation assumed in the plant model. The power plant characteristics correspond to a standard reference coal-fired power plant defined by NETL [20].

Table 1. Reference Power Plant Design and Operation Parameters

Parameter	Units	Value
Plant Net Capacity	MW	550
Plant Efficiency	%	36.8
Boiler Efficiency	%	89
Condenser Waterboxes		2
$T_{in,design}$	°C	32.2
$T_{out,design}$	°C	43.3
$T_{shell,design}$	°C	54.4
F_t		1
U_{clean}	W/m^2*K	2840
$Q_{condenser,\ design}$	MJ/hr	2.90×10^6
$m_{cw,design}$	kg/hr	6.25×10^7
$m_{s,design}$ @ 1 psia	kg/hr	1.10×10^6
A (F_o = 0.85)	m^2	20800
$t_{95\%}$ for Fouling Rate	days	150
COC		4
Makeup Flow Rate	ML/day	29.3

The key cost parameters and assumptions utilized in this study are listed in Table 2. The cost parameters of interest include the price of coal, water purchasing, treatment chemicals, and electricity, as well as the heating value of coal and various capital costing factors.

Table 2. Key Cost Parameters (2009 USD) and Assumptions

Material	Units	Value	Reference
Coal Price	$/(1000 kg)	59.90	EIA 2009 [21]
Coal *HHV*	kJ/kg	27100	DOE-NETL 2007 [20]
River Water (RW)	$/kL	0.08	DRBC 2011 [22], MDNR 2011 [23], WMP-LCRA 2011 [24]
Municipal Wastewater (MWW)	$/kL	0.05	Niblick, 2012 [25]
Hydrated Lime	$/(1000 kg)	150.00	USGS, 2010 [26]
Soda Ash	$/(1000 kg)	143.00	USGS, 2012 [27]
H_2SO_4	$/kg	0.55	Brainerd Chemical Inc. [28]
Monochloramine (MCA)	$/kg	1.01	Kroff Chemicals [29]
Tolytriazole (TTA)	$/kg	6.06	Kroff Chemicals [29]
Retail Price of Electricity	cents/kWh	9.87	EIA 2011 [1]
Cost of Electricity Production	cents/kWh	6.84	DOE-NETL 2007 [20]
Cost of Cleaning	$	13,500	Conco Systems Inc. 2010 [30]
Cleaning Downtime	Hours	24	Saxon and Howell [8]
Discount Factor	%	12	de Neufville, 1990 [31]
Labor and Maint. Factor	%	8	Ray and Sneesby, 1998 [32]
Foundation Cost Factor	%	25	N.A. Water Systems, 2009 [33]
Aux. Equip Factor	%	15	Ray and Sneesby, 1998 [32]
Capital Contingency	%	35	Westney, 1997 [34]
Project Lifetime	years	25	Assumption

Detailed information on the MWW tertiary treatment scenarios considered in this study is provided in Table 3. As shown, Cases 1-5 were chosen to evaluate the freshwater conservation cost for plants utilizing purchased secondary MWW under five different tertiary treatment scenarios. These cases were considered relative to a baseline, Case 6, which utilizes water from a nearby river to supply the power plant cooling system.

Table 3. MWW Tertiary Treatment and Reference Scenarios

	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8
Water Type	MWW	MWW	MWW	MWW	MWW	RW	RW	MWW
Treatment[†]	F,C	S,F,C	N,F,C	N,S,F,C	pH,F,C	F,C	F,C	S,F,C
MCA Dose (ppm)	64	52	52	52	70	52	52	52
TTA Dose (ppm)	1	1	1	0.5	1.25	0.5	0.5	1
H_2SO_4 Dose (mM)	0	0	0	0	1.25	0	0	0
Water Price $/kL	0.05	0.05	0.05	0.05	0.05	0.08	0.21	0.05
Delivery Distance (km)	16	16	16	16	16	0	0	16
Head Increase (m)	0	0	0	0	0	8	8	0
Asymptotic Fouling Level m^2*K/W [16]	5.6×10^{-5}	3.5×10^{-6}	5.3×10^{-6}	3.5×10^{-6}	8.8×10^{-5}	3.5×10^{-6}	3.5×10^{-6}	3.5×10^{-4}

[†]F = Filtration, C = Conditioning, S = Softening, N = Nitrification, pH = Acid Addition

The treatment scenarios (Cases 1-5) evaluated were chosen for the purpose of determining the most cost effective method of scaling control in recirculating cooling systems utilizing treated MWW. Case 1, which represents the minimum treatment scenario, includes filtration, biocide addition and corrosion inhibitor addition. All remaining cases incorporate the use of filtration and chemical addition. As shown in Table 3, the dosage of treatment chemicals such as the biocide monochloramine (MCA) and the corrosion inhibitor tolytriazole (TTA) are slightly different from case to case; these dosage levels were set based on experience operating pilot scale cooling towers [10]. Case 2 introduces the use of cold-lime softening for the purpose of reducing calcium ion levels and carbonate levels. Cold-lime softening is a long-employed, effective technology for reducing water hardness [6]. Case 3 applies the use of nitrification, a biological process that oxidizes ammonia and reduces alkalinity [35]. Case 4 combines softening with nitrification, filtration and minimum conditioning chemical addition. Case 5 incorporates a different treatment strategy in which problematic salt forming species are left in solution but the pH of the solution is decreased to reduce scaling potential through the addition of sulfuric acid. The baseline for this study, Case 6, considers the use of river water with the minimum treatment of filtration and chemical addition.

Case 7, which also considers the use of river water, was included to examine how increased river water prices will affect the economic viability of degraded water use for power plant cooling. Case 7 was defined in a similar manner to Case 6, with the exception that freshwater price was considered to be $0.21 /kL. Case 8 was included to examine the impact of higher fouling levels on the ability of a typical MWW treatment scenario to meet the NETL 2020 water conservation cost targets. Case 8 is the same treatment scenario as Case 2 with an assumed fouling rate that is one-hundred times the value used in Case 2.

This study considered the combined costs of water treatment and the costs that arise as a result of fouling. To estimate the combined costs of treatment and fouling it is necessary to know the relationship between the quality of the treated water and the fouling that will result from the use of that water in a recirculating cooling system. This relationship was established using data from studies of scale formation with synthetic tertiary-treated MWW in a bench scale cooling loop [10,11]. Liu et al. [11] utilized synthetic cooling waters with compositions similar to those associated with the treatment scenarios in Cases 1-5 of Table 3. These experimental results [10,16] provided asymptotic fouling rates for the synthetic water in each treatment scenario which were then applied to the respective cases in this study.

In a survey by Niblick et al. [25] power plant personnel were questioned regarding the amount paid to wastewater treatment plants for reuse of wastewater in the power plant cooling system. Most respondents reported payments below $0.17/kL (in 2009 USD) for secondary treated MWW. The price paid for secondary treated MWW with no tertiary treatment and minimal supply fee was taken to be $0.05/kL in this case study based on responses in the survey.

Table 4 lists representative river water withdrawal costs in three different regions of the U.S.: the northeast, northern mid-west, and west. River water rates as reported in Table 4 are determined by availability and state resource conservation authorities. Withdrawal fees are higher in the drier western regions of the country.

Table 4. Raw River Water Rates (2009 USD) From Various Sources

Source of river water rate	**Rate ($/kL)**	**Reference**
Delaware River Basin Commission Rates	$0.02	DRBC 2011[22]
Minnesota Dept. of Natural Resources	$0.11	MDNR 2011[23]
Lower Colorado River Basin	$0.12	WMP-LCRA 2011[24]
Average River Water Costs	$0.08	

In the baseline Case 6, the purchase price of river water was assumed to be the average river water cost, \$0.08/kL (2009 USD). This study also incorporated the delivery costs associated with water sourcing, including piping, pump purchase, and electricity costs for pumping. As the baseline plant was assumed to be located next to a river or other freshwater supply source, a hydraulic head increase of 8 m was assumed for delivery to the plant cooling system. For plants utilizing MWW this study assumed a delivery distance of 16 km from which pipeline installation, pump purchase and operation costs were estimated.

Note that this evaluation did not consider treatment of the blowdown stream prior to discharge. This decision was made to provide the best comparison between the freshwater and MWW cases. Consider, when freshwater is used for cooling, the secondary MWW from the local publicly owned treatment works (POTWs) is still discharged to the local water source, along with all of the TDS and TSS in the MWW stream. On the other hand, when MWW is used for cooling (1) freshwater is no longer consumed; and (2) the MWW feed to the power plant undergoes tertiary treatment, thereby significantly reducing the presence of a number of constituent species including carbonates, ammonia, calcium and TSS. The blowdown effluent that is discharged from the plant will therefore release a lower total amount of TDS and TSS than the MWW influent, although the blowdown itself will be more concentrated in certain TDS. Furthermore, the utilization of MWW results in a net savings of freshwater that is equal to the makeup demand of the plant, thus lessening the overall impact to the local water source in terms of both water depletion and TDS/TSS addition. It is therefore clear that it is not appropriate to consider blowdown treatment costs for the MWW case.

3. Results and Discussion

The results of the cost analyses performed for the reference power plant and the various makeup water supply cases are presented in Table 5, which contains information on water treatment unit costs and negative costs that arise due to fouling (CNCF) for each case. The total combined cost (TCC) of treatment and fouling is utilized as the basis for three key cost statistics, which were developed to best relate the results to the specific questions addressed in this manuscript. The first key cost statistic is the differential cost of the case in question vs. the freshwater reference scenario, Case 6. The second is the TCC expressed in the conservation cost metric of $/kL freshwater conserved. The third is the breakeven differential cost of freshwater, also expressed in $/kL. The third statistic represents the differential cost of freshwater to MWW, at which the use of MWW would yield the same TCC as the use of freshwater.

Table 5. Summary of Combined Cost Analysis Results (2009 USD)

	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8
Case Note	MWW FC	MWW SFC	MWW NFC	MWW NSFC	MWW pHFC	RW FC	High RW Cost	High Foul. Case
Number of Cleanings	0	0	0	0	0	0	0	3
Nitrification (million $/yr)	0.00	0.00	0.80	0.80	0.00	0.00	0.00	0.00
Softening (million $/yr)	0.00	0.87	0.00	0.82	0.00	0.00	0.00	0.87
Acid Addition (million $/yr)	0.00	0.00	0.00	0.00	0.85	0.00	0.00	0.00
Filtration (million $/yr)	0.32	0.32	0.32	0.32	0.32	0.32	0.32	0.32
Chemical Addition (million $/yr)	0.90	0.75	0.75	0.72	0.98	0.72	0.72	0.75
Water Supply & Transport (million $/yr)	1.17	1.17	1.17	1.17	1.17	0.88	2.29	1.17
CNCF (million $/yr)	0.62	0.04	0.06	0.04	1.00	0.04	0.04	3.37
Total Combined Cost (TCC) (million $/yr)	3.01	3.15	3.10	3.87	4.33	1.96	3.37	6.48
TCC – TCC (Case 6) (million $/yr)	1.06	1.20	1.15	1.91	2.37	-	1.41	4.52
Total Combined Cost (TCC) ($/kL)	0.28	0.30	0.29	0.36	0.40	0.18	0.31	0.60
Breakeven Differential Cost of FW ($/kL)	0.13	0.14	0.14	0.21	0.25	-	-	0.45

[†]F = Filtration, C = Conditioning, S = Softening, N = Nitrification, pH = Acid Addition

The minimum MWW tertiary treatment considered, Case 1, is shown to have the lowest treatment and supply cost, $2.39 milliion/yr, of the five treatment scenarios. The impact of uncontrolled scaling in Case 1 results in a CNCF of $0.62 million/yr, and therefore a TCC of $3.01 million/yr. In contrast, Case 2 integrates cold-lime softening in addition to the minimum treatment of filtration with biocide and corrosion control. As a result, the CNCF in Case 2 is shown to drop to only \$0.04 million/yr. However, because of increased treatment costs associated with softening, the TCC estimated for Case 2, \$3.15 million/yr, is slightly higher than the minimum treatment scenario. A similar trend is observed for Case 3, in which nitrification is applied as treatment; here, the CNCF is shown to be \$0.6 million/yr and the TCC is shown to be \$3.10 million/yr.

It is important to note that the relative TCCs of the scenarios in the study are highly dependent on the differences between the asymptotic fouling rates assigned to these cases in the study. As noted, these fouling rates were obtained from experimental work which involved study of synthetic cooling water in a bench scale cooling loop [10,11]. It is possible that the relative performance of the cases with similar TCCs (Cases 1-3) would be different with fouling rates obtained in a real system.

Case 4 utilizes both nitrification and softening and is shown to result in a TCC of \$3.87 million/yr. In this scenario, the asymptotic fouling rate was assumed to be equal to Case 2, as the fouling rate for Case 2 was close to the lower limits of detection, and the cooling water compositions for Cases 2 and 4 were estimated to be similar [16]. From a practical standpoint it is obvious that there is no benefit to including another treatment unit if there is no decrease in the fouling characteristics of the treated water. Nonetheless, the results of Case 4 provide a view of how the TCC of degraded water use may change if two tertiary treatment processes were required beyond the assumed minimum of filtration and chemical addition.

Case 5 represents the use of sulfuric acid to decrease recirculating system pH and thereby reduce the tendency of the system toward calcite formation. The experimental results used to obtain fouling rates [10,11] indicated that instead of decreasing the fouling properties of the degraded water, lowering the pH of the system causes increased precipitation of other salts, specifically amorphous calcium phosphate. The presence of phosphate in MWW presents unique challenges for scaling control. Therefore, as compared to the minimum treatment scenario, the TCC estimated for Case 5 exhibits both increased treatment and fouling costs. Thus, the treatment scenario proposed for Case 5 would not be a desirable option to facilitate MWW usage for thermoelectric power plant cooling.

Case 6 represents the freshwater baseline. In this case, makeup water was considered to have been drawn directly from a nearby river, filtered and treated with biocide and corrosion inhibitors. While water purchase costs are greater in Case 6 due to the increased price of freshwater vs. MWW ($0.08/kL vs. $0.05/kL), the total water costs are lower because transport costs (piping and pumping) are much lower than those estimated for MWW. This is because the study assumed an existing plant that sources water from a nearby river or lake for the freshwater baseline (delivery only involves pumping against 8 m hydraulic head). In contrast, the MWW cases were considered to require 16 km of installed pipeline and the related pumping costs. As the fouling rate assumed for the baseline was low, the resulting TCC for Case 6 is only $1.96 million/yr.

The performance of the case study scenarios vs. the freshwater baseline is illustrated in Figure 5a which provides a breakdown of the TCCs by case and cost element. Figure 5b presents the freshwater conservation costs for each scenario in $/kL, similarly broken down by cost element.

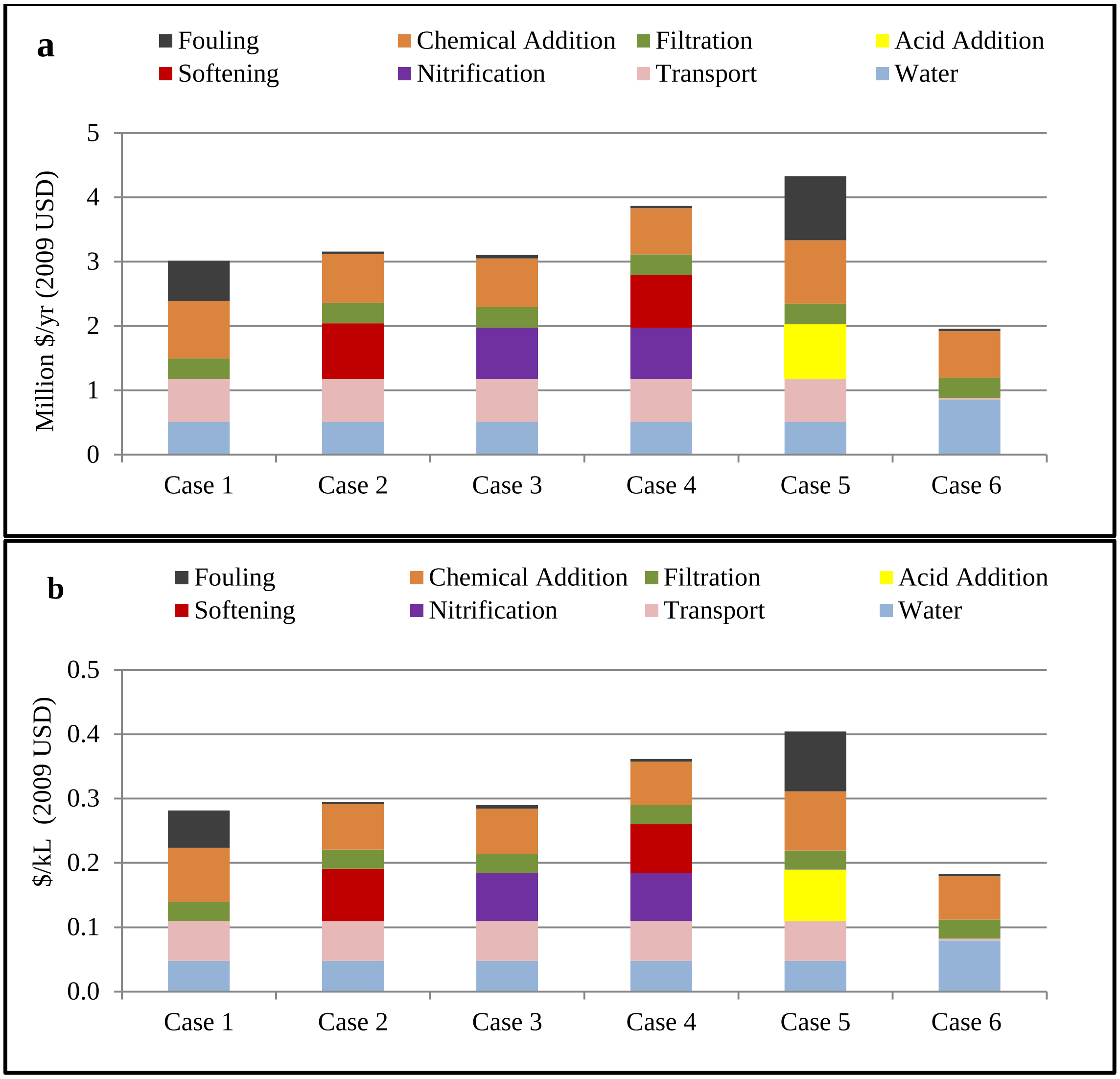

Figure 5. Costs Associated with the Use of Tertiary Treated MWW in a Power Plant Recirculating Cooling System (a) million $/yr and (b) $/kL. All costs in 2009 USD.

Under the assumed water pricing scenario, the use of tertiary-treated MWW over freshwater is not economically beneficial. However, it is important to consider that the cost of freshwater resources varies from region to region, and is projected to increase in the coming years [2]. When the cost of freshwater considered is higher, as in Case 7 ($0.21/kL), the TCC of freshwater use can rise above that of MWW use. Also, in some areas freshwater may simply not be available.

To broaden the applicability of the analyses performed herein to different water pricing conditions, the differential price of freshwater was calculated for each tertiary treatment case. The results estimate that a differential of \$0.13 - 0.14/kL between the price of freshwater and MWW will result in equal usage costs. Therefore, if pricing conditions in a location are such that the differential is greater than this range, it is possible to obtain savings through the tertiary treatment and use of MWW. Alternatively, in water constrained regions where promoting freshwater conservation is a priority, the results of these analyses can be used to inform policy decisions regarding consumptive withdrawal pricing for thermoelectric plants.

The results of this study can be used to evaluate the water conservation costs of using tertiary-treated MWW to replace freshwater for thermoelectric power plant cooling, and to compare these costs against other conservation strategies. Considering the results of Cases 2-4 as a reasonable estimation of the expected costs of tertiary-treated MWW use, it is clear that the water conservation cost of tertiary-treated MWW use (\$0.29/kL) is well below both the cost of DACT and the NETL 2020 target, \$1.5/kL and \$0.74/kL, respectively [19]. Because of the uncertainty associated with the applicability of the fouling rates obtained through bench scale experimentation to commercial scale units, Case 8 is presented to demonstrate the influence of higher fouling rates to the evaluation of the conservation cost of treated MWW use against DACT and the NETL 2020 target. The assumed asymptotic fouling level in Case 8 is 3.5×10^{-4} (m^2*K/W), one-hundred times that measured for Case 2. As seen in Figure 6, this results in a sharp increase in the water conservation cost of Case 8 vs. Case 2. Despite the increased fouling levels considered in Case 8, the freshwater conservation cost (\$0.61/kL) is still estimated to be below the NETL 2020 and DACT cost targets.

It is therefore clear that while the simple economic viability of using municipal wastewater for cooling in thermoelectric plants is dependent upon local water pricing conditions, this strategy is shown to have a very attractive freshwater conservation cost. This is particularly true in comparison to the conservation costs of leading alternative options, such as DACT. In light of growing water constraints and supply issues, it is vital that these types of effective, proven and available conservation strategies be applied when possible. The use of degraded water in thermoelectric power plants offers a unique opportunity in this regard because of the enormous volumes of water utilized in these systems and the impact they have on water sustainability.

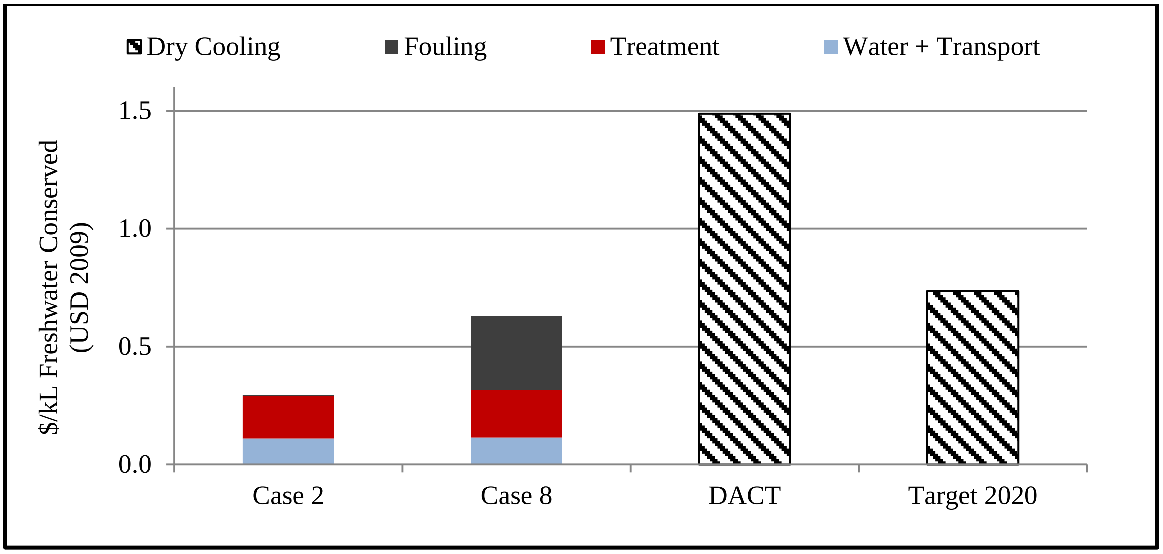

Figure 6. Freshwater Conservation Cost Estimates for Makeup Water Supply Cases 2 and 8 vs. NETL Targets

4. Summary and Conclusions

The results presented in this paper show that the use of treated municipal wastewater (MWW) to replace freshwater as makeup water to a recirculating cooling system in a thermoelectric power plant is economically viable when the price differential of freshwater and tertiary-treated MWW is greater than or equal to $0.13 – 0.14/kL (2009 USD). The total combined cost (TCC) of tertiary-treated MWW use for thermoelectric cooling is estimated to be $3.0 – 3.2 million/yr for a 550 MW sub-critical coal fired plant that consumes makeup water at a rate of 29.3 ML/day. Since MWW is available in sufficient quantities in proximity to many generation sources [36], it is clear that treating and utilizing recycled MWW for thermoelectric cooling will be a viable economic option as freshwater resources become constrained and more expensive.

The TCC estimates calculated in this study indicate that the freshwater conservation cost of treated MWW use for thermoelectric power plant cooling, $0.29/kL, is considerably lower than the conservation cost of dry air cooling technology (DACT), $1.5/kL, as well as the 2020 conservation cost target set by the National Energy Technology Laboratory (NETL), $0.74/kL. Furthermore, the results of this study indicate that even if the fouling behavior of treated MWW is one-hundred times that assumed for the evaluations presented herein, the TCC of MWW is still less than the NETL 2020 target.

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