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Fired Power Plants**

Journal:	<i>Environmental Science: Water Research & Technology</i>
Manuscript ID	EW-CRV-04-2018-000264.R1
Article Type:	Critical Review
Date Submitted by the Author:	30-May-2018
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Water Impact Statement

In 2015, the US Environmental Protection Agency promulgated regulations governing wastewater discharge from coal fired power plants, including wastewater from flue gas desulfurization (FGD) units. This paper reviews FGD wastewater composition, critically evaluates existing and emerging treatment technologies, and highlights ongoing research needs to address compliance challenges, improve process performance, and minimize the cost of FGD wastewater treatment.

Fundamental Challenges and Engineering Opportunities in Flue Gas Desulfurization Wastewater Treatment at Coal Fired Power Plants

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Abstract

In November 2015, the United States Environmental Protection Agency (EPA) promulgated the Effluent Limitations Guidelines (ELGs) for the Steam Electric Power Generating Sector. These guidelines either eliminate or lower permissible discharge limits for six wastewater streams produced at coal fired power plants (CFPPs), including flue gas desulfurization (FGD) wastewater. This paper summarizes the state of the art, describes fundamental challenges, and highlights critical research needs in FGD wastewater treatment. We begin by describing the processes that influence FGD wastewater production and composition. We then critically evaluate the best available technologies for treating FGD wastewater identified by the EPA during the regulatory process. Finally, we identify four critical challenges and research needs in complying with the 2015 ELGs including (1) removing selenium species from FGD wastewater, (2) achieving zero liquid discharge of pollutants from FGD wastewater while enabling water reuse at CFPPs, (3) developing water treatment systems that can respond to short-term fluctuations in CFPP electricity generation and wastewater production, and (4) optimizing the balance of capital and operational costs for FGD treatment when the power plant lifespan is uncertain.

1. Introduction

Continued reliance on coal fired power plants (CFPPs) to meet electricity demand has necessitated widespread deployment of pollution control technologies at these facilities. While the US Environmental Protection Agency (EPA) has phased in several rules limiting air emissions at CFPPs, the agency has only recently set effluent concentration standards for aqueous emissions of heavy metals (arsenic, mercury, and selenium), total dissolved solids, and nitrates. These 2015 Effluent Limitations Guidelines for the Steam Electric Power Generating Sector (ELGs)¹ updated discharge limits promulgated in 1982 and covered a broad range of wastewater streams, including fly ash transport water, bottom ash transport water, flue gas mercury control wastewater, gasification wastewater, coal combustion residual (CCR) leachate from ash ponds or on-site landfills, and flue gas desulfurization (FGD) wastewater.² At existing CFPPs, the first four of these streams will move to dry ash handling systems or treated to eliminate the discharge of pollutants, while CCR leachate and FGD wastewater may be discharged to the environment following treatment. In September 2017, the EPA announced that it is reviewing the FGD wastewater and bottom ash standards for existing facilities and expects to reissue a final rule in 2020, postponing implementation of the 2015 ELGs for these two streams until Nov. 1, 2020.³ This review details the technical challenges and engineering opportunities for bringing FGD wastewater treatment systems into compliance with the 2015 ELG standards.

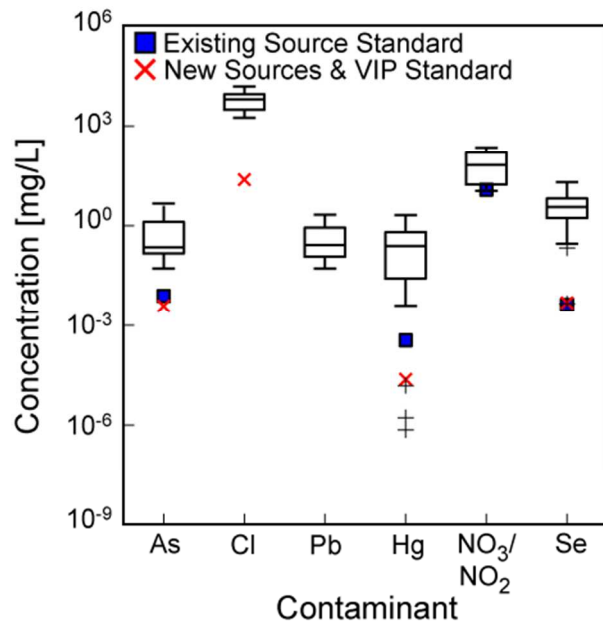


Figure 1. Arsenic, chlorides, lead, mercury, nitrate and nitrite, and selenium contaminant concentrations in FGD wastewater. Data collected by Eastern Research Group in 2010 and 2011 at 11 plants as part of the ELG rule-making process.⁴ Discharge standards under the 2015 ELGs are indicated by the blue squares (for existing sources) and red crosses (for new sources and the voluntary incentives program (VIP)).

In a survey of CFPPs conducted between 2007-2009, the Eastern Research Group found that 63% of plants discharge FGD wastewater into the environment. Many of these plants rely on surface impoundments (28% of plants) or chemical precipitation (24% of plants) for wastewater treatment,⁵ but the discharged water often contains significant concentrations of chlorides, arsenic, selenium, lead, mercury, and other metals that impact ecosystem and human health (Fig 1). These discharges impact sensitive waterbodies. For the year 2015, these sensitive waterbodies included 70 that are classified as impaired under the Clean Water Act, 140 under a fish consumption advisory, 138 that are habitats for threatened or endangered species, and 113 that are source waters for drinking water systems.⁶ Utilities have upgraded, and continue to

upgrade, their wastewater treatment trains to include chemical precipitation and biological treatment processes designed to reduce the environmental impact of FGD wastewater discharges. Many metals in discharged FGD wastewater have a tendency to bioaccumulate, impairing fish reproduction and reducing the biodiversity in lakes.^{6,7} These ecological impacts can also impact human health when fish from CFPP contaminated waters are routinely consumed. Researchers have observed reduced IQs in children⁸ and a higher risk of cardiovascular disease in adults⁹ stemming from high rates of fish consumption from waters downstream of CFPPs.¹⁰ The risks to drinking water quality are minimal in municipal water treatment systems with robust treatment trains,^{6,7} though elevated levels of brominated disinfection byproducts may occur during low streamflow periods.^{11, 12}

Table 1. FGD Wastewater Discharge Limits under the 2015 ELGs²

	Maximum Average Daily Concentration Limits Over 30 Consecutive Days		
	Average Untreated Concentrations Reported by EPA*	Existing Sources	New Sources and Voluntary Incentives Program for Existing Sources**
Arsenic (µg/L)	507	8	4
Mercury (ng/L)	289,000	356	24
Selenium (µg/L)	3,130	12	5
Nitrate/Nitrite (mg/L)	91.4	4.4	Not Regulated
TDS (mg/L)	33,300	Not Regulated	24

* Plant average concentrations during EPA sampling activities between 2007-2011.⁴

** Existing sources can choose to meet these standards for a delay of the compliance deadline to 2023.

This work addresses both mature and emerging technologies for treating FGD wastewater at CFPPs to comply with the 2015 ELGs (Table 1). We first review factors impacting FGD wastewater composition, examining trace elements in coal, the impacts of air pollution control processes on trace element fate, and the volume of FGD wastewater produced. We then describe the advantages and limitations of the best available technologies (BATs) for FGD wastewater

treatment that were identified by the EPA when setting the 2015 ELGs. Finally, we discuss ELG compliance challenges and areas of future research that would improve the performance and reliability of existing and emerging FGD wastewater technologies.

2. Factors Influencing FGD Wastewater Quantity and Composition

There are 211 CFPPs currently operating wet FGD units for SO₂ removal in the United States,¹³ and others around the world. Utilities often prefer wet FGD systems over dry or semi-dry FGD systems due to their higher SO₂ removal (wet $\geq 90\%$; dry = 50-90%, depending on the reagent used).¹⁴⁻¹⁶ In wet FGD systems, SO₂ is removed by contacting flue gas with a limestone slurry^{17, 18} creating a gypsum-saturated wastewater in the process.¹⁹ In 2014, 210 million m³ of FGD wastewater was produced in the United States²⁰ at a rate of 0.16-0.20 m³/MWh of electricity.²¹

In addition to being saturated with gypsum, this FGD wastewater contains trace elements that have partitioned into the scrubbing liquor.^{6, 22-26} This scrubbing liquor is recycled through the FGD system until the chloride concentrations pose a corrosion risk for the FGD unit.¹⁴ Chloride concentrations are typically maintained at less than 20,000 mg/L via a slip stream that is diverted for treatment,^{21, 26} though corrosion resistant scrubber materials allow some systems to maintain chloride concentrations as high as 40,000 mg/L.²⁷ The use of corrosion resistant scrubber materials allows for greater recycling rates and less FGD wastewater to be produced.

As the source of chloride and other regulated trace elements in CFPPs, coal plays an important role in determining the composition of FGD wastewater.²⁸ Trace elements in coal can either be attributed to metals originally present in the peat beds that formed the coal or through partitioning of coalphile trace elements into coal from groundwaters.²⁹ There is underlying spatial variation in the concentration of trace elements (Figure 2) due to variations in trace

elements in the atmosphere (e.g. volcanic gasses), solids (e.g. particulate matter), and liquids (hydrotherms, surface waters, groundwater, and water trapped in sedimentary rocks) interacting with the peat and coal beds during their formation.³⁰ Several coalphile elements are of particular concern in FGD wastewater systems, including selenium (with median concentration in coal worldwide five times that of sedimentary rocks), mercury (with median concentration 1.5 times that of sedimentary rocks), and arsenic (with median concentration 1.1 times that of sedimentary rocks). The EPA cited a need to better understand how FGD wastewater composition varies as a function of coal rank in their decision to delay compliance for the 2015 ELGs for FGD wastewater.³

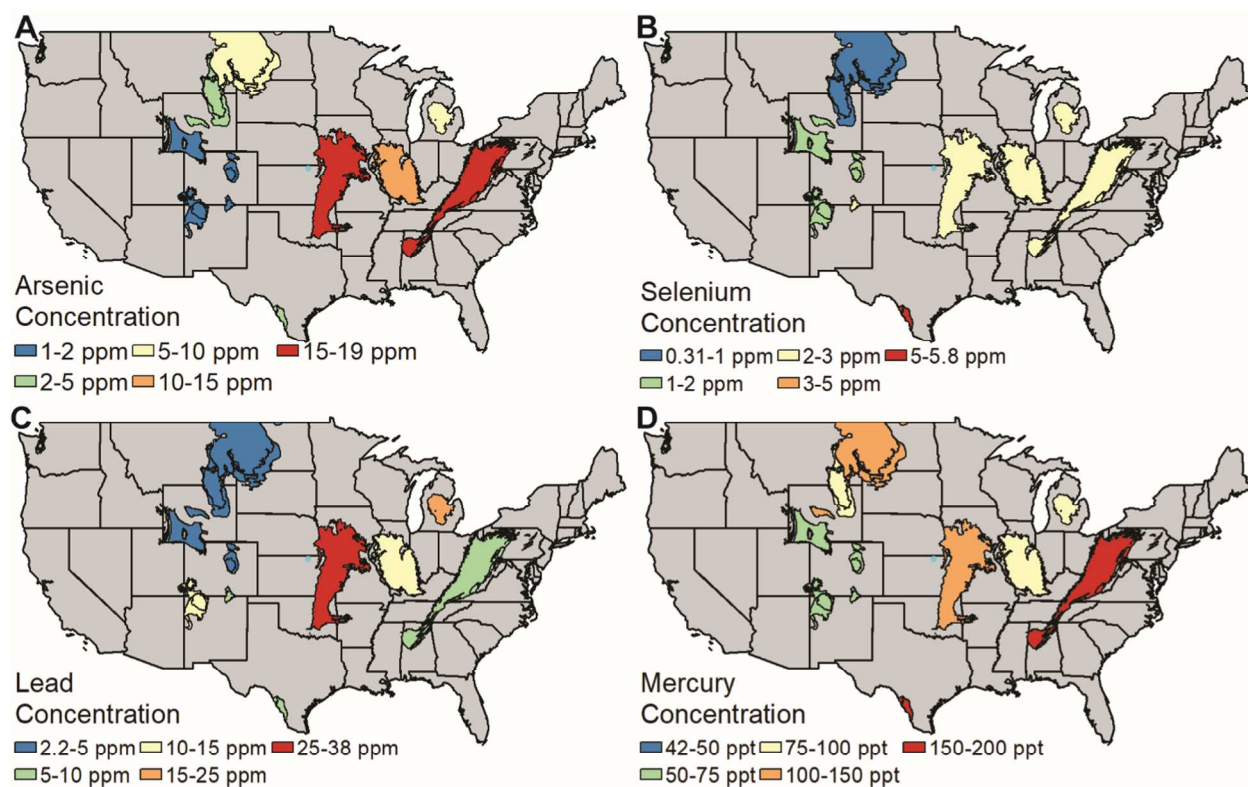


Figure 2. Median concentrations of (A) arsenic, (B) selenium, (C) lead, and (D) mercury in United States coal fields.³⁰

Air pollution control devices (APCDs) upstream of the wet FGD unit can also impact trace element speciation and concentration in wastewaters by removing trace elements before they enter the FGD process. Measuring trace element concentrations throughout power plants to understand the influence of APCDs in trace element partitioning across solid, liquid, and air phases is an active area of research.^{23, 25, 31-35} However, these studies have not typically accounted for trace element speciation, limiting their ability to inform water treatment decisions where an understanding of speciation is necessary for system design and evaluation (as is the case for selenium). Utilities have performed analyses to understand the speciation of selenium and mercury, however, this data is not publicly available. Furthermore, the conclusions drawn from power plant trace element studies are often limited to the power plant under analysis due to the large variability in combusted coal quality and installed APCDs across power plants. Future research in this area should focus on collecting speciation data, increasing data collection at more facilities and at intermediate points in the plant (i.e. not just in the exhaust or coal combustion residuals), and translating the results into open-source, generalizable models. Robust models may ultimately be useful for assessing the required performance of treatment technologies and identifying CFPPs at a greater risk for emissions non-compliance.^{36, 37}

3. Best Available Technologies for FGD Wastewater Treatment

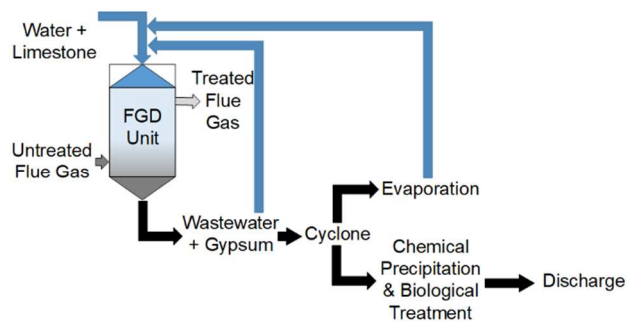


Figure 3. In the FGD process, untreated flue gas containing SO_2 and trace elements are contacted with a limestone slurry. The limestone slurry reacts with treated flue gas and

produces a gypsum-saturated wastewater stream. While most of this wastewater stream is recycled within the FGD system, a portion of this stream is purged and treated.

A variety of FGD wastewater treatment technologies are currently installed at CFPPs. These include surface impoundments, chemical precipitation, biological treatment, desalination systems, evaporation systems, and constructed wetlands.^{17, 21} In establishing the 2015 ELGs, the EPA selected “best available technologies”, or BATs, for regulatory compliance. These standards for existing and new CFPPs are based on the performance of chemical precipitation and biological treatment (CPBT) processes and mechanical vapor compression and crystallization (MVCC) systems, respectively. While CFPPs must meet the standards that are achievable by these technologies,¹ they have flexibility in the actual technologies and treatment trains that they choose to install. At 60% of existing CFPPs in the United States, FGD wastewater is treated with noncompliant systems (e.g. surface impoundments or constructed wetlands) and will require treatment train upgrades to meet discharge standards under the ELGs⁵ and to achieve compliance with the Coal Combustion Residuals Rule.³⁸ An additional 37% of plants use zero liquid discharge (ZLD) operating practices that may or may not meet the statutory requirements established in the 2015 ELGs.⁵

Regardless of the selected wastewater treatment technology, the first step in most FGD wastewater treatment trains is a cyclone or other settling process to remove gypsum solids present in the FGD wastewater.^{17, 21} Gypsum is commonly sold as a soil additive to improve crop yields³⁹ or mixed with fly ash for prefabricated building materials such as drywall.⁴⁰ The economic opportunities created by gypsum sales may have driven a small amount (~2%) of SO₂ reductions observed following the 1990 Clean Air Act Amendments (CAAAAs).⁴¹

Following solids removal in a cyclone, the BAT treatment train for new and existing CFPPs is chemical precipitation for arsenic, mercury, and lead removal from FGD wastewater.² The addition of organosulfide and ferric chloride^{17, 26} precipitants raises the pH of the wastewater to form insoluble products that settle out in a clarifier. Lime and soda ash addition can also be incorporated for softening as needed, but is not necessary for trace metals removal. While 85% of the FGD wastewater toxicity is removed in the chemical precipitation process,²⁷ submicron mercury, arsenic, and selenium are often poorly removed without additional treatment. Submicron mercury has been successfully removed using powdered activated carbon.²⁶ Selenium (and to a lesser extent arsenic) removal is expected to require attached growth anaerobic biological treatment at existing CFPPs or evaporation at new CFPPs.^{5, 26, 42}

In fixed bed systems, microorganisms grow on a substrate and either utilize selenium oxyanions as electron acceptors, reducing Se(VI) and Se(IV)⁴³⁻⁴⁵ to elemental selenium and selenide through dissimilatory reduction, or incorporate selenium into amino acids and selenoproteins through assimilatory reduction.^{46, 47} Scientists have observed selenium reduction in at least 19 different genera of microorganisms that utilize selenium as a terminal electron acceptor.⁴⁸ A review by Nancharaiah and Lens⁴⁸ provides a thorough overview of the selenium cycle, selenium reducing bacteria, and the biochemical pathways used in selenium reduction. Dissimilatory reduction ending at Se(0) appears to be the dominant pathway for selenium reduction in bioreactors, as the primary end product of biological treatment is elemental selenium instead of organic selenium compounds or selenide.^{47, 49} The end products of dissimilatory reduction are amorphous nanospheres of elemental selenium that form at the bacterial cell wall⁵⁰⁻⁵² or in the extracellular environment,^{46, 47, 52} but they may also form colloids that remain in the aqueous phase and are discharged with the bioreactor effluent.⁵³⁻⁵⁵ Additional research on the

potential for assimilatory reduction and organoselenide formation will assist in the design of polishing processes for bioreactor effluent.

Despite two decades of research in the microorganisms responsible for selenium reduction, designing and operating bioreactors remain a challenge for utilities. In particular, there is a large gap in understanding the significance of individual selenium reducing bacteria species and the conditions that influence selenium speciation and uptake kinetics. The EPA has focused on the oxidation-reduction potential (ORP) of the wastewater as a critical operating parameter for these systems, with an optimal ORP for selenium removal occurring between -300 mV and -150 mV.¹⁷ However, this is just one potential factor governing system performance and, given the inconsistent selenium removal performance of biological systems installed at CFPPs,⁵⁶ there is a need to systematically understand the factors influencing selenium removal efficiency. Additionally, plant operators are less familiar with biological treatment processes than chemical treatment processes. Guidance on how to operate these systems and interpret monitoring data from biological treatment process will assist operators in efficiently managing these systems. Arsenic reductions of 70% have been observed as a co-benefit of biological treatment processes at one test site,⁵⁶ sufficient to achieve ELG compliance for this facility. Future work on biological treatment should also measure arsenic removal to determine if this polishing effect is a consistent feature of biological processes or limited to this one installation.

While the EPA established biological treatment as the BAT for existing CFPPs, they identified MVCC as the BAT for new CFPPs.⁵ Under the 2015 ELG voluntary incentives program, the EPA also provided existing facilities with the option of installing processes that could achieve the same performance as MVCC processes in exchange for delaying ELG compliance until December 31, 2023. In MVCC systems, electrical energy is used to compress

steam, which is then pumped into the tubes of a falling film evaporator where FGD wastewater is evaporated upon contact.^{57,58} An alternative form of this same technology, thermal vapor compression and crystallization (TVCC), uses steam from the turbine or a dedicated boiler to heat the motive steam. However, the cost of steam-carrying pipes typically makes MVCC the more attractive vapor compression system option.²⁷ If softening is used as a pretreatment step for MVCC, the brine from the MVCC process can then be sent to a crystallization step and the water vapor can be collected for reuse in the plant.

A challenge at both existing and new CFPPs is minimizing the costs of ELG compliance. For existing facilities, installing CPBT trains is expected to cost the industry an estimated \$110 million annually nationwide.²⁰ The EPA estimated that installing and operating ZLD systems at existing and new facilities would be prohibitively expensive for many utilities.⁵⁹ In addition to these direct costs, there are likely to be indirect social costs in the form of air emission externalities associated with producing electricity and chemicals used in FGD wastewater treatment. Recent work estimated that the air emission damages associated with wastewater treatment increased the net costs of CPBT and ZLD treatment trains by 76% and 43%, respectively.²⁰ These challenges highlight the need to also consider social costs from chemical manufacturing and electricity generation in selecting and designing FGD wastewater treatment systems.

4. Challenges and Opportunities for FGD Wastewater Treatment

Following the announcement of the proposed ELGs, the electricity industry raised several concerns about the EPA identified BATs.^{56,60-63} First, as noted above in Section 3, installations of CPBT systems after ELG promulgation have shown poor selenium removal performance, especially for wastewaters with greater than 25,000 mg/L of chlorides.^{26,56} Highly variable FGD

wastewater compositions between and within plants have prevented the industry from identifying universally applicable, corrosion-resistant alloys for use in MVCC systems,⁶⁴ which results in shorter system lifespans and increased ZLD compliance costs.²⁷ Trends in the electricity generation sector toward extensive ramping of CFPPs suggest that FGD wastewater treatment systems will need to accommodate large fluctuations in FGD wastewater flowrates.²⁶ And finally, uncertainties surrounding CFPP retirement timelines further complicate the optimization of capital and operating expenses to minimize ELG compliance costs.

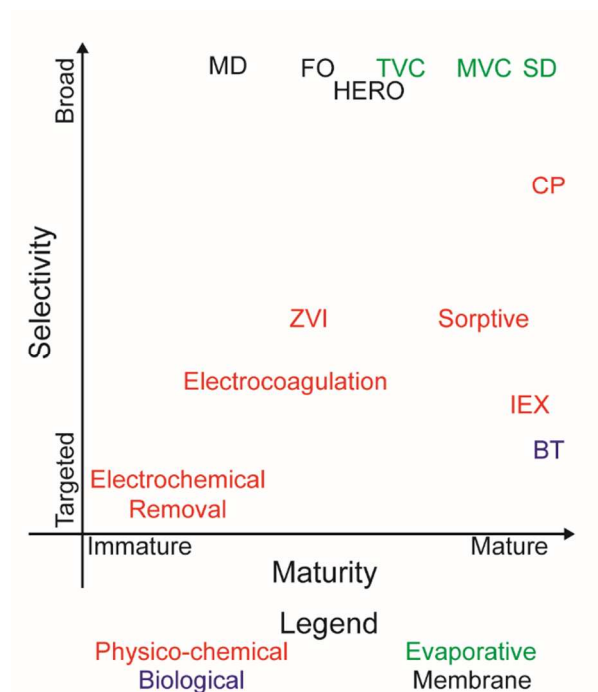


Figure 4. Technologies for FGD wastewater treatment. The x-axis represents the current maturity of the technology (i.e. technologies on the right side are already deployed at scale and technologies on the left side are still being developed). The y-axis represents the selectivity of the technology (i.e. technologies lower on the axis can be designed to remove specific contaminants whereas technologies higher on the axis remove all contaminants). The technologies can be divided into four categories, including physico-chemical (electrochemical

removal; electrocoagulation; zero-valent iron, ZVI; sorption-based technologies; ion exchange systems, IEX; and chemical precipitation, CP), biological treatment (biological treatment, BT), evaporative technologies (spray dryer, SD; mechanical vapor compression, MVC; and thermal vapor compression, TVC), and membrane technologies (membrane distillation, MD; forward osmosis, FO; and high-efficiency reverse osmosis, HERO).

4.1 Removal of Selenium from FGD Wastewater

Table 2. Technologies for selenium removal from FGD wastewater

	Description	Advantages	Disadvantages
Biological Treatment ⁴⁶	Se(VI) and Se(IV) are reduced to Se(0) by microbial action forming particles attached to the cell wall or in the extracellular environment.	Demonstrated technology for Se removal; Provides As polishing of chemical precipitation effluent.	Some systems have low chloride tolerance (<25,000 mg/L); Performance is erratic and difficult to control; Requires pre-treatment to reduce nitrates and nitrites concentrations.
Oxide Sorption Systems ^{28, 65, 66}	Selenium adsorbs on to the surface of GFO, GFH, or GTO sorbents. Se(VI) is slightly favored over Se(IV). Media is single use.	Novel sorbents have achieved effluent Se levels of <2 µg/L.	No studies of performance in FGD wastewater; Sorption media requires replacement; Competition from vanadium, phosphate, and silica.
Ion Exchange ⁶⁷⁻⁷⁰	Selenium adsorbs to ligands on ion exchange resin beads, releasing a weakly attached co-ion. Se(VI) is slightly favored over Se(IV).	Resins for selenium removal already exist.	Not suitable for high TDS waters. Requires pre-treatment for sulfate and suspended solids removal.
Zero-Valent Iron ⁷¹⁻⁷⁴	Selenium ions are converted to elemental selenium by redox reactions with ZVI. Se(IV) is favored over Se(VI).	ZVI is already in use as pre-treatment for constructed wetlands; Cost-competitive with BATs for ELG compliance.	No commercial experience with ZVI; narrow pH range; Requires pre-treatment to remove nitrates and nitrites and address NH ₃ generation.
Electrochemical Systems ^{43, 75-77}	In electrocoagulation, the most commonly deployed technology, ions released from sacrificial electrodes react with selenium to form insoluble precipitants.	Electrocoagulation is a well-established technology for metal plating wastewater and can also be used to remove colloidal Se(0) from biotreatment effluent; Potential for selective removal of Se using electrosorption	Electrocoagulation is only cost-competitive for small CFPPs; Selenium selective electrodes do not yet exist; High electricity consumption.

Following the promulgation of the 2015 ELGs, utilities reported difficulty with reliable selenium removal in FGD wastewater treatment systems. Removing selenium using biological processes relies on microorganisms that are sensitive to co-contaminants in FGD wastewater, most notably chlorides,²⁷ and competition from sulfate-reducing bacteria.⁵⁶ The GE ABMet system, the technology the 2015 ELGs for existing sources are based upon, is designed to handle wastewaters with chloride levels less than 25,000 mg/L,²⁷ but some FGD wastewater streams can reach 40,000 mg/L of chlorides.¹⁷ In addition, microbial activity may also be impaired by high levels of nitrites/nitrates, further reducing the ability of microorganisms to reduce selenium concentrations.^{27, 56} Finally, elemental selenium not retained in microorganisms or the extracellular environment is present in discharged in the effluent as colloidal selenium,⁵³⁻⁵⁵ possibly requiring the use of additional filtration steps or coagulation and flocculation polishing processes^{47, 54, 55} to achieve ELG compliance. Several alternative systems (Figure 4) have been identified for selenium removal, either in conjunction with or instead of biological processes. These technologies include oxide sorption systems, ion exchange processes, zero valent iron, and electrochemical systems. Demonstration on FGD wastewaters will be critical to assessing the viability of these technologies as a compliance strategy.

4.1.1 Oxide Sorption Systems

Ferric or titanium oxide sorption systems are frequently used in drinking water treatment for arsenic removal^{78, 79} and have been identified as potential alternatives for removing selenium from FGD wastewater.²⁸ In sorption based systems, wastewater is fed into beds containing granular ferric oxides (GFO), ferric hydroxides (GFH), or titanium oxides (GTO) and selenium adsorbs on to the surface of the media. These beds are occasionally backwashed to remove suspended solids.²⁸ Lab-scale demonstrations of selenium removal using GFH sorbents have

shown a selenium adsorption capacity of 2.5 mg-Se/g-adsorbent.⁶⁵ When tested at an FGD wastewater relevant concentration of 2 mg/L of Se, the observed effluent Se concentrations of 50-100 µg/L exceeded the ELG standard of 12 µg/L. More recently, a novel Mg-Al-CO₃ layered double hydroxide sorbent with a selenium adsorption capacity of 89.5 mg-Se/g-adsorbent has been demonstrated on selenium contaminated groundwater, with the authors noting potential applications in FGD wastewater treatment.⁶⁶ Selenate removal is slightly preferred over selenite removal by this sorbent. A challenge associated with adsorption systems is competition for active sites on ferric oxides in high pH wastewaters from vanadium (present in untreated FGD wastewater at concentrations of >1.3 mg/L on average),⁵ phosphate (1 mg/L),⁴ and silica (280 mg/L).⁴ Finally, analyses by the Electric Power Research Institute (EPRI) of sorption media concluded that the most cost-effective media for FGD wastewater treatment are single-use, despite the high operating expenses associated with disposing of and replacing spent media.²⁸ The life-cycle impacts of generating single-use hydroxides, in addition to chemicals required for pH control to keep the system in its operating pH window, can also impose significant social costs.⁸⁰ Given their promise, however, we recommend further work to demonstrate their performance in treating real FGD wastewaters at the bench- and pilot-scales.

4.1.2 Ion Exchange Systems

FGD wastewater can also be treated using ion exchange (IEX) systems in order to achieve compliance with the 2015 ELGs.¹⁷ In IEX systems, wastewater is fed into the top of a column containing beads coated in ion exchange resins that have ligands with weak counter ions (e.g. chloride). When wastewater is introduced to the column, the selenium displaces the counter ion from the ligand.^{67, 68} This process favors selenate removal rather than selenite removal.⁸¹ IEX systems have several advantages that make them well suited for FGD wastewater treatment.

First, IEX is one of the most common technologies for heavy metal removal in industrial wastewater applications.⁶⁸ These applications include power plants, where IEX systems are commonly used for boiler feedwater treatment, indicating that power plant operators are familiar with how to manage IEX systems should they be used for FGD wastewater treatment. Second, resins already exist for selenium removal from industrial wastewaters (at mg/L levels) and raw water (at µg/L levels).^{69, 70} However, IEX systems are sensitive to scaling and fouling from suspended solids and sulfate compounds,²⁸ and removal of sulfate is not practical given the order of magnitude difference in concentration between sulfate and selenium. This challenge is highlighted in several industry and academic studies, including Staicu et al., where FerriIX A33E resins were evaluated in batch mode on FGD wastewater with an initial Se concentration of 1.2 mg/L.⁸² The authors observed Se removal of 3% without a desulfurization step and 80% removal following a BaCl₂ desulfurization processes. This removal following the desulfurization process is still well below what is necessary for compliance with the ELGs, suggesting that the application of IEX to FGD wastewater treatment is likely to be severely hindered. Furthermore, IEX processes share the same drawbacks as granular hydroxide sorbents, including high capital and operating costs⁸³ and the environmental impacts of manufacturing single-use weak base anion exchange resins.⁸⁰

4.1.3 Zero-Valent Iron Systems

Zero-valent iron (ZVI) has previously been used as a pre-treatment step for FGD wastewater treatment in constructed wetlands,²⁸ but can also be paired with chemical precipitation to achieve ELG compliance for selenium removal.¹⁷ Previous work has shown that ZVI can reduce selenate and selenite to elemental selenium,^{71, 84} with selenite more easily reduced in ZVI processes than selenate.⁷⁴ ZVI processes are poorly suited for nitrate removal as

it produces ammonium^{84, 85} and requires chemical addition to maintain acidic conditions⁸⁴ following the alkaline conditions of the chemical precipitation process. By adding FeCl₂ (iron (II) chloride) solution to ZVI reactors, nitrates and Fe(II) are converted to ammonia and magnetite, creating hybrid ZVI systems (hZVI) that are also capable of removing selenium, arsenic, and mercury.⁷⁴ FGD wastewater treatment using this hZVI system has been demonstrated at the pilot-scale,^{72, 73} and techno-economic assessments suggest these systems may have lower compliance costs than CPBT trains.⁷⁴ Ongoing research and demonstration will be critical to evaluating the generalizability of these results to CFPPs with varied FGD wastewater chemistries.

The drawbacks of ZVI systems are their narrow pH operating window, high required residence times, the generation of ammonium ions, and large bed volumes due to their low reactivity. These large beds require significant amounts of costly media (~\$1.50/kg)⁷⁴ that will ultimately need to be disposed. A further challenge for non-hybrid ZVI systems is interference from nitrates and nitrites found in FGD wastewater.¹⁷ The hZVI system is capable of reducing nitrates, and so can avoid this concern. Further work developing a mechanistic understanding of the removal process⁷⁴ and performing larger scale pilot studies^{72, 73} will be necessary before hZVI systems can be deployed for compliance. Particular attention should be paid to hZVI performance during start-up and intermittent operation⁷⁴ as bench- and pilot-scale tests have required up to a week to optimize operations during this period in order to achieve consistent compliance.

4.1.4 Electrochemical Systems

Electrochemical water treatment processes, including electrocoagulation, electrodialysis, and electrosorption, have not been widely evaluated for FGD wastewater treatment. In

electrocoagulation, iron or aluminum ions are released from a sacrificial anode into the wastewater by passing a direct current through an electrode system.⁷⁶ These dissolved ions react to form aluminum and ferric hydroxides, which sorb selenium and other trace metals.^{75, 86-88}

When paired with a microfiltration step to remove these selenium-laden sorbents, selenium removals of 99% have been observed from a solution containing an initial selenium concentration of 2.3 mg/L (a concentration relevant to FGD wastewater treatment).⁸¹

Electrocoagulation has also been used as a polishing step to remove colloidal selenium from bioreactor effluent at bench-scale.⁸⁹ Typical electrocoagulation systems are small ($\sim 2\text{-}6\text{ m}^3/\text{hr}$) and the maximum economically competitive size for current electrocoagulation systems is roughly $20\text{ m}^3/\text{hr}$.⁷⁵ As a result, these electrocoagulation systems are only suitable for application at CFPPs with generation capacities less than 200 MW, below the 300-450 MW size of typical CFPPs with installed wet FGD units.²⁰ Future work on electrocoagulation should focus on characterizing trace element removal from complex wastewaters, instead of single-species wastewaters, reducing the large electricity consumption (on the order of $1\text{-}5\text{ kWh/m}^3$) of these processes, and designing cost-effective larger systems.⁸⁶

Two additional electrochemical technologies include electrodialysis and electrosorption. In electrodialysis, wastewater enters an electrodialysis cell that is divided into feed channels and concentrate channels by ion exchange membranes. When an electrical current is applied to the electrodes located in the concentrate channels, ions in the wastewater migrate from the feed channel towards the membranes. These ions then pass through the ion exchange membrane to form a concentrated brine.^{90, 91} Selenium removal in electrodialysis processes is heavily pH dependent, with $>80\%$ removal observed at acidic pHs and $<50\%$ removal observed under basic conditions.⁹² This is due to change in speciation and ion charges resulting from changes in pH.⁹²

The chemical precipitation pretreatment process raises the pH, and so may inadvertently reduce the efficiency of selenium removal in electrodialysis.^{5, 45} Removal is also dependent on species mobility in aqueous and membrane phases and the relative concentration of selenium ions relative to other anions in the wastewater. Given their low concentration, competition with other anions in FGD wastewater (an average in untreated wastewater of 3.1 mg/L dissolved selenium vs. 7.2 g/L for chlorides and 13 g/L for sulfates)⁵ is likely to result in low selenium selectivity and may stymie application of electrodialysis to FGD wastewaters.

In electrosorption processes, ions adsorb or are galvanically deposited onto electrodes under the influence of an electrical field.^{43, 77} When these electrodes are formed of capacitive materials such as activated carbon, this technology is often referred to as capacitive deionization. Electrosorption has been used for arsenic and heavy metal removal, and electrosorption may also be a viable strategy for selenium removal.^{93, 94} A small scale capacitive deionization process has been commercialized as SeClear.⁴³ Separate bench-scale testing on galvanic deposition on Cu/Fe electrodes has also been reported.⁷⁷ Future work is needed to develop and tailor electrodes for selenium removal, evaluate removal efficacy in the presence of mixed ion systems, and reduce the energy consumption from current estimates of 10-20 kWh/m³.⁶⁸

4.1.5 Other Considerations Surrounding Selenium Compliance

Researchers have noted that FGD wastewater can be a potential source of selenium nanomaterials for industrial applications during the transition to a circular economy.^{54, 95} Biological processes produce biogenic selenium that can be recovered through a variety of techniques, with density-gradient centrifugation being the most suitable given the variability in diameters of the polydisperse Se(0) nanoparticles produced.⁹⁵

In addition to installing technologies to remove selenium, utilities can also consider switching to coals with lower selenium concentrations to eliminate the need for a polishing step following biological treatment. As shown in Figure 2, different coal fields have different concentrations of regulated contaminants. In particular, coals from the western US have average selenium concentrations that are one-half to one-third lower than those of eastern US coals (e.g. Powder River Basin averages 0.9 mg-Se/kg-coal, Fort Union 0.7 mg-Se/kg-coal, and Green River 1.1 mg-Se/kg-coal, while Appalachian coals average 2.2-3.2 mg-Se/kg-coal).³⁰ The Powder River Basin has low concentrations for all trace elements regulated under the 2015 ELGs with selenium concentrations of 0.9 mg-Se/kg, arsenic concentrations of 3.8 mg-As/kg, and mercury concentrations of 85 µg-Hg/kg. This switch will include sourcing coal from farther away than is currently done in many cases, and that will increase the cost of generation and the social costs of air pollution from coal transportation. A switch in coals is unlikely to eliminate the need for a biological treatment process as the effluent of chemical precipitation processes have selenium concentrations an order of magnitude higher than the discharge limits. However, at systems that are close to achieving compliance with biological treatment, reducing selenium loading into the wastewater treatment process by reducing the amount of selenium in the coal combusted may avoid the need for selenium polishing.

One potential concern with the coal switching approach is that low selenium coal may also be low chlorine coal, which would increase the safe FGD slurry recycle rate and still lead to high selenium concentrations in the FGD purge. An analysis of COALQUAL data³⁰ indicates that the correlation between selenium concentration and chlorine concentration is positive (Fig. 5), but weakly so (Pearson correlation coefficient of 0.094), and so increased cycling may not occur as a result of a fuel switch. This strategy of switching to a cleaner burning coal is a tested

approach for SO₂ and Hg emissions reductions in response to the 1990 CAAAs and the 2011 Mercury and Air Toxics rule.^{96, 97}

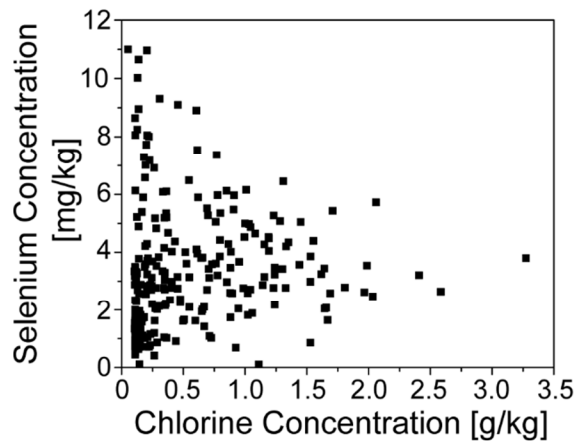


Fig 5. Average county-level concentrations of chlorine and selenium in coal samples reported in the USGS COALQUAL data. There is a weak positive relationship between chlorine and selenium concentration. N.B. that chlorine concentrations are in grams per kilogram of coal while selenium concentrations are in milligrams per kilogram of coal.

Coal switching may also allow CFPPs to move from wet FGD to dry FGD systems. Dry scrubbers are essentially a ZLD option for FGD wastewater treatment, since there is only minimal water use and a wastewater purge stream is not created. Dry FGD systems have a lower SO₂ removal efficiency than wet systems,¹⁶ and utilities have selected wet FGD scrubbers more frequently to comply with SO₂ emissions standards. Switching to low sulfur coals (<3.5% S content)⁹⁸ and controlling the temperatures of the flue gas entering the FGD unit to be 150-180°C (10-15°C above the saturation temperature)^{15, 16} enables CFPPs to use dry FGD to simultaneously meet the 1990 CAAA requirements⁹⁹ and eliminate the discharge of FGD wastewater for ELG compliance. This approach is more suited to small CFPPs with a capacity of less than 200 MW,^{15, 16} or a flue gas flow rate of 800,000 Nm³/hr.⁹⁸ Above these levels, multiple dry FGD units will need to be installed. These small CFPPs are a shrinking fraction of

the nation's coal fired fleet, with the average CFPP retiring between 2008 and 2018 having a capacity of 105 MW (compared to 319 MW for the remaining fleet).¹⁰⁰ This option may therefore be a less attractive option for utilities that may not want to install multiple FGD systems in the remaining, larger systems. Retrofitting CFPPs with dry FGD systems will incur upfront capital costs to remove the existing FGD system and the capital cost for the dry FGD system (\$125-\$216/kW in 2015 US dollars) will prevent many utilities from switching to dry FGD systems, but there could be some savings from the lower operating costs of dry FGD systems (\$0.0059-\$0.0070/kWh compared to \$0.0078-\$0.0156/kWh for wet FGD in 2015 US dollars).⁹⁸

Finally, early installations of CPBT trains have shown that chemical precipitation alone is unable to meet the discharge standards for arsenic. For at least one CFPP, biological treatment has played a role in achieving compliance with the existing 2015 ELGs for arsenic.⁵⁶ If utilities choose not to deploy biological treatment for selenium removal, they may need to install additional processes to comply with the arsenic standard. Fortunately, many of the technologies identified above for selenium removal can also be tailored for arsenic removal, including granular oxides,²⁸ and electrochemical systems.⁶⁸

4.2 Recovering and Reusing FGD Wastewater

Table 3. Technologies for FGD wastewater recovery and reuse

	Description	Advantages	Disadvantages
Mechanical Vapor Compression & Crystallization (MVCC) ²⁷	Motive steam is compressed and fed into the tubes of an evaporation unit, FGD wastewater evaporates as it contacts the tubes.	Demonstrated for FGD wastewater treatment at CFPPs.	Energy consuming process; Susceptible to corrosion from high chloride wastewater
Spray Dryers (SD)	FGD wastewater is evaporated using a portion of boiler flue gas typically used for air preheating, producing a solid product.	Low capital cost; Can achieve zero liquid discharge without a crystallization step.	Imposes a 1-2% reduction on the heat rate of the CFPP; Does not produce a liquid stream that can be reused.
Thermal Vapor Compression & Crystallization (TVCC) ¹⁰¹	Motive steam is compressed and fed into the tubes of an evaporation unit, FGD wastewater evaporates as it contacts the tubes.	Can utilize low-pressure steam.	Energy consuming process; Susceptible to corrosion from high chloride wastewater; Steam sourcing can require a dedicated boiler if co-location near turbines is not feasible.
Forward Osmosis (FO) ¹⁰²⁻¹⁰⁵	FGD wastewater and a highly concentrated draw solution are fed into membrane module, water diffuses across the semipermeable membrane, diluting the draw solution and concentrating the feed solution into a brine.	Can utilize low-temperature waste heat as the energy source for draw solute regeneration.	Requires crystallization step to achieve ZLD; Requires softening to avoid gypsum and CaCO ₃ scaling.
High-Efficiency Reverse Osmosis (HERO) ²⁸	FGD wastewater pH is adjusted to ~11.5 to allow for reverse osmosis at higher water recoveries with reduced silica scaling	Currently used for cooling water blow down treatment at CFPPs.	Requires crystallization step to achieve ZLD; Requires softening to avoid gypsum scaling; High electricity consumption.
Membrane Distillation	A vapor pressure gradient is	Can utilize low-temperature	Not demonstrated at scale for

(MD) ¹⁰⁶⁻¹¹⁰	created on opposite sides of a hydrophobic membrane by heating the FGD wastewater, water vaporizes and passes through the membrane to condense on the cool side.	waste heat as the energy source; Can achieve zero liquid discharge without a crystallization step.	FGD wastewater treatment.
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ZLD treatment trains eliminate aqueous emissions of pollutants and, depending on treatment technology selection, can reduce water withdrawals by enabling treated water reuse within the plant.^{111, 112} Despite these advantages, there are several technical challenges associated with MVCC systems that may hinder their adoption. First, MVCC systems contact FGD wastewaters with high chloride levels, necessitating the use of expensive alloys to protect against corrosion. Within the past decade, utilities began observing corrosion in new FGD systems, including at least one system that had been in operation for less than three months.¹¹³ This same water will contact ZLD systems, albeit at higher temperatures that may further accelerate alloy oxidation. Selecting appropriate alloys to resist this corrosion is complicated by the variability of FGD wastewater composition both across plants and for the same plant, preventing standardization of material selection for MVCC systems.⁶⁴ Furthermore, the high concentration of gypsum in FGD wastewater induces rapid scale formation, which reduces the efficiency of the MVCC process and necessitates frequent system cleaning.^{27, 114} Finally, ZLD treatment trains using MVCC are energy intensive, consuming 50-60 kWh/m³ of feed water and imposing a significant energy penalty on plants.^{20, 27} Given these challenges, there is a need for active research in lower cost, lower energy consumption, and more robust alternatives to MVCC.

Any process used to recover water from FGD wastewater will also generate a brine or solid waste stream. This waste stream will need to be stabilized and disposed. Brine encapsulation is a process that involves creating a paste by mixing the brine with fly ash and other ingredients and transporting the paste to a landfill to harden as a solid monolith.¹¹⁵ This process has been tested at the bench- and field-scales,¹¹⁶ but additional work on brine encapsulation is needed to evaluate the techno-economic feasibility of different transportation

options (truck, barge, conveyor belt, and pipeline) and quantify the trace element concentration from the landfill run-off and leachate.¹¹⁶

4.2.1 Thermal Evaporation Systems

One alternative to MVCC is thermal spray dryers designed to efficiently evaporate FGD wastewater. FGD wastewater is injected into a spray dryer, where the water is evaporated using a fraction of the boiler flue gas that would otherwise be used for air preheating.²⁸ A solid product is generated, which is normally removed in a particulate collection device downstream of the spray dryer. While these systems are simple to operate, spray dryers that pull heat upstream of the air preheater reduce the efficiency of the power plant by 1-2%. Despite the high operating costs associated with reduced power plant efficiency, the low capital costs of spray dryer systems are attractive for plants that are nearing retirement. A fruitful area of research for spray dryer systems will be continuing to quantify and minimize the efficiency losses associated with the use of these systems via controlling the size of the injected droplets.

4.2.2 Membrane Systems

Membrane technologies such as forward osmosis (FO),¹⁰³ high-efficiency reverse osmosis (HERO),¹⁷ and membrane distillation (MD),¹¹⁰ can also be used to recover high quality water for reuse within the plant. In FO, wastewater is osmotically concentrated across a semi-permeable membrane by a draw solution. The diluted draw solution is then regenerated using either thermal or electrical energy, depending on the draw solute.^{103-105, 117-126} For thermally decomposable draw solutes (e.g. NH_4HCO_3 or switchable polarity solvents), regeneration can be performed using waste heat recovered upstream of the wet FGD system at temperatures of 120-130°C.¹²⁷ Leveraging heat integration to drive FO water treatment processes reduces both the energy penalty on the plant and the treatment costs.^{102, 103, 128} Indeed, techno-economic

assessment of NH_4HCO_3 FO has shown that waste heat utilization is required for this technology to be economically competitive with MVCC.¹⁰²

Recovering the waste heat necessary for this process will require the use of large heat exchangers that can overcome the shallow temperature gradient between the exhaust gas and the working fluid needed for FO systems. The use of large heat exchangers is complicated by the need to fit the exchanger within existing flue gas piping,¹²⁹ and designing dense, high surface area heat exchangers will be critical to the viability of waste heat capture and utilization.

A second concern with FO systems is the potential for gypsum to irreversibly scale or damage thin film composite (TFC) and polyamide membranes (this is not a concern for cellulose acetate membranes where gypsum scaling is reversible).^{130, 131} To overcome these scaling issues, most TFC membranes used in FGD wastewater treatment systems¹³² make use of hollow fiber membranes or submerged membrane modules to minimize precipitate formation around spacers.¹³¹ Softening processes can also be used to reduce scaling potential in FO (and other membrane processes), although the use of soda ash increases the cost of water treatment.

The second membrane process, HERO, can be used for ELG compliance at facilities with low total dissolved solids content in their FGD wastewater. By raising the pH to 11.5, HERO systems reduce silica membrane scaling that would prevent the use of conventional reverse osmosis processes.¹⁷ Utilities are already familiar with HERO systems, as HERO has been installed at several power plants for ZLD treatment of cooling tower blowdown.²⁸ The HERO process relies heavily on chemical addition, with sodium hydroxide used to raise the pH to 11.5 and water softening pretreatment via lime addition or an ion exchange resin, raising the costs and increasing the environmental impact of this process. Gypsum scaling is unaffected by pH adjustment¹³⁰ and so will remain a concern at the elevated pHs of HERO operation.

Furthermore, given HERO's high electricity and chemical usage to drive separation and adjust the pH, life-cycle assessment of HERO processes should be performed to ensure that FGD wastewater treatment provides net environmental benefits when HERO is utilized.

In the third membrane technology, MD, the driving force is the vapor pressure difference between a warm feed stream and a cold permeate stream.^{110, 133, 134} Water evaporates at the feed side membrane interface, diffuses across a porous hydrophobic membrane, and recondenses on the permeate side. MD can be operated using only the heat of the FGD wastewater (~50°C), although heating FGD wastewater with moderate temperature waste heat will significantly increase the flux and reduce the required membrane area.^{107, 108, 135} MD can also achieve 90% water recovery of brines by cycling the brine through the MD process.^{136, 137} Water recoveries of 95% or higher have been observed in integrated MD-crystallizer (MDC) systems when the crystallizer is driven by heat at 80-90°C.^{106, 109, 136, 138, 139} Similar to FO, exhaust gas is a promising source of heat at temperatures that can be used to drive MD and MDC processes with large heat exchangers in the flue gas system required. However, the large heat duties of MD systems (3-4 GJ/m³) mean that the energy needs may not be fully met using waste heat and a dedicated boiler may be required to meet heat demand. Membrane wetting, in which liquid water fills the pores of membranes, is a known concern for membrane distillation and would allow for dissolved contaminants to cross the membrane into the permeate stream.¹¹⁰ Research on the design of membranes that are resistant to pore wetting have focused on modifying the membrane surface. The use of superhydrophobic membranes offer increased wetting resistance compared to conventional MD membranes.¹⁴⁰ Continued research should focus on determining the long-term performance and wettability resistance of superhydrophobic membranes in FGD wastewater.

In MD processes, unlike FO or HERO, gypsum crystals are more likely to form in the bulk solution rather than on the membranes and so gypsum scaling is less of a concern. Gypsum crystals should still be removed from the bulk solution to minimize clogging in the membrane channel, but this can be performed using cartridge filtration or a chemical precipitation pretreatment step.⁵ Given the difference in gypsum scaling propensity and the higher water recovery observed in membrane distillation,^{106, 109, 138, 139} MD shows significant potential for FGD wastewater treatment. Future work on MD includes a need to demonstrate MD treatment at full scale, to verify that gypsum crystallization occurs in the bulk solution rather than at the membrane surface,¹⁴¹ and to perform techno-economic assessments of MD/MDC systems that utilize recovered heat from the flue gas.

4.3 Flexible Operation of FGD Wastewater Systems

Electricity is not generated continuously at CFPPs, but varies over time. Since FGD wastewater production roughly follows electricity generation, wastewater flow rates are also subject to day-night cycling, plant startup, and fuel blend changes. This creates engineering challenges for right-sizing treatment and identifying technologies that can handle this variability. The large variability in flow rates led EPRI to conclude that “there is an immediate need to understand the issues and quantify the effects from flexible operation during startup/shutdown, day-night cycling, fuel switching, and periods of low-load operations.”²⁶

While the electricity industry is concerned about fluctuations in wastewater production, environmental engineers have a history of developing systems for variable wastewater flowrates. Volume equalization tanks are widely used to buffer against short term variations in wastewater quantity and quality at municipal wastewater treatment facilities¹⁴² and would provide similar services for FGD wastewater.²⁶ Of concern for utilities, however, is that installing equalization

tanks is likely to increase FGD wastewater treatment costs and the required footprint of wastewater treatment infrastructure.

Utilities also need to consider variability in wastewater composition and flow rate when selecting FGD wastewater treatment technologies. For chemical precipitation and thermal evaporation systems that are designed to treat wastewater with a constant composition, variability poses a challenge for effective process control. Cycling can also reduce the efficiency of biological treatment processes for selenium removal. Systems that generate significant auxiliary loads (e.g. through the use of steam in thermal processes or electricity in membrane processes) may require dedicated boilers or generators if they are to operate when the CFPP is not generating electricity. Fortunately, many of the technologies described in Sections 4.1 and 4.2 are expected to perform well under variable flow rates and intermittent operation, including oxide sorption systems, ZVI systems, and membrane technologies. However, quantifying the impact of these intermittencies through pilot- and demonstration-scale testing will be important in assuaging industry concerns.

4.4 Uncertainty Surrounding FGD Wastewater System Lifespans

The share of coal in the US grid mix is declining and the future of conventional coal-fired electricity generation units is highly uncertain.¹⁴³ Environmental regulations are expected to increase the levelized cost of electricity from CFPPs,^{59, 144-146} while falling natural gas and renewables prices have made these lower impact electricity generation methods more competitive.^{146, 147} In addition, there is a high likelihood that any future carbon capture requirements will reduce dispatch from CFPP and force early system retirement.^{148, 149} These trends all point to a future in which CFPPs transition from baseload generators to marginal generators that bring in reduced revenue or retire early.

Given this uncertainty, utilities may think differently about the relative importance of capital and operating expenses. Investing in technologies with low capital costs and higher operating expenses (e.g. spray dryers) may be economical if plants expect to retire early. However, if utilities do not expect to retire CFPPs early, investing in technologies where the levelized cost of water is driven by capital costs (e.g. membrane distillation)¹⁵⁰ may lead to lower annualized costs due to their comparatively lower operating expenses.

Further complicating this analysis is the lack of reliable estimates of capital and operational costs for FGD wastewater treatment technologies. For those technologies where cost estimates do exist, costs were often developed for drinking water systems or wastewaters with less complexity and variability than FGD wastewater. Robust techno-economic assessments and life-cycle cost models for ELG compliance, especially ones that consider both mature and emerging technologies,¹⁰² are vital in promoting cost effective compliance with the 2015 ELGs.

5. Conclusion

Treating FGD wastewater represents an opportunity to meaningfully reduce the water quality impacts of coal-fired electricity generation, while also providing secondary benefits associated with in-plant wastewater reuse. The critical compliance challenges will entail meeting the 12 µg/L standard for selenium, reducing plant water withdrawals by recovering water, designing FGD wastewater infrastructure to accommodate variability associated with non-baseload generation, and selecting treatment trains that balance capital and operational costs given the uncertain lifespans for CFPPs.

Compliance timelines for the 2015 ELGs will also be a significant driver in technology selection. While the EPA has granted a two-year delay in compliance with the FGD wastewater standards, utilities are currently operating under the assumptions that FGD wastewater treatment

trains will need to be ready for full-scale implementation at existing CFPPs beginning in November of 2020. This short timeline is likely to force adoption of high TRL technologies. In contrast, existing plants opting to comply with the voluntary incentives program (as well as any new plants) are expected to have until 2023 to install ZLD treatment trains. This provides a window of opportunity for further research in low TRL ZLD technologies that are resilient to scaling, are cost effective for the plant, can handle variability, and do not impose large social costs. Regardless of technology selection, these treatment trains will need to be designed for large flowrate fluctuations associated with intermittent plant operation as utilities work to reduce the environmental impact of coal-fired electricity generation in the coming decades.²⁶

6. Glossary

APCD: Air pollution control device

BAT: Best available technologies

CAAA: 1990 Clean Air Act Amendments

CCR: Coal combustion residuals

CFPPs: Coal-fired power plants

CPBT: Chemical Precipitation and Biological Treatment

ELGs: Effluent Limitations Guidelines for the Steam Electric Power Generating Sector

EPA: U.S. Environmental Protection Agency

EPRI: Electric Power Research Institute

FGD: Flue gas desulfurization

FO: Forward osmosis

GFO: Granular ferric oxide

GFH: Granular ferric hydroxide

GTO: Granular titanium oxide

HERO: High-efficiency reverse osmosis

hZVI: Hybrid zero-valent iron

IEX: Ion exchange systems

MD: Membrane distillation

MDC: Membrane distillation and crystallizer

MVCC: Mechanical vapor compression and crystallization

ORP: Oxidation-reduction potential

SD: Spray dryer

TFC: Thin film composite

TVCC: Thermal vapor compression and crystallization

VIP: Voluntary incentives program

ZLD: Zero-liquid discharge

ZVI: Zero-valent iron

7. Acknowledgements

Support for DBG was provided by appointment to the National Energy Technology Laboratory Research Participation Program, sponsored by the U.S. Department of Energy and administered by the Oak Ridge Institute for Science and Education. The authors would also like to acknowledge Jeffery Preece, Sneha Shanbhag, Alexander V. Dudchenko, and Amanda N. Quay for discussion and feedback on portions of the manuscript.

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TOC Entry

TOC Art



Summary

This review identifies challenges and opportunities facing the electricity generation sector in treating flue gas desulfurization wastewater.