Spatially resolved air-water emissions tradeoffs improve regulatory impact analyses for electricity generation

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Coal-fired power plants (CFPPs) generate air, water, and solids emissions that impose substantial human health, environmental, and climate change (HEC) damages. This work demonstrates the importance of accounting for cross-media emissions tradeoffs, plant and regional emissions factors, and spatially variation in the marginal damages of air emissions when performing regulatory impact analyses for electric power generation. As a case study, we assess the benefits and costs of treating wet flue gas desulfurization (FGD) wastewater at US CFPPs using the two best available treatment technology options specified in the 2015 Effluent Limitation Guidelines (ELGs). We perform a life-cycle inventory of electricity and chemical inputs to FGD wastewater treatment processes and quantify the marginal HEC damages of associated air emissions. We combine these spatially resolved damage estimates with Environmental Protection Agency estimates of water quality benefits, fuel-switching benefits, and regulatory compliance costs. We estimate that the ELGs will impose average net costs of $3.01 per cubic meter for chemical precipitation and biological wastewater treatment and $11.26 per cubic meter for zero-liquid discharge wastewater treatment (expected cost-benefit ratios of 1.8 and 1.7, respectively), with damages concentrated in regions containing a high fraction of coal generation or a large chemical manufacturing industry. Findings of net cost for FGD wastewater treatment are robust to uncertainty in auxiliary power source, location of chemical manufacturing, and binding air emissions limits in noncompliant regions, among other variables. Future regulatory design will minimize compliance costs and HEC tradeoffs by regulating air, water, and solids emissions simultaneously and performing regulatory assessments that account for spatial variation in emissions impacts.

benefit–cost analysis | coal-fired power plants | Effluent Limitation Guidelines | spatially resolved marginal damages | emissions tradeoffs

An important recent driver of the US transition away from coal-fired electricity generation has been the implementation of new air and water emission regulations, including the Cross State Air Pollution Rule (1), the Mercury and Air Toxics Standards (2), the Clean Power Plan (3), and the Final Effluent Limitation Guidelines (ELGs) for Steam Electric Power Generation Facilities (4). Although each of these rules targets the human health, environmental, and climate change (HEC) externalities of coal-fired power generation, there has been little work characterizing the interactions between these regulations at the plant or regional levels. In particular, the control systems plants use to meet air and water regulations are interconnected, with wastewater being produced in air pollution control systems and air pollution being produced by water pollution control systems.

For example, the most prevalent sulfur dioxide (SO_2) air emission control technology is wet flue gas desulfurization (FGD), which uses an aqueous slurry to scrub SO_2 from coal-fired power plant (CFPP) flue gas (5–7). In 2014, wet FGD systems prevented emission of 2.7 million short tons of SO_2, with tens of billions of dollars in benefits to human health (5). These same wet FGD systems produced an estimated 210 million m^3 of wastewater contaminated with chloride, bromide, mercury, arsenic, boron, selenium, and other aqueous toxicants scrubbed from the flue gas (8, 9). Release of these aqueous contaminants poses risks to human health via fish consumption, drinking water disinfection byproduct formation, and recreational exposure routes (10).

On the other hand, treating or eliminating this wastewater discharge will increase auxiliary power consumption at CFPPs, decrease generation efficiency, and increase air emissions per unit of energy that is effectively delivered to the grid. These processes will also consume chemical precipitants, nutrients, soda ash, and antiscalants manufactured offsite, the production of which results in additional air emissions that are outside the scope of the ELG regulatory analyses (7, 11). The extent of air-water emissions tradeoffs will vary with the composition of the wastewater, the treatment process, the energy inputs, and the location of the plant.

Benefit–cost analysis (BCA) is the institutionalized method for assessing tradeoffs stemming from regulatory decisions (4, 12–15). Systematic BCA facilitates accounting across a diverse set of outcomes and may reduce the influence of special interests or political pressure on regulatory decisions (16–18). On the other hand, narrowly conceived regulatory assessments that rely exclusively on BCA tend to undervalue nonmarket goods (17), simplistically assess risks, disproportionately prioritize the here and now, and promote efficiency over equity (17). These shortcomings of BCA may be exacerbated by national-level analyses that obscure the distribution of benefit/cost (B/C) ratios at the regional or local levels (16).

Significance

The human health, environmental, and climate change implications of regulations affecting the electric power generation sector are typically assessed at the national scale. Variability in power plant emissions factors, regional grid composition, and location-specific marginal damages may lead to significant regional differences in the net benefits of regulations, including the recently promulgated Effluent Limitation Guidelines. Regional variation is further exacerbated by differences in the marginal damages of air, water, and solids emissions. Minimizing the externalities of electricity generation and reducing the compliance costs of emissions control require future regulatory design to use spatially resolved estimates of marginal damages and address air, water, and solids emissions control processes simultaneously.

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Over the past decade, several interdisciplinary research efforts have produced spatially resolved estimates of the marginal human health and environmental damages of additional air emissions (19, 20). Facile approximation of these damages with county-level resolution significantly reduces the barriers to assessing the distribution of B/C ratios for regulation affecting air emissions (21), but very few federal BCAs currently use these methods (22). There is also a need for comparable tools to assess the spatial distribution of marginal damages from aqueous emissions, allowing BCA to be performed at the local airshed and watershed scales relevant to public health.

Explicitly quantifying air-water emissions tradeoffs at the local scale is particularly important when designing national regulation for distinct regional power grids. A large fraction of the purported benefits of recent air and water regulations at CFPPs are attributed to increases in the levelized cost of electricity and associated decreases in the deployment of coal-based electricity generation at the margin (10, 12). In North American Electric Reliability Corporation (NERC) regions with a diverse electricity generation mix, fuel switching is likely to lead to large net benefits. Near-term fuel switching is less likely in NERC regions where a large fraction of electricity generation occurs at CFPPs, especially if the best available technologies for regulatory compliance are capitally intensive and installing them represents large sunk costs. This heterogeneity in generation infrastructure may lead to unintended local impacts and significant regional inequities in net damages. More broadly, the reliance on criteria air emissions benefits to justify regulatory interventions in carbon dioxide (CO_2), solids, and aqueous emissions control (10, 12) raises questions about whether the policy design is most efficiently and effectively targeting high HEC impact pollutants.

Finally, plant-level analysis of air-water emissions tradeoffs is relevant to guiding the selection of emissions control technologies at CFPPs. The slate of forthcoming or promulgated regulation will require implementation of multiple additional processes for gas (1–3), water (4), and solids handling (4, 23). Comprehensive planning and simultaneous implementation of these processes would enable a systems-level redesign of power plants, whereas staged implementation of capital-intensive infrastructure forced by piecemeal regulatory design will lead to technology lock-in and reduced flexibility in cost-effectively minimizing air and water emission tradeoffs. Indeed, previous work analyzing the pulp and paper industry suggests that companies make more cost-effective decisions when designing for air and water emissions control simultaneously (13).

The present work leverages and augments the US Environmental Protection Agency's (EPA's) detailed BCA for the final ELG rule (10) to analyze the tradeoffs in air and water emissions associated with the two best-available technology options (BATs) for treating wet FGD wastewater at CFPPs. Specifically, we extend the regulatory analysis to include the emissions and HEC damages associated with off-site manufacturing the chemical inputs to FGD wastewater treatment, a substantial fraction of total HEC damages. We also quantify the auxiliary power consumption, emissions, and HEC damages associated with zero liquid discharge (ZLD) processes for FGD wastewater treatment, a BAT option that was not fully evaluated in the ELG regulatory analysis. Finally, we combine plant-level analyses with spatially resolved marginal damage estimates to assess air-water emissions tradeoffs associated with wet FGD wastewater treatment at the state, NERC region, and national scales.

FGD Wastewater Treatment Process Inventories

Under the finalized ELGs, CFPPs are required to eliminate or treat wastewater discharge from fly ash transport waters, bottom ash transport waters, flue gas mercury control wastewater, coal gasification wastewater, combustion residual leachate, and FGD wastewater (7, 10). Wastewater from most processes will be eliminated through dry-handling techniques, but for FGD wastewater, CFPPs are provided a choice between two different BAT wastewater treatment approaches with significantly different air and water emissions profiles (7). Under the first option, plants will comply with effluent water quality standards starting in 2018 using chemical precipitation and biological treatment (CPBT). Under the second option, plants may delay implementation of water treatment capacity starting in 2023 but are required to comply with a more stringent ZLD plan using a combination of chemical precipitation and softening pretreatment followed by mechanical vapor compression (MVC) and crystallization technologies that will further reduce metal emissions and eliminate dissolved solids discharges unaddressed by CPBT technology. Although existing plants have a mix of installed FGD wastewater management approaches (e.g., impoundments, chemical precipitation, anaerobic biological treatment, distillation, and constructed wetlands), the present analysis is performed relative to a baseline of impoundment management. Detailed descriptions of FGD installations, water quality standards, and BAT options are provided in *SI Appendix*, *1.0 Flue Gas Desulfurization Systems and Wet Flue Gas Desulfurization Wastewater Treatment*, Tables S1 and S2, and Fig. S1.

We develop process models of the ELGs' two BATs options for FGD wastewater treatment (7): CPBT (Fig. 1*A*) and ZLD (Fig. 1*B*), as described in *SI Appendix*, *2.1 Developing Treatment Process Inventories*. These process models are drawn from peer reviewed literature and regulatory documentation and include estimates of electricity consumption (24, 25), water entrainment (11), and chemical inputs (11) (*SI Appendix*, Tables S3–S5) for each unit process in the treatment train. We estimate FGD wastewater treatment will consume an average 0.71 kWh/m^3 of auxiliary power using CPBT processes and 37.4 kWh/m^3 of auxiliary power using ZLD processes. Detailed estimates of soda ash, lime, hydrochloric acid, and nutrient mix consumption are provided in *SI Appendix*, *2.0 Detailed Methods*. Additional methodological details associated with developing the process inventories are reported in *SI Appendix*, *2.1 Developing Treatment Process Inventories*.

Air Emissions from FGD Wastewater Treatment on a Cubic Meter Basis at the Plant Level

We estimate the nitrogen oxides (NO_x), SO_2, fine particulate matter ($PM_{2.5}$), and CO_2 emissions associated with auxiliary electricity consumption (24, 25) and the manufacturing of chemical inputs [ref. 26 and the National Renewable Energy Laboratory (NREL) Life-Cycle Inventory Database (www.nrel.gov/lci)] to FGD wastewater treatment processes at US CFPPs at the plant

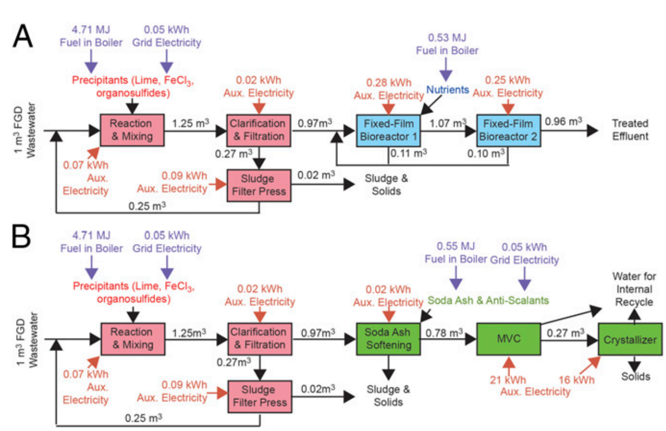

Fig. 1. Process trains, auxiliary electricity consumption, and chemical consumption associated with treating 1 m^3 of FGD wastewater. Water lost during treatment reduces the volumetric flow between processes, and this reduction is accounted for in the quantified electricity and chemical inputs. (*A*) Chemical precipitation (with four reaction and mixing tanks) followed by biological treatment. (*B*) Chemical precipitation (with four reaction and mixing tanks) followed by soda ash softening, MVC, and crystallization.

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level. To estimate the air emissions associated with auxiliary electricity consumption per m^3, we multiply the electricity consumed in the treatment process by the emissions factor for each CFPP with a wet FGD system installed (Eq. **1**).

$$m^{W}_{elec,g,i} = \sum_{h} E^{W}_{elec,h} e^{E}_{af,i}. \quad [1]$$

Here, $m^{W}_{elec,g,i}$ is the mass of air pollutant g [g/m^3 of wastewater treated] emitted as a result of auxiliary electricity consumption for each US CFPP with a wet FGD system, i; h is an indicator variable representing the unit process; $E^{W}_{elec,h}$ is the electricity consumed by each unit process [kWh/m^3 of wastewater treated]; and $e^{E}_{af,i}$ is the emissions factor [g/kWh] at plant i derived from eGRID (27) and National Emissions Inventory data (28) for the year 2012, the latest year for which eGRID data are available. Further details on the calculation of plant emission factors are provided in *SI Appendix, 2.2 Calculating Air Emissions from FGD Wastewater Treatment on a Cubic Meter Basis at the Plant Level*. We estimate the generation weighted average emissions factor across all US CFPPs with installed wet FGD capacity, $\overline{e^{E}_{af,g}}$, was 1,000 g/kWh for CO_2, 1.3 g/kWh for SO_2, 0.82 g/kWh for NO_x, and 0.32 g/kWh for $PM_{2.5}$ in 2012.

In addition to air emissions from auxiliary electricity consumption, there are embedded emissions associated with the manufacture of chemical inputs to FGD treatment processes, m^{C}_{g} [g/m^3]. These air emissions are a function of the quantity of chemical used in each unit process and the sum of (*i*) direct emissions produced during manufacturing (i.e., emissions released during chemical production) reported in NREL's Life-Cycle Inventory Database and in ecoinvent 2.0 (26) (*SI Appendix, 3.0 Life Cycle Emissions Inventory Data and Data Sources*); (*ii*) indirect emissions from thermal energy consumption (i.e., boiler emissions) derived from the same NREL database; and (*iii*) emissions from electricity consumption in chemical manufacturing determined by multiplying state-level grid marginal emissions factors (29) by the fraction of US chemical production that occurs in state l (30) (Eq. **2**).

$$m^{C}_{g} = \sum_{h}\sum_{j} Q_{j,h}\left(e^{C}_{cm,j} + \sum_{k} E^{c}_{k,j} e^{J}_{k} + E^{c}_{elec,j}\sum_{l} e^{E}_{mf,l}\frac{V_l}{\sum_l V_l}\right), \quad [2]$$

where m^{C}_{g} is the mass of pollutant g per cubic meter of wastewater treated [g/m^3 of wastewater treated] from chemical manufacture; $Q_{j,i}$ is the mass of chemical j used in process h per cubic meter of wastewater [kg-chemical/m^3 of wastewater treated]; $e^{C}_{cm,j}$ are the direct emissions produced during manufacturing [in g-pollutant/kg-chemical]; $E^{c}_{k,j}$ is the thermal energy input from fuel source k (bituminous coal, lignite, petroleum, residual fuel oil, natural gas, diesel) [MJ/kg-chemical]; e^{J}_{k} is the emission factor from combustion of fuel k [g-pollutant/MJ fuel]; $E^{c}_{elec,j}$ is the electrical energy consumed in the manufacturing process [kWh/kg-chemical]; V_l is the value of chemical products from US state l [\$]; and $e^{E}_{mf,l}$ is the marginal emissions factors for CO_2, NO_x, and SO_2 (29), and average emissions factors for $PM_{2.5}$ (28) from the electricity generated in state l [g-pollutant/kWh]. The methods used to calculate direct, thermal energy, and electrical energy emissions factors for chemical manufacturing are reported in *SI Appendix, 2.2 Calculating Air Emissions from FGD Wastewater Treatment on a Cubic Meter Basis at the Plant Level*.

We assume that chemical inputs are commodities purchased on the national market and that the spatial distribution of chemical manufacturing for wastewater treatment follows that of US chemical production as reported in the 2013 Annual Survey of Manufacturers (30). Using this approach, we estimate a single value for the embedded air emissions from chemical manufacturing on a m^3 basis and determine the effective air emission impacts at the plant level by adjusting for the volume of FGD wastewater treatment. Sensitivity analysis on the spatial distribution of chemical manufacturing is provided in *SI Appendix, 4.0 Distribution of Chemical Manufacturing*, including cases where we assume that (*i*) chemicals are manufactured evenly throughout the 48 contiguous states, (*ii*) chemicals are manufactured in the states where the chemicals are used, chemicals are manufactured (*iii*) only in Nebraska (the state with the lowest marginal damages) or (*iv*) only in New Jersey (the state with the marginal highest damages), and (*v*) chemicals are manufactured offshore (*SI Appendix*, Fig. S2 and Tables S6–S10). Although the total mass of emissions does not change significantly under these alternative cases, the spatial distribution of the emissions and the populations exposed to those emissions vary widely. As a result, subsequent monetization of incurred damages varies by 32–310% of total chemical damages incurred by CPBT treatment and 34–370% incurred by ZLD treatment.

We sum emissions from auxiliary electricity consumption and chemical manufacturing $(m^{W}_{elec,g,i} + m^{C}_{g})$ to obtain net air emissions per cubic meter for CPBT and ZLD processes at the plant level. Fig. 2 reports average net air emissions per cubic meter of CPBT and ZLD wastewater treatment, $\overline{m_g}$, at US CFPPs normalized by plant generation (W_i [kWh/y]) in 2014 (Eq. **3**), whereas *SI Appendix*, Table S11 tabulates these same values. Plant-level emission factors vary significantly by age, boiler efficiency, coal quality, and installed air emissions control technologies, and the distribution of these emissions factors for CFPPs with wet FGD systems is provided in *SI Appendix*, Fig. S3.

$$\overline{m_g} = \frac{\sum_i m^{W}_{elec,g,i} W_i}{\sum_i W_i} + m^{C}_{g}. \quad [3]$$

Additional electricity for operating wastewater treatment processes could also be drawn from the grid, where the marginal emissions factors are lower due to the mix of coal, natural gas, nuclear, and renewable sources. We report state and NERC region marginal air emissions distributions in *SI Appendix*, Fig. S3. Using a state-level grid reduces the median emissions per cubic meter of wastewater to 1.6 g/m^3 of NO_x, 49.3 g/m^3 of SO_2, and 1.5 kg CO_2/m^3 for CPBT and to 20 g/m^3 of NO_x, 35 g/m^3 of SO_2, and 20 kg CO_2/m^3 for ZLD. Using the NERC-level grid reduces the median emissions per cubic meter of

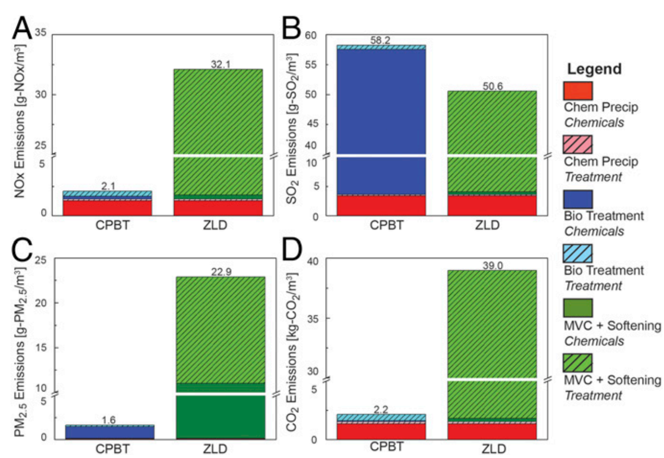

Fig. 2. Average air emissions per 1 m^3 of FGD wastewater treatment using CPBT or ZLD processes. Emissions are determined at the plant level, and the averages reported here are normalized to plant generation in 2014. (*A–D*) NO_x (*A*), SO_2 (*B*), $PM_{2.5}$ (*C*), and CO_2 (*D*) emissions generated due to auxiliary power consumption and chemical manufacturing. Processes correspond to those detailed in Fig. 1. Results are tabulated in *SI Appendix*, Table S11, and the distribution of air emissions at the plant, state, and NERC region levels is reported in *SI Appendix*, Fig. S3.

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wastewater to 1.6 g/m^3 of NO_x, 49.2 g/m^3 of SO_2, and 1.8 kg CO_2/m^3 for CPBT and to 20 g/m^3 of NO_x, 29 g/m^3 of SO_2, and 20 kg CO_2/m^3 for ZLD.

Most emissions from CPBT processes stem from chemical inputs to the treatment process, whereas emissions from ZLD processes are dominated by auxiliary electricity consumption at the plant. Air pollutant emissions from CPBT processes are an order of magnitude lower than from ZLD processes for pollutants other than SO_2. In this case, manufacturing of nutrient inputs to biological processes has a significant SO_2 footprint, whereas SO_2 emission factors at plants with FGD control technology are relatively small.

Total Annual Air Pollutant Emissions from FGD Wastewater Treatment at US CFPPs

We estimate the total annual air emissions from FGD wastewater treatment, M_g [g/y], under each ELG option by multiplying the volumetric emissions factors $(m^W_{elec,g,i} + m^C_g)$ of pollutant [g/m^3] by estimated FGD wastewater volume at the plant level (Eq. **4**).

$$M_g = \sum_i \left[\left(m^W_{elec,g,i} + m^C_g \right) \left(v \sum_i Capacity_i * G_{scrubbed,i} \right) \times \left(\frac{G_{scrubbed,i} * W_i}{\sum_i G_{scrubbed,i} * W_i} \right) \right]. \qquad [4]$$

Here, the second term is the national annual wastewater production volume determined by multiplying EPA's estimate of the national average annual volume of wastewater produced per unit of wet FGD scrubbed nameplate capacity (11), v [m^3/kW·y], by the sum of plant capacity, $Capacity_i$ [kW], and percent of the plant exhaust gas scrubbed via wet FGD, $G_{scrubbed,i}$, over all US CFPPs. Finally, the third term, $\left(\frac{G_{scrubbed,i} * W_i}{\sum_i G_{scrubbed,i} * W_i} \right)$, represents the fraction of national scrubbed electricity generation at plant i. Sensitivity analysis on the volume of FGD wastewater produced per kWh of generation is provided in *SI Appendix, 1.0 Flue Gas Desulfurization Systems and Wet Flue Gas Desulfurization Wastewater Treatment*. A detailed description of the methods is reported in *SI Appendix, 2.3 Calculating Total Annual Air Pollutant Emissions from FGD Wastewater Treatment at U.S. CFPPs*.

There are several policies and regulations that may limit emissions increases. Clean Air Act Title V requires operating permits for large point source emitters (31) and MATS establishes a total PM limit for existing CFPPs (2). In addition, National Air Quality Standards mandate State Implementation Plans (SIPs) for realizing emissions reductions in noncompliant regions. SIPs may limit emissions from both existing sources (32) and new facilities (33). Although our base case analysis assumes no binding air emission regulation limits, we consider the effect of limited emissions increases in our sensitivity analysis by evaluating scenarios with no additional emissions of SO_2, NO_x, and $PM_{2.5}$ from electricity generation, from chemical manufacturing in states containing a nonattainment area, or from both electricity and chemical manufacturing.

National Annual HEC Damages from Air Emissions Associated with FGD Wastewater Treatment at US CFPPs

Monetizing the HEC damages associated with air emissions from FGD wastewater treatment facilitates efficient policy design. We estimate human health and environmental damages at the plant level using marginal damages from the AP2 model (19), a widely implemented integrated assessment model that estimates the human health and ecological damages associated with a marginal change in the emissions of SO_2, NO_x, and $PM_{2.5}$ from point sources in US counties (detailed in *SI Appendix, 2.4 Estimating National Annual HEC Damages from Air Emissions Associated with FGD Wastewater Treatment at U.S. CFPPs, 6.0 Estimating Damages from Marginal Emissions*, and Fig. S4). To estimate damages associated with CO_2 emissions, we adopt the average social cost of carbon (SCC) estimate at a 3% discount rate provided by the Interagency Working Group of \$43.43 per short ton CO_2 in 2014 dollars based on a pulse in 2020 (34).

To account for significant disagreement in the methodological approach and numerical assumptions used in valuing carbon emissions reductions, we perform a sensitivity analysis by varying the SCC between \$0 and \$100 per short ton (*SI Appendix, 7.0 Sensitivity Analysis – Price of Carbon*, Table S12, and Fig. S6). Low CO_2 emissions factors for CBPT processes (Fig. 2) mean that the total damages change by only 12% over this SCC range. The CO_2 emissions of ZLD processes are substantially greater, leading to a change of 55% in the total damages over the SCC range. In neither case does a \$0/short ton CO_2 SCC price impact the conclusion of the BCA.

We estimate annual HEC damages from air emissions associated with FGD wastewater treatment at each US CFPP at the county level. The distribution of downwind damages for the G.G. Allen CFPP, for which precise FGD wastewater volumes are available (11), is provided in *SI Appendix, 6.2 County-Level Damage Distribution Case Study using APEEP* and Fig. S5. The estimated total annual HEC damages are \$318 million for CPBT treatment processes and \$1,100 million for ZLD treatment processes, with expected cost-benefit ratios of 1.8 (range of 1.5–2.5) for CPBT and 1.7 (range of 1.4–1.9) for ZLD treatment processes (Fig. 3, *SI Appendix, 8.0 Damages by Pollutant Using Plant and Marginal Emission Factors*, and Table S13). Note that

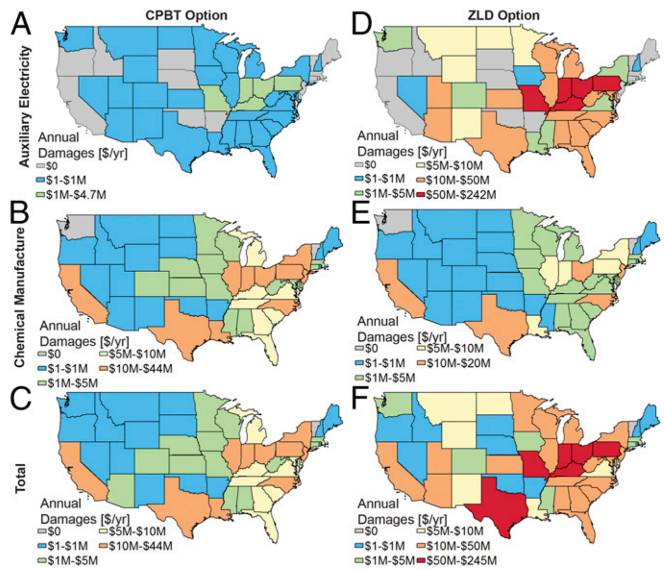

Fig. 3. Estimated annual HEC damages associated with transitioning from FGD wastewater impoundment to FGD wastewater treatment by CPBT or ZLD processes. Damages downwind of power plant and chemical manufacturing are aggregated to the state in which the emissions were generated. HEC damages from CPBT wastewater treatment accounting for only auxiliary electricity generation (*A*), only chemical manufacture (*B*), and both auxiliary electricity generation and chemical manufacture (*C*). HEC damages from ZLD wastewater treatment accounting for only auxiliary electricity generation (*D*), only chemical manufacture (*E*), and both auxiliary electricity generation and chemical manufacture (*F*). Damages are tabulated in *SI Appendix*, Table S13. This analysis is performed relative to a baseline of no advanced FGD wastewater treatment (i.e., wastewater impoundment) and uses estimated wastewater volumes from 2014. We assume that chemical manufacturing follows the 2013 chemical sector distribution, that auxiliary power is generated onsite, a value for the SCC of \$43.43 per short ton of CO_2, a value of a statistical life of \$8.5 million, and nonbinding NO_x and SO_2 regulations. Sensitivity analyses on these assumptions are detailed in *SI Appendix, 14.0 Sensitivity Analyses Summary*.

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although the costs of FGD wastewater treatment exceed the benefits of FGD wastewater treatment, the HEC benefits of FGD processes are at least an order of magnitude higher than the costs of FGD wastewater treatment (10). Annual emissions from chemical manufacturing account for a large fraction of total air emission damages for the CPBT treatment process, especially in states with large chemical manufacturing bases (e.g., California, Texas). The air emission damages from chemical manufacturing will be much smaller for ZLD processes, where the majority of emissions are associated with auxiliary electricity generation. Under the ZLD option, states with large amounts of coal generation capacity (e.g., Ohio, Pennsylvania) would be responsible for the majority of air emission damages.

Air-Water Emissions Tradeoffs from FGD Wastewater Treatment

Comprehensive assessment of air and water emissions tradeoffs for FGD wastewater treatment requires comparing the HEC and technology implementation costs against the human health, ecosystem, and fuel switching benefits of installing aqueous emission control technologies. *Ex ante* estimates of future costs and benefits are highly uncertain (35) and improving these estimates is an active area of research. Nevertheless, this work adapts and extends the EPA's analysis regulatory analysis of the full ELG rule (10) to estimate the stand-alone benefits and costs of FGD wastewater treatment. We disaggregate the benefits and costs of FGD wastewater treatment from those of other wastewater streams covered under the ELG regulation and we reference our analysis to a baseline of impoundment water management. Detailed descriptions of methods, assumptions, and sensitivity analysis on these assumptions are provided in *SI Appendix, 4.0 Distribution of Chemical Manufacturing* (*SI Appendix*, Tables S6–S10 and Fig. S2) and *SI Appendix, 7.0 Sensitivity Analysis – Price of Carbon–14.0 Sensitivity Analyses Summary* (*SI Appendix*, Tables S12–S24 and Figs. S6–S12).

The social costs of FGD wastewater treatment under the assumptions detailed above exceed the estimated social benefits for CPBT and ZLD by a factor of 1.8 and 1.7, respectively (Fig. 4*A*, *SI Appendix*, Table S17). The largest costs are the capital and operational costs of the technology, whereas the largest source of benefits stem from fuel switching, and the associated reductions in CO_2 and criteria air emissions, resulting from these increased electricity generation costs. Because these costs and benefits are directly related (*SI Appendix*, Fig. S8), reducing the cost of technology operation is also expected to reduce the fuel switching benefits.

Our conclusion that FGD wastewater treatment imposes net costs is robust to sensitivity analyses reported in Fig. 4*B* and *SI Appendix*, Tables S17, S23, and S24, including the distribution of FGD wastewater treatment technologies currently installed at CFPPs and assumptions about the location of chemical manufacturing, the value of a statistical life, the presence of binding regulations limiting NO_x, SO_2, and $PM_{2.5}$ emissions from power plants and chemical manufacturing facilities in nonattainment areas, the compliance cost to fuel switching relationship, the SCC, and the origin of auxiliary power supplied for wastewater treatment. Even in scenarios where we assume no additional marginal emissions of SO_2, NO_x, and $PM_{2.5}$ from electricity generation or from chemical manufacturing in states with a nonattainment area, treating FGD wastewater using BATs recommended by the EPA still imposes net costs as a result of compliance costs, chemical manufacturing emissions in states without nonattainment areas, and CO_2 emissions damages (*SI Appendix*, Table S22).

This sensitivity analysis also highlights the importance of using plant or location-specific emissions factors and spatially resolved marginal damage values in regulatory analysis of the national electricity grid. Replacing regional or national average emissions factors with plant or location-specific emissions factors increases estimates of total emissions and resulting damages from auxiliary electricity generation for FGD wastewater treatment by 26–36% ($3.9–$5.5 million dollars annually for CPBT and $200–$280 million dollars annually for ZLD) (*SI Appendix, 8.2 Sensitivity to Grid Electricity Mix*). Similarly, assumptions about the location of chemical manufacturing influence the associated estimates of air emissions damages by an order of magnitude (*SI Appendix, 4.0 Distribution of Chemical Manufacturing*).

Replacing national average marginal damage estimates with spatially resolved marginal damage values has comparable implications. We compare results using county-level marginal damage estimates provide by AP2 to results computed using (*i*) national average marginal damage determined by averaging all county-level marginal damages and (*ii*) using national average marginal damage estimates provided by the EPA. The first case underestimates the air emissions damages of FGD wastewater treatment by 4% for CPBT and 10% for ZLD. In contrast, the national average marginal damage estimates provided by the EPA overestimates air emissions damages by 25% for CPBT and 7% for ZLD. Additional details of these calculations are available in *SI Appendix, 15.0 Non-Spatially Resolved Damages* and Table S25.

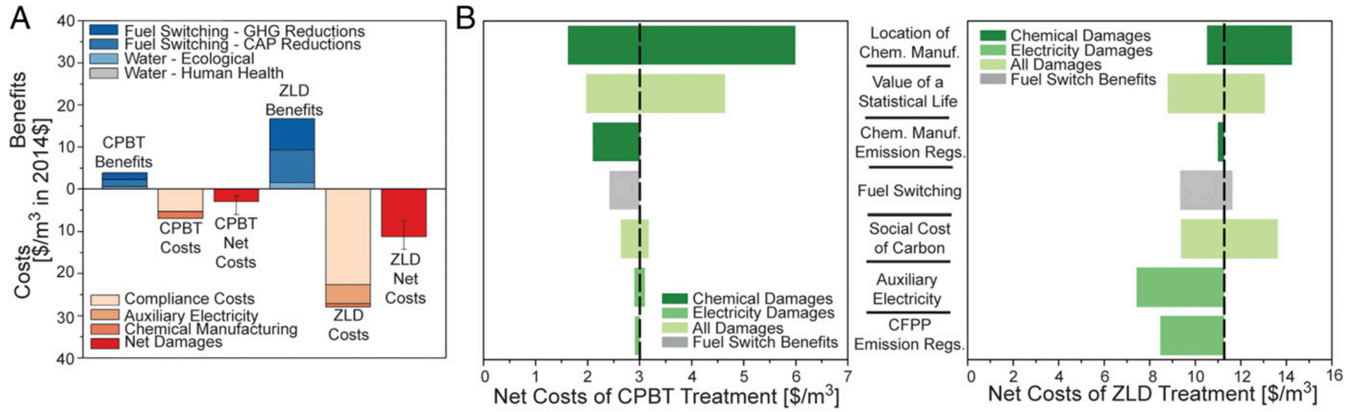

Fig. 4. (*A*) Estimated benefits and costs of CPBT and ZLD technologies for FGD treatment on a per cubic meter basis. Benefit estimates are derived from the EPA's regulatory analysis of the ELG rule and include reduced greenhouse gas (GHG) and criteria air pollution (CAP) emissions that stem from fuel switching and reduced water emissions leading to improved human and ecological heath. Damage estimates are derived through a combination of EPA's regulatory analysis for compliance costs and the analysis described in this work for damages associated with auxiliary electricity and chemical manufacturing emissions. The error bars on the net cost value represent the extremes of the sensitivity analysis for seven key variables reported in *B* and detailed in *SI Appendix*, Tables S17, S23, and S24.

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Implications for Regulatory Analysis of Air and Water Emissions Controls at CFPPs

Although market conditions and regulatory pressure have reduced the fraction of electricity generation by CFPPs to 33% in 2015 (36), a full transition to low-carbon electricity generation will take several decades (33–35). In the interim, CFPPs are likely to make significant capital investments in emissions control technologies. Quantifying the air-water emissions tradeoffs of these capital improvements will be critical to avoiding unintended HEC consequences, to mitigating these consequences through technology innovation, and to maximizing the value of investments emissions control technologies.

This work adopted a life-cycle emissions inventory framework to assess air-water emissions tradeoffs of treating FGD wastewater. As previously noted, damage estimates from wet FGD wastewater treatment are at least one to two orders of magnitude smaller than the health and environmental benefits of removing SO_2 emissions via wet FGD processes. This analysis does not reconsider implementing SO_2 controls, or evaluate options for replacing wet FGD systems with dry FGD alternatives. Instead, we assess only the air emission implications of a recent policy shift—regulation of wet FGD wastewater discharge—under two different wastewater treatment technology options.

When accounting for emissions from chemical manufacturing processes that occur off-site, using the appropriate plant or regional level emissions factors, and applying spatially resolved marginal damage estimates, we estimate that the costs of FGD wastewater treatment by BAT treatment processes exceed the benefits by a factor of 1.7–1.8 for our base-case analysis. Sources of systematic error in this estimate exist due to the absence of models that spatially resolve the marginal benefits of reduced aqueous pollution, the difficulty of accurately capturing the ecosystem benefits of higher water quality, methodological issues associated with valuing the SCC, and the difficulty of projecting improvements in the energy and chemical efficiency of FGD wastewater treatment technology. Despite these limitations, this BCA aids comprehensive decision-making processes that include nonmonetary benefits of FGD wastewater treatment by establishing priorities for plant retrofit, identifying wastewater treatment technologies that maximize HEC benefits, and highlighting the need for improved energy and chemical efficiency of wastewater treatment technologies.

This analysis also highlights the magnitude of HEC benefits available from reducing criteria air emissions from the electricity generation sector. The largest benefits of FGD wastewater treatment are the reduced HEC damages associated with fuel switching, rather than the averted damages caused by reduced water pollution. Although it is desirable that CFPPs reduce their environmental impacts from both water and air pollution, the most efficient pathway toward reducing air pollution damages is to directly regulate greenhouse gas and criteria air emissions.

Minimizing sustainability tradeoffs and reducing the compliance costs of emissions control requires future regulatory design to address air and water emissions control processes simultaneously. This work reinforces the need for comprehensive regulation that allows plants to strategically redesign the electricity generation process to minimize costs and HEC damages across all emissions control processes. Spatially resolved water emission marginal damage models to compliment those for estimating air emissions marginal damages would greatly facilitate that effort.

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1. US Environmental Protection Agency (2015) *Cross-State Air Pollution Rule* (US Environmental Protection Agency, Washington, DC).
2. US Environmental Protection Agency (2012) *Mercury and Air Toxics Standards* (US Environmental Protection Agency, Washington, DC).
3. US Environmental Protection Agency (2015) *Clean Power Plan* (US Environmental Protection Agency, Washington, DC).
4. US Environmental Protection Agency (2015) *Steam Electric Power Generating Effluent Guidelines - 2015 Final Rule* (US Environmental Protection Agency, Washington, DC).
5. US Energy Information Administration (2015) *Form EIA-860 Detailed Data* (US Energy Information Administration, Washington, DC).
6. US Environmental Protection Agency (2008) *Steam Electric Power Generating Point Source Category 2007/2008 Detailed Study Report* (US Environmental Protection Agency, Washington, DC).
7. US Environmental Protection Agency (2015) *Technical Development Document for the Effluent Limitations Guidelines and Standards for the Steam Electric Generating Point Source Category* (US Environmental Protection Agency, Washington, DC).
8. Rubin ES (1999) Toxic releases from power plants. *Environ Sci Technol* 33(18):3062–3067.
9. US Environmental Protection Agency (2015) *Environmental Assessment for the Effluent Limitation Guidelines and Standards for the Steam Electric Power Generating Point Source Category* (US Environmental Protection Agency, Washington, DC).
10. US Environmental Protection Agency (2015) *Benefit and Cost Analysis for the Effluent Limitations Guidelines and Standards for the Steam Electric Power Generating Point Source Category* (US Environmental Protection Agency, Washington, DC).
11. Eastern Research Group (2012) *Final Power Plant Monitoring Data Collected Under Clean Water Act Section 308 Authority* (Eastern Research Group, Chantilly, VA).
12. US Environmental Protection Agency (2015) *Regulatory Impact Analysis for the Clean Power Plan Final Rule* (US Environmental Protection Agency, Washington, DC).
13. Gray WBS, Ronald J (2015) *Multimedia Pollution Regulation and Environmental Performance: EPA's Cluster Rule* (Resources for the Future, Washington, DC).
14. National Center for Environmental Economics (2014) *Guidelines for Preparing Economic Analyses* (US Environmental Protection Agency, Washington, DC).
15. Office of Management and Budget (1992) *Circular A-94: Guidelines and Discount Rates for Benefit-Cost Analysis of Federal Programs* (Office of Management and Budget, Washington, DC).
16. Arrow KJ, et al. (1996) Is there a role for benefit-cost analysis in environmental, health, and safety regulation? *Science* 272(5259):221–222.
17. Lave LB (1996) *Benefit-Cost Analysis: Do the Benefits Exceed the Costs? Risks, Costs, and Lives Saved: Getting Better Results from Regulation*, ed Hahn RW (AEI Press, Washington, DC), pp 104–134.
18. Graham JD (2008) Saving lives through administrative law and economics. *Univ PA Law Rev* 157(2):395–540.
19. Muller NZ (2013) Using index numbers for deflation in environmental accounting. *Environ Dev Econ* 19(04):466–486.
20. Heo J, Adams PJ, Gao HO (2016) Public Health Costs of Primary PM2.5 and Inorganic PM2.5 Precursor Emissions in the United States. *Environ Sci Technol* 50(11): 6061–6070.
21. Siler-Evans K, Azevedo IL, Morgan MG, Apt J (2013) Regional variations in the health, environmental, and climate benefits of wind and solar generation. *Proc Natl Acad Sci USA* 110(29):11768–11773.
22. Muller NZ, Mendelsohn R, Nordhaus W (2011) Environmental Accounting for Pollution in the United States Economy. *Am Econ Rev* 101(5):1649–1675.
23. US Environmental Protection Agency (2015) *Coal Ash (Coal Combustion Residuals, or CCR)* (US Environmental Protection Agency, Washington, DC).
24. Plappally AK, Lienhard VJH (2012) Energy requirements for water production, treatment, end use, reclamation, and disposal. *Renew Sustain Energy Rev* 16(7):4818–4848.
25. Subramani A, Jacangelo JG (2014) Treatment technologies for reverse osmosis concentrate volume minimization: A review. *Sep Purif Technol* 122:472–489.
26. Althaus H-J ea (2007) *Life Cycle Inventories of Chemicals: Data v.2.0, ecoinvent Report No. 8* (Dübendorf, Switzerland).
27. US Environmental Protection Agency (2015) *eGRID* (US Environmental Protection Agency, Washington, DC).
28. US Environmental Protection Agency (2015) *Emissions Inventories* (US Environmental Protection Agency, Washington, DC).
29. Siler-Evans K, Azevedo IL, Morgan MG (2012) Marginal emissions factors for the U.S. electricity system. *Environ Sci Technol* 46(9):4742–4748.
30. United States Census Bureau (2015) *Annual Survey of Manufacturers 2013* (US Department of Commerce, Washington, DC).
31. US Environmental Protection Agency (2016) *Title V - Permits* (US Environmental Protection Agency, Washington, DC).
32. US Environmental Protection Agency (2016) *Applying or "Implementing" Sulfur Dioxide Standards - Sulfur Dioxide Pollution* (US Environmental Protection Agency, Washington, DC).
33. US Environmental Protection Agency (2016) *Nonattainment NSR Basic Information - New Source Review Permitting* (US Environmental Protection Agency, Washington, DC).
34. Interagency Working Group on the Social Cost of Carbon (2015) *Technical Support Document: Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis* (Interagency Working Group on the Social Cost of Carbon, Washington, DC).
35. Morgenstern RD (2015) *The RFF Regulatory Performance Initiative: What Have We Learned* (Resources for the Future, Washington, DC).
36. US Energy Information Administration (2016) *Electric Power Monthly Data for August 2016* (US Energy Information Administration, Washington, DC).

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