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ARTICLE

Funding a Just Transition Away from Coal in the U.S. Considering Avoided Damage from Air Pollution

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Abstract

Coal is declining in the U.S. as part of the clean energy transition, resulting in remarkable air pollution benefits for the American public and significant costs for the industry. Using the AP3 integrated assessment model, we estimate that fewer emissions of sulfur dioxide, nitrogen oxides, and primary fine particulate matter driven by coal's decline led to \$300 billion in benefits from 2014 to 2019. Conversely, we find that job losses driven by less coal plant and mining activity resulted in \$7.84 billion in foregone wages over the same timeframe. While the benefits were greatly distributed (mostly throughout the East), costs were highly concentrated in coal communities. Transferring a small fraction of the benefits to workers could cover these costs while maintaining societal net benefits. Forecasting coal fleet damages from 2020 to 2035, we find that buying out or replacing these plants would result in \$589 billion in air quality benefits, which considerably outweigh the costs. The return on investment increases when policy targets the most damaging capacity, and net benefits are maximized when removing just facilities where marginal benefits exceed marginal costs. Evaluating competitive reverse auction policy designs akin to Germany's Coal Exit Act, we find that adjusting bids based on monetary damages rather than based only on carbon dioxide emissions – the German design – provides a welfare advantage. Our benefit–cost analyses clearly support policies that drive a swift and just transition away from coal, thereby clearing the air while supporting communities needing assistance.

1. Introduction

Over the past decade, damages from air pollution in the United States (U.S.) have decreased substantially due in large part to rapid changes within the utility sector (Tschofen *et al.*, 2019). From 2010 to 2017, annual social costs from U.S. power plant emissions fell by more than \$100 billion (Holland *et al.*, 2020). This decline is due to the U.S.'s ongoing transition toward a cleaner energy economy, a considerable part of which is moving away from coal (Kolstad, 2017). Regulatory and market forces have increasingly put pressure on the coal industry. The U.S. Environmental Protection Agency (EPA) recently promulgated several policies (U.S.

EPA's Clean Air Markets Division, 2023) that have required many coal plants to increase pollution abatement or otherwise cut production.[1] However, there is emerging consensus that market forces, namely natural gas prices, have been the key driver of coal's decline (Culver & Hong, 2016; Linn & McCormack, 2019; Coglianese *et al.*, 2020). As a result, hundreds of coal-fired electric generating units (EGUs) retired between 2010 and 2019 (Johnson & Chau, 2019), and coal's contribution to net generation, which was between 44 and 57% historically through 2010, now accounts for little more than 20% (U.S. EIA, 2023*c*).

Both benefits and costs result from the decline of coal in the U.S. One of the major consequences of burning coal is the release of criteria air pollutants, including sulfur dioxide (SO_2), nitrogen oxides (NO_x), and primary fine particulate matter ($PM_{2.5}$) (U.S. EPA's Office of Air and Radiation, 2018, 2022*a*; U.S. EPA's Clean Air Markets Division, 2022). These local air pollutants are all precursors to ambient $PM_{2.5}$, which drives increased mortality risk (Burnett *et al.*, 2014) and, more broadly, accounts for most of the air pollution-related health damages in the U.S. (U.S. EPA's Office of Air and Radiation, 2011). Hence, the U.S.'s decreased reliance on coal yields substantial benefits by avoiding SO_2, NO_x, and primary $PM_{2.5}$. Coal also emits carbon dioxide (CO_2), a greenhouse gas (GHG) that drives global climate change and a plethora of consequences (Nordhaus, 2013; IWG, 2016; NOAA Education, 2021). As such, there are further benefits from fewer CO_2 emissions associated with coal's decline, but supplanting coal with natural gas risks offsetting much of these gains (Gordon *et al.*, 2023).

Primary among the costs of coal's decline are those incurred by coal-dependent workers and communities. To illustrate, national coal mining jobs fell by half in just 10 years – from 80,000 in 2010 to 40,000 in 2020 (U.S. BLS, 2023). This has led to unemployment and lost wages in areas where coal plays a significant role in the local economy, accounts for a large portion of tax revenue, and serves as a way of life (Carley & Konisky, 2020; Morris *et al.*, 2021; Raimi *et al.*, 2022). In addition, tens of thousands of retired coal workers receive pensions from programs that essentially collapsed due to bankruptcies in the industry and now receive hundreds of millions of dollars in federal support annually (Rep. Pascrell, 2019; Sen. Manchin, 2019; Walsh, 2019). These factors highlight the vulnerability of, if not existential threat to, coal-dependent communities and partially explain their resistance to the clean energy transition. Meanwhile, evidence shows that the U.S. is not moving away from coal fast enough to limit global temperature rise to a 1.5-degree Celsius target (GEM *et al.*, 2022), with its current trajectory set to result in significant environmental damage (Mayfield, 2022).

This article uses benefit–cost analysis (BCA) to evaluate solutions for a swift and just transition away from coal. Specifically, we focus on the net benefits of two public policies: worker compensation for lost wages and paid decommissioning of remaining coal-fired power plants. We begin by estimating recent damages from coal emissions and future damages from the current fleet. Reductions in damage, either retrospectively or prospectively, yield social benefits. We use the AP3 integrated assessment model (IAM) (Clay *et al.*, 2019; Tschofen *et al.*, 2019; Sergi *et al.*, 2020*a*, *b*) to monetize the impacts of SO_2, NO_x, and

[1] The Obama administration pursued the Cross-State Air Pollution Rule (CSAPR), the Mercury and Air Toxics Standards (MATS), and the Clean Power Plan (CPP) all during the 2010s. CSAPR sets caps on criteria air pollutants emitted by upwind states leading to soot and smog in downwind states, critically limiting interstate credit trading. MATS sets limits on hazardous air pollutants from power plants. CPP set carbon emissions targets for states, but it was promptly halted by lawsuits. See Revesz and Lienke (2016) for an in-depth discussion on the details and impacts of these policies and their predecessors affecting U.S. coal since the inception of the Clean Air Act.

primary $PM_{2.5}$. Considering emissions from 2014 to 2019, we calculate the avoided damages from the decline (i.e., less coal), rather than improvement (i.e., lower emission rates), of coal. Forecasting from 2020 to 2035, we determine possible benefits from further retirements in the coal fleet. We then compare the benefits to costs associated with the proposed policy interventions to assess the impact on social welfare.

The first policy examined in this study would provide financial assistance for coal communities through support for displaced workers – a policy with broad, bipartisan support (Mayer, 2022). We employ regression analyses that relate power plant and mining activity to employment. We monetize labor market impacts using wage data. Comparing the retrospective benefits from avoided damages to the costs of lost wages on a cumulative basis from 2015 to 2019, we find that the benefits far exceed the costs. Thus, we argue that there is an opportunity for policies to transfer financial resources to coal communities while still yielding large, positive national net benefits.

The second policy accelerates the removal of remaining coal-fired power plants via buyouts, a version of which currently takes place in Germany (Scott *et al.*, 2022; Tiedemann & Müller-Hansen, 2023). First, we consider both a one-time buyout across the fleet, where the decision rule that informs our design compares the current book value of capital assets (RMI, 2022) or, alternatively, the cost of constructing substitute generation capacity (U.S. EIA, 2022) to the present value of prospective damage from forecasted future emissions. Then, we assess a series of buyouts over time through reverse auctions. The German design adjusts firms' bids such that they are assessed as the cost per annual ton of CO_2 removed from the retired power plants (Scott *et al.*, 2022). We extend this approach to consider several different bid adjustment mechanisms. Our analyses demonstrate considerable net benefits from compensating coal plants to retire early. The greatest returns on investment (ROI) accrue when prioritizing the removal of capacity with the highest damage per MW, which is best achieved in reverse auction schemes considering SO_2 emissions or air pollution damages.

1.1. Background

1.1.1. Policy analysis framework

The U.S. government has long used BCA to evaluate impacts on social welfare resulting from the Clean Air Act (U.S. EPA, 1997; U.S. EPA's Office of Air and Radiation, 2011). In a similar manner, this study estimates the benefits of less air pollution from coal to evaluate federal policy solutions supporting a swift and just transition. While benefiting many, the movement toward a cleaner energy economy in the U.S. drives substantial costs for the workers and industries dependent on coal. Our analysis demonstrates a possible path forward, where a transfer of resources could offset losses while maintaining large societal net benefits. In this sense, we frame the movement away from coal as a Kaldor–Hicks improvement, where society overall is better off, there are "winners" and "losers," and financial transfers may offset costs for the "losers." In principle, public policies can facilitate this transfer to yield a Pareto improvement.[2]

[2] Importantly, our benefits of focus result from a reduction in negative externalities. These are non-market gains, essentially a collective willingness to pay to avoid mortality risk from $PM_{2.5}$ exposure. Hence, policy interventions would need to procure funding to enact such transfers.

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1.1.2. Social costs of emissions from coal-fired power plants

Prior research shows the substantial contribution of power plants to air pollution and its associated social costs in the U.S. (Levy *et al.*, 1999; Sundqvist, 2004; Muller *et al.*, 2011). Some studies have focused on how damages vary by source (Levy *et al.*, 2009; Cohon *et al.*, 2010; Buonocore *et al.*, 2014; Henneman *et al.*, 2023). Others have explored the heterogeneity of damage incurrence (Jaramillo & Muller, 2016; Penn *et al.*, 2017; Thind *et al.*, 2019; Sergi *et al.*, 2020*b*). Much recent work in the field has focused on the benefits of fossil fuel displacement (Siler-Evans *et al.*, 2013; Lueken *et al.*, 2016; Brown *et al.*, 2017; Strasert *et al.*, 2019; Sergi *et al.*, 2020*a*). This article contributes to the literature by assessing the net benefits of just transition policies that consider the avoided impacts of coal emissions.

Perhaps most similar to our work looking at retrospective damages is that of Holland *et al.* (2020), who decomposed changes in annual damage from the power sector by several effects. We perform a similar analysis (with key differences outlined in Appendix B of the Supplementary Material) to isolate the cumulative benefits from coal's decline, excluding those resulting from its improvement. Considering prospective damages, our work builds upon that of Mayfield (2022), who optimized the order of coal plant retirements based on future air pollution damages. Our article, however, weighs both the benefits and costs of bringing about coal plant retirements through financial compensation.

1.1.3. Social costs of unemployment

Many researchers have explored economic impacts related to the coal industry (Black *et al.*, 2005; Ivanova & Rolfe, 2011; Deaton & Niman, 2012; Betz *et al.*, 2015; Lobao *et al.*, 2016; Pollin & Callaci, 2019). Our analysis of labor markets is most closely related to Weber (2020), who looked at the spatial distribution of coal mining-related losses, and Walker (2013), who concluded that the benefits from the 1990 Clean Air Act Amendments far outweighed foregone wages for workers at newly regulated plants. Methodologically, this study is similar to Mayfield *et al.* (2019), who compared the county-level employment benefits and environmental costs of natural gas development in Appalachia. To the best of our knowledge, this article is the first to examine and quantify the labor market impacts from coal's recent decline.

1.1.4. Reverse auctions

The academic literature on reverse auctions is limited. Scott *et al.* (2022) and Tiedemann and Müller-Hansen (2023) assessed the first few rounds of Germany's Coal Exit Act. Other authors have studied the ability of reverse auctions to encourage environmentally beneficial behavior (Thurston *et al.*, 2010; Boxall *et al.*, 2013; Mayr *et al.*, 2014), but none of these focused on power plants. Related work proposed reverse auctions to close sub-critical coal (Caldecott & Mitchell, 2014) but did not quantify the benefits of doing so. Our research is the first to look at the potential net benefits of coal plant buyouts in the U.S. and to assess the advantage of different bid evaluation procedures for competitive reverse auctions.

2. Methods

We succinctly discuss our methods in this section, but more details are in the Supplementary Material. We first review our damage modeling and then discuss the quantitative analyses of labor markets and paid decommissioning.

2.1. Avoided air pollution damages

2.1.1. Emissions data

Our empirical analysis begins by assembling emissions data, including SO_2, NO_x, and primary $PM_{2.5}$ for coal-fired EGUs each year from 2014 to 2019. These data are obtained from the EPA's Clean Air Markets Program Data (CAMPD) (U.S. EPA's Clean Air Markets Division, 2022) and National Emissions Inventory (NEI) (U.S. EPA's Office of Air and Radiation, 2018, 2022*a*).[3] As discussed in subsequent subsections, these data provide the basis for our retrospective and prospective damage assessments.

2.1.2. AP3 integrated assessment model

We use the AP3 IAM (Clay *et al.*, 2019; Tschofen *et al.*, 2019; Sergi *et al.*, 2020*a*, *b*) to estimate the marginal damages (MDs) – in dollars-per-ton – of SO_2, NO_x, and primary $PM_{2.5}$ emissions from coal-fired EGUs each year from 2014 to 2019.[4] The model first estimates baseline ambient $PM_{2.5}$ and the associated mortality risk and monetary damage. AP3 employs a reduced complexity, Gaussian plume-based air quality model to estimate ambient $PM_{2.5}$ in every county throughout the contiguous U.S. resulting from all emissions of criteria air pollutants from all sources nationally [also from the NEI (U.S. EPA's Office of Air and Radiation, 2018, 2022*a*)]. AP3 calibrates predictions of baseline pollution levels using data from EPA ambient air quality monitors (U.S. EPA's Office of Air and Radiation, 2022*b*).

Exposure to air pollution has several adverse health consequences, but we focus on premature mortality linked to long-term exposure to ambient $PM_{2.5}$. Again, these damages account for most of those from air pollution (U.S. EPA's Office of Air and Radiation, 2011), but this also ensures we avoid cases where morbidity leads to eventual death and, consequently, the double counting of impacts (Künzli *et al.*, 2001). AP3 employs dose–response (DR) functions from epidemiological cohort studies to connect increased exposure to $PM_{2.5}$ with increased mortality risk. Equation (1) shows the form of the adult mortality DR function (Krewski *et al.*, 2009):

$$\Delta Mort = y_0\left(1 - \frac{1}{exp(\beta \times \Delta PM)}\right) \times Pop. \tag{1}$$

Equation (1) estimates expected premature mortality ($\Delta Mort$) from increased $PM_{2.5}$ (ΔPM) for the exposed population (Pop). The population data are age- and county-specific, provided by the Centers for Disease Control and Prevention's (CDC's) WONDER database (CDC, 2021). y_0 represents baseline age- and county-specific mortality rates, derived using

[3] See Supplementary Table B1 for coal fleet emissions, heat input, and emission rate data. CAMPD does not report primary $PM_{2.5}$ emissions; therefore, we interpolate them using data from CAMPD and the NEI. This is a multi-step process discussed in detail in Appendix B of the Supplementary Material.

[4] All monetary values in this study are reported in 2020 U.S. dollars.

data from the CDC (CDC, 2023). β is the statistically estimated parameter governing the change in mortality risk per unit of pollution. Our base case modeling utilizes the American Cancer Society cohort study's estimate of β (Krewski *et al.*, 2009), but our sensitivity analysis considers the higher coefficient reported in the most recent update to the Harvard Six Cities study (Lepeule *et al.*, 2012). Infant mortality is assessed using the DR function from Woodruff *et al.* (2006).

AP3 uses the value of a statistical life (VSL) to convert mortality risk to monetary units (Viscusi & Aldy, 2003; Cropper *et al.*, 2011). Federal agencies and academic researchers commonly use the VSL in the context of environmental policy analysis. This study uses the recommended VSL from the EPA (U.S. EPA's National Center for Environmental Economics, 2014). Our sensitivity analysis considers an alternative, lower VSL from Mrozek and Taylor (2002). The VSL is applied uniformly for all affected populations, and we adjust the VSL for inflation and national changes in income over time (Hammitt & Robinson, 2011; U.S. EPA's Office of Air and Radiation and Office of Policy, 2016). See Supplementary Table A4 for the VSL values used herein.

Using AP3, we estimate specific MDs for each source, pollutant, and year. This is accomplished by adding a ton of emissions to the baseline and assessing the corresponding change in ambient $PM_{2.5}$ concentrations, mortality, and damage. Total damages (and benefits) are computed by multiplying total emissions (and avoided emissions) from each coal-fired EGU by the matched MDs. This approach follows that of previous work employing the APEEP family of models (Muller *et al.*, 2011; Jaramillo & Muller, 2016; Tschofen *et al.*, 2019).[5]

2.1.3. Decomposition

We conduct a decomposition to differentiate retrospective emission changes driven by the decline and the improvement of coal-fired EGUs. We differentiate these effects because our policy analysis of worker compensation focuses on changes in jobs from declining coal industry activity rather than other influences – that is, progress leading to fewer workers producing the same output (Kolstad, 2017). We define the decline effect to encompass decreases in output, facilities going offline, and conversion to another fuel source. This aligns with changes to heat input [from CAMPD (U.S. EPA's Clean Air Markets Division, 2022)], the direct result of combustion creating pressurized steam that eventually powers a plant's generator(s). Contrarily, the improvement effect encompasses emission rate changes that do not stem from fuel switching (e.g., increased pollution abatement).

We use the two-variable Marshall–Edgeworth decomposition depicted in Equation (2):

$$\Delta e = \Delta h \bar{r} + \bar{h} \Delta r. \tag{2}$$

We estimate emission changes from the decline effect by allowing heat input to change (Δh) while keeping emission rates constant ($\bar{r}$) at the average between years. We isolate the improvement effect by keeping heat input constant ($\bar{h}$) and allowing emission rates to change (Δr).

[5] Air Pollution Emission Experiments and Policy analysis (APEEP) is the original model from which AP3, and its direct predecessor AP2, are derived (Muller & Mendelsohn, 2007).

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2.1.4. Forecasting

Our prospective policy analysis requires a forecast of damages from coal to estimate the benefits of coal plant retirements. We use six years of historical data (2014–2019) to forecast emissions and MDs separately for SO_2, NO_x, and primary $PM_{2.5}$ from the 250 coal-fired power plants remaining as of 2020. The forecast extends to 2035, aligning with the Biden administration's pledge to create a carbon pollution-free power sector (GEM *et al.*, 2022). Forecasting MDs and emissions separately allows us to disentangle two trends. First, emissions are generally decreasing as plants decline in use and improve emission rates. Conversely, MDs are increasing due to population and income growth (which affects the VSL) over time. We also forecast net generation from these power plants, using data reported by the U.S. Energy Information Administration (EIA) (U.S. EIA, 2023*d*), which is vital for understanding grid losses and energy security risks.

We employ an exponential smoothing state space modeling framework to construct the forecasts (Hyndman *et al.*, 2008). Exponential smoothing forecasts are based on past observations, with the influence of each point exponentially decreasing with age. State space models allow for flexibility in the specification of the error, trend, and seasonality components of the time series. The parametric structure of the model is selected via an iterative process that identifies the best-performing specification. Our emissions and net generation forecasts incorporate preannounced closures as of 2021 (U.S. EIA, 2023*b*). See Appendix C of the Supplementary Material for more details.

This process has some critical caveats that we cannot reconcile without a detailed plant-by-plant investigation. For example, coal plants may plan to switch fuel sources or employ emission control technologies or strategies, cutting their emissions in ways not captured in the 2014-to-2019 trends. They also may "unexpectedly" decrease their operations, reducing pollution and output. Still, some facilities scheduled to go offline may change their plans, which the data reveal is not an uncommon occurrence (U.S. EIA, 2023*b*).

2.1.5. Natural gas substitution offsetting benefits

Natural gas is among the most likely power sources to replace coal in any location. From 2015 (33%) to 2020 (41%), natural gas comprised the largest share of power generation in the U.S. (U.S. EIA, 2023*b*). This research assumes all coal is replaced by natural gas, which also emits SO_2, NO_x, and primary $PM_{2.5}$, offsetting some gains from retired coal. However, natural gas has far lower emission rates than coal (U.S. EPA's Clean Air Markets Division, 2022).[6] While natural gas also emits less CO_2 than coal upon combustion, upstream methane leakage further contributes to GHG emissions. A recent study found that life cycle GHG intensities of natural gas can be on par with coal under certain scenarios (Gordon *et al.*, 2023).[7] While estimates provided by the National Renewable Energy Laboratory suggest that natural gas is still notably better than coal (NREL, 2023), we model the "worst-case scenario" where natural gas and coal GHG damages are equal.

[6] We consider lost heat input from coal and average natural gas fleet emission rates from U.S. EPA's Clean Air Markets Division (2022) for added damage computations. This likely results in an overestimation because natural gas has a higher thermal efficiency – that is, more power output per unit of heat input – than coal (NAS, 2023).

[7] Specifically, the study found that a leakage rate of 4.7% results in the same GHG emissions (i.e., CO_2-equivalent) for natural gas and coal considering a 20-year timeframe. This finding is similar to other research in the field (Alvarez *et al.*, 2012; Zhang *et al.*, 2014; Ladage *et al.*, 2021).

Using an alternative to the worst case described above, we also compute benefits from CO_2 reductions assuming emissions-free alternative substitution. Benefits of avoided CO_2 are modeled using the social cost of carbon (SCC), the year-specific discounted present values of the globally incurred stream of total damages due to one additional ton of CO_2 (IWG, 2016, 2021). The default approach uses the SCC corresponding to a 3% social discount rate (SDR), but we also consider a 5% SDR and values corresponding to catastrophic climate change outcomes for sensitivity analyses. Finally, we differentiate domestic and international damages (Ricke *et al.*, 2018).

2.2. Costs of moving away from coal

2.2.1. Coal sector labor market analysis

We use ordinary least squares regression analysis to test for associations between coal industry activity and employment in the utility and mining sectors. Specifically, we use two-way fixed effects models (Wooldridge, 2010), as shown in Equation (3):

$$y_{ct} = \beta_1 x_{1,ct} + \beta_2 x_{2,ct} + Z_{ct}\theta + \alpha_c + \gamma_t + \varepsilon_{ct}. \tag{3}$$

In Equation (3), y is the number of sectoral jobs in each county with coal activity (c) during each year (t), provided by the Bureau of Labor Statistics (BLS) (U.S. BLS, 2020). $x_{1,ct}$ and $x_{2,ct}$ are the variables of interest: coal-fired capacity and generation in the utility sector and number of mining contracts and quantity of coal sales in the mining sector; the data are from the EIA (U.S. EIA, 2023*b*, *d*). Z_{ct} represents a vector of control variables, reviewed in Appendix B of the Supplementary Material. α_c and γ_t are county and year fixed effects, respectively. ε_{ct} is the error term. β_1 and β_2 are the parameter estimates used in our subsequent labor market analysis. These coefficients represent the marginal effects of capacity, generation, contracts, and sales on jobs.[8] θ represents a vector of fitted regression coefficients for the control variables.

To estimate the labor impacts of coal's decline, we multiply the modeled marginal employment effects (β_1 and β_2) by county-level changes in coal sector activity. Then, to facilitate a comparison of the monetary benefits from reduced emissions to the costs borne by workers in the coal industry, we monetize employment changes using lost wages paid to plant operators and miners differentiated by state (U.S. BLS, 2020). Our modeling likely overestimates these costs because we do not account for workers finding new jobs.[9] The social costs of job losses are typically lower than the job's associated earnings (Bartik, 2015*a*, *b*) and can instead be considered as compensation lost during unemployment plus the impact of job loss on future earnings and employment possibilities (Haveman & Weimer, 2015).[10] That said, quantifying gross job and wage losses in the industry helps illustrate the

[8] For a discussion addressing the potential for simultaneity to bias our estimates, see Appendix B of the Supplementary Material. In summary, our labor market models avoid simultaneous equation bias based on (i) the specific changes that occurred in the coal sector from 2014 to 2019 and (ii) our used of fixed effects, which looks at within group variation.

[9] In fact, some workers may seamlessly transition from working with a coal EGU to a natural gas EGU at the same facility; however, this would be a phenomenon limited to the utility sector.

[10] Other factors to consider may be the cost of searching for new work, the value of leisure time during unemployment, or the effects on health and well-being.

changing economic landscape in coal-dependent communities with often less economic diversity and is, therefore, the more prudent choice for our BCA.

2.2.2. Buyouts and reverse auctions

We compare the benefits (avoided forecasted damages) and costs (government expenditures) of coal-fired power plant buyouts or replacements in 2020. We set the buyout payment to operators at $650 thousand per MW, which aligns with fleetwide net book value (RMI, 2022). We identify natural gas capacity installation costs to be about $1.12 million per MW (U.S. EIA, 2022). We employ a 3% discount rate to express future cash flows in present value terms.

We also consider a reverse auction policy as an alternative to a one-time removal. In doing so, we mimic Germany's Coal Exit Act, passed in July 2020 (Scott *et al.*, 2022; Tiedemann & Müller-Hansen, 2023). The German design allows firms to submit bids, or prices per MW they would be willing to accept to decommission sooner than otherwise planned. The German design requires that the bids are lower than a maximum allowable bid. Then, the lowest bidders are awarded compensation until the round removes a prespecified aggregate capacity.

An additional feature of the German design is that each firm's bid is subject to an adjustment factor that embodies its average annual CO_2 emissions over the past 3 years, as shown in Equation (4):

$$Emission\ Rate\ Adjusted\,Bid\left[\frac{EUR}{Avg.CO_2}\right] = Firm\,Bid\left[\frac{EUR}{MW}\right] \times Adjustment\left[\frac{MW}{Avg.CO_2}\right]. \quad (4)$$

The emission rate adjusted bid in Equation (4) is, effectively, the per-ton cost to the regulator of removing annual amounts of CO_2 utilizing the auction. The final bid design provides an advantage for modern plants with higher capacity factors, driving more CO_2 per unit of capacity. In contrast, it creates a disadvantage for older plants with lower capacity factors, lower CO_2 per unit of capacity, and typically higher CO_2 per unit of generation.[11]

We experiment with several bid adjustment frameworks in our reverse auction analysis to jointly maximize avoided future damage and retained generation. We consider eight bid adjustment factors that use the following criteria: CO_2 emissions, SO_2 emissions, nearby population counts, and air pollution damage.[12] We normalize each criterion per unit of capacity and per unit of generation. Our focus is on evaluating the proposed adjustment factors rather than strategic behavior by firms, so we make two simplifying and admittedly restrictive assumptions. First, we assume that every coal plant opts into the reverse auction. In other words, all firms submit bids. Second, we assume all firms submit bids equal to the maximum allowable bid, which controls for would-be competition and instead allows for an assessment of adjustment factor performance. Our design features annual auctions from 2020 to 2034 with equal capacity retirement targets achieving a complete phaseout by 2035. We report all cash flows in present value terms with respect to 2020.

[11] The auctions also consider grid operations and energy security (Scott et al. 2022). For example, no coal-fired power plant in Germany's southern region could participate in the first auction, and these plants were then disadvantaged in the following rounds via a grid adjustment factor. See Appendix C of the Supplementary Material for a further discussion of the German policy.

[12] Supplementary Table C9 summarizes the evaluated bid adjustment factors. The population criterion considers a 350-mile radius and is multiplicative, unlike emissions and damages. See Appendix C of the Supplementary Material for a further explanation.

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2.2.3. Other costs from coal's decline

Like with any BCA, we must limit the scope of what is included in our analysis. Here, we focus on air pollution and the costs associated with the proposed policies. Given that this research shows the benefits substantially exceed the costs, we are less concerned with excluded benefits. These include but are not limited to fewer on-the-job mining accidents (National Safety Council, 2021) and improved property values from coal-to-gas switching (Rivera & Loveridge, 2022).

On costs, the contraction of the coal industry may affect other sectors. Prior evidence is mixed. Focusing on local effects, Weber (2020) found that the loss of one coal mining job actually led to a slight increase in non-coal jobs, while Black *et al.* (2005) found the opposite.[13] However, the Economic Policy Institute reports indirect job multipliers across the broader economy of 9.58 and 3.90 for the utility and mining sectors, respectively (Bivens, 2019).[14] Another cost resulting from the decline of coal is lost tax revenue, which can play a major role for local governments (Haggerty *et al.*, 2018). We use data from Raimi *et al.* (2022) to determine rough estimates of \$800 per GWh of fossil fuel-fired power generation and \$3 per short ton of coal mined (see Supplementary Tables B29 and B30). Importantly, our study excludes costs that may result from existential threats to the well-being of coal-dependent communities, including, for example, increased "deaths of despair" (Boslett & Hill, 2022).

Another important cost to acknowledge is the loss of generation. On one hand, if market forces drive the decline of coal, there is effectively no loss because coal generation is replaced by a cheaper (and likely cleaner) alternative.[15] If, on the other hand, policies induce coal's decline (e.g., via paid decommissioning), it is not clear that low-cost replacement capacity will be immediately available. As such, costs stemming from power shortages, disruptions, and energy insecurity may occur, and the value of lost load is far from negligible (Gorman, 2022). In light of these considerations, we incorporate costs to replace the coal fleet with natural gas generators in our prospective analysis into our BCA framework. Lastly, there is the loss of productive capital at retired coal-fired power plants to consider. However, there is evidence that decommissioned coal plants provide a unique opportunity for various clean energy solutions (Warren, 2023); added value associated with repurposing these properties is possible.

3. Results

We organize results into three subsections. The first reports changes in damages from coal-fired EGUs between 2014 and 2019. The second reports labor market costs and retrospective net benefits, relevant to worker compensation policies. The third details the prospective benefits and costs, relevant to compensated decommissioning policies.

[13] Weber (2020), finding a 0.10 job increase in local non-coal jobs for every lost coal mining job, explained why this may have occurred in the empirical data analysis (that part-time and full-time jobs were considered the same) and asserted that it may understate the local economic impacts.

[14] A critical consideration for using indirect job multipliers, however, is utility and mining sector interdependencies. See Appendix B of the Supplementary Material for a further discussion.

[15] For our retrospective analysis, this is assumed to be the case, based on the work of Coglianese *et al.* (2020), Linn and McCormack (2019), and Culver and Hong (2016).

3.1. Benefits from coal's decline

From 2014 to 2019, annual SO_2 from coal EGUs decreased by nearly 70%. NO_x and primary $PM_{2.5}$ both decreased by more than 50%. (CO_2 decreased by 37%.) Overall, coal's decline accounted for more emission reductions than its improvement. Across the criteria air pollutants, the decline effect accounted for over 70% of the total decrease by 2019. (For CO_2, nearly all emission reductions were due to decline rather than improvement.) Accordingly, the decline effect dominated the cumulative changes over time as plants went and stayed offline. Nevertheless, even year-over-year changes were mainly driven by coal's decline; improvement seldom played a more prominent role. See Supplementary Figure B1 for percent changes in coal emissions by effect from 2015 to 2019 relative to 2014 and the previous year. Using AP3, we estimate that damages from criteria air pollution from coal-fired EGUs were \$151 (\$57.0 to \$316)[16] billion in 2014. These damages were due to approximately 15,700 premature deaths from $PM_{2.5}$ exposure.[17] By 2019, these damages decreased to \$54.0 (\$20.4 to \$114) billion. Supplementary Table B2 reports annual damages.

Table 1 shows the benefits of avoided air pollution damages each year from 2015 to 2019 compared to a 2014 counterfactual (i.e., assuming conditions in 2014 held over the subsequent years). The five-year cumulative benefit from avoided criteria air pollution was \$454 (\$172 to \$958) billion. Benefits from CO_2 reductions were \$90.6 (\$26.6 to \$262) billion, \$9.96 (\$0 to \$39.4) billion of which accrued domestically and the rest internationally. However, as discussed above, we assume these benefits are entirely offset by upstream methane leakage. The movement away from coal [the benefits from the decline effect of \$306 (\$116 to \$646) minus additional damages from natural gas of \$5.75 (\$2.17 to \$12.1) billion] resulted in \$300 (\$113 to \$634) billion in air quality benefits for the U.S., about two-thirds of the total.

These benefits were dominated by SO_2, which exhibits high marginal damages (see Supplementary Table A7) and is released in much larger amounts when combusting coal relative to natural gas (see Supplementary Tables B1 and B7). SO_2 accounted for 69% of decline benefits with emissions-free alternative substitution and a greater percentage with natural gas substitution; SO_2 accounted for 91% of improvement benefits. Intuitively, the most significant contributions to benefits were in 2019 due to the accumulation of decreased production and increased abatement; however, much of the marginal progress occurred early in the assessed timeline. The greatest year-over-year gains were in 2015 and 2016 when natural gas prices fell steeply, several environmental policies were enacted, and SO_2 control technology installations surged (Holland *et al.*, 2020; U.S. EIA, 2023*a*, *b*). See Supplementary Figure B2 for changes in coal damages by effect from 2015 to 2019 relative to 2014 and the previous year.

Figure 1 shows spatially disaggregated five-year benefits from decreased criteria air pollution from the decline of coal. Avoided damages from less SO_2, NO_x, and primary $PM_{2.5}$ were primarily experienced throughout the eastern half of the U.S., where most coal damages occurred historically (Siler-Evans *et al.*, 2013; Jaramillo & Muller, 2016; Thind

[16] We report uncertainty via (*low estimate* to *high estimate*) immediately following the *base case estimate*. For a summary of variable changes for our damage uncertainty assessments, see Supplementary Table A6.

[17] Premature mortality aligning with the reported damages from criteria air pollution can be calculated using the VSLs in Supplementary Table A4; the values derived using the EPA's recommendations are in the realm of \$10 million.

Table 1. *Avoided air pollution damages from coal in the U.S. relative to the 2014 counterfactual by the decline and improvement effects and assuming natural gas substitution*

		Benefits from avoided damages in the U.S. (billion $)					
Pollutant	Effect	2015	2016	2017	2018	2019	Five-year total
SO_2	Total	41.2	77.2	88.6	92.9	107	407
	Decline	29.0	49.3	56.5	62.3	75.9	273
	Improve	12.3	28.0	32.3	30.7	31.3	135
	Added natural gas	−0.0903	−0.147	−0.169	−0.208	−0.213	−0.828
NO_x	Total	3.07	4.36	5.81	6.52	7.87	27.6
	Decline	2.52	3.55	4.07	4.68	6.39	21.2
	Improve	0.933	1.33	2.31	2.56	2.51	9.63
	Added natural gas	−0.379	−0.516	−0.569	−0.722	−1.03	−3.22
Primary $PM_{2.5}$	Total	1.21	2.42	2.90	3.30	4.08	13.9
	Decline	1.16	1.94	2.38	2.79	3.70	12.0
	Improve	0.223	0.757	0.848	0.900	0.922	3.65
	Added natural gas	−0.172	−0.277	−0.321	−0.390	−0.545	−1.71
Air pollution total	Total	45.5	84.0	97.3	103	119	448
	Decline	32.7	54.8	62.9	69.8	86.0	306
	Improve	13.4	30.1	35.4	34.2	34.8	148
	Added natural gas	−0.641	−0.941	−1.06	−1.32	−1.79	−5.75

Notes: Benefits are in billions of 2020 U.S. dollars. Added natural gas offsets some air quality benefits (see Supplementary Table B7) and all CO_2 benefits, assuming a "worst-case scenario" where coal and natural gas life cycle GHG intensities are equivalent. See Supplementary Table B3 for an expanded version of Table 1, including avoided damages from CO_2 as well as criteria air pollution, greenhouse gas, and global avoided damage totals assuming emissions-free alternative substitution. See Supplementary Tables B5 and B6 for lower and upper estimates, respectively.

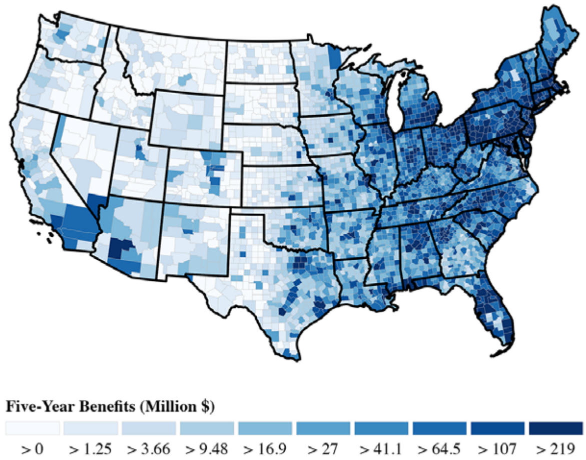

Figure 1. *Five-year benefits of avoided air pollution from coal's decline in the U.S. by county. Notes: Benefits are five-year cumulative totals (2015 to 2019 vs. 2014) in 2020 U.S. dollars. Benefits are from fewer emissions of SO_2, NO_x, and primary $PM_{2.5}$. Benefits are from coal's decline in the U.S., excluding those from its improvement. Benefits incorporate added damages from natural gas substitution, assuming additional SO_2, NO_x, and primary $PM_{2.5}$ consistent with average natural gas emission rates. Color scale divides counties into equally sized groups. See Supplementary Figure B3 for maps showing benefits from coal's improvement and benefits per capita from both effects.*

et al., 2019). The largest gains were in highly populated urban centers; the counties home to Chicago, Detroit, Pittsburgh, and Cleveland all experienced five-year benefits exceeding $3 billion.[18] More than 650 counties experienced five-year benefits surpassing $100 million. Nationwide, per capita benefits were $186. However, there was wide variability, ranging from more than $1,000 per person in six counties throughout Mississippi, West Virginia, Indiana, and Virginia to less than $4 per person in several counties in western states. While our focus is on coal's decline, we also investigate the spatial benefits of its improvement (see Supplementary Figure B3). The geographic patterns are like those in Figure 1 but with lower total and per capita benefits. Notably, only 32 counties (about 1%) saw benefits from the improvement effect that exceeded those from the decline effect.

3.2. *Labor market impacts and wage replacement policies*

Our labor market analysis reveals significant associations between employment and economic activity in the coal industry. In the utility sector, we estimate marginal employment effects of 37.2 (6.11 to 68.2)[19] jobs per GW of coal capacity and 9.61 (1.30 to 17.9)

[18] Supplementary Table B4 summarizes the benefits for these counties. Next in line were the counties home to Philadelphia, Brooklyn, Columbus, Queens, and Indianapolis, all achieving $2 billion in benefits or more.

[19] We report uncertainty for the marginal employment estimates (i.e., β coefficients) via 90% confidence intervals (see Supplementary Table B10).

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jobs per TWh of coal generation. In the mining sector, we estimate marginal employment effects of 8.38 (4.19 to 12.6) jobs per mining contract and 38.9 (20.1 to 57.6) jobs per million short tons of coal sales. Supplementary Tables B8 and B9 present the fitted regression models.[20]

Table 2 shows our estimates of labor market changes in the coal industry from 2015 to 2019 relative to the 2014 baseline. We show both annual job losses (year-over-year) and cumulative job-year losses. The latter compound over time since we assume that a worker losing a job in 2015 would have worked in 2016 and thereafter and that workers stay unemployed. Changes in coal-fired capacity and generation were associated with 26.9 (7.04 to 43.1)[21] thousand lost job-years. Changes in coal mining activity were associated with 53.2 (35.4 to 79.1) thousand lost job-years. Forgone wages in the utility sector were \$3.14 (\$0.822 to \$5.02) billion. Those in the mining sector were \$4.71 (\$3.15 to \$7.11) billion.

Figure 2 shows the spatial disaggregation of the five-year labor market costs from declining coal industry activity. Figure 2A shows lost wages in the utility sector. We find that 391 counties experienced job losses amounting to \$3.20 billion in lost wages and that these counties intuitively reflect the location of coal plants (U.S. EIA, 2023*b*). Ten counties had costs exceeding \$40 million, and more than 100 counties exceeded \$10 million in lost wages. Our estimates indicate that the greatest losses manifested in counties that hosted large coal EGUs that decommissioned or converted to another fuel source in the latter half of the 2010s (U.S. EIA, 2023*b*). Thirty-three counties saw increased coal activity and corresponding jobs; these additional wages amounted to \$63.2 million.

Figure 2B shows that lost wages in the mining sector occurred in counties within the Appalachian, Interior, and Western coal regions. All told, 134 counties incurred costs, with lost wages equal to \$5.03 billion. However, nearly 40% of this was experienced in just eight counties. Notably, costs in Campbell County, Wyoming, were 50% more than those of the county with the second highest (Greene County, Pennsylvania), which lost more than twice the wages foregone in the third highest (Pike County, Kentucky).[22] Interestingly, 57 counties increased their coal mining output such that extra wages exceeded \$300 million.

We next compare the benefits (from reduced emissions) and costs (from lost wages) associated with the decline of coal. The upshot of this comparison is that costs amounted to less than 3% of benefits. The net benefits of the movement away from coal in the U.S. were \$293 billion. Using our low damage assumptions and the high-end employment impacts, net benefits were still \$101 billion, with costs at 11% of benefits. Using the high damage assumptions and low-end employment impacts, net benefits were \$630 billion, with costs at less than 1% of benefits.

[20] See Appendix B of the Supplementary Material for details of our model evaluation and selection procedure. Relevant empirical work is summarized in SupplementaryFigures B4–B7 and Supplementary Tables B8–B19.

[21] These estimates account for correlation in coefficient estimate variation. See Appendix B of the Supplementary Material for more information.

[22] Supplementary Table B24 summarizes costs for these counties. Notably, Campbell County, Wyoming, accounts for an extraordinary share of coal mining activity in the U.S. (see Supplementary Table B20). In our labor market regression modeling, we find it to be an influential outlier with high leverage and discrepancy, having a much lower marginal employment effect (jobs per unit) of coal sales than the rest of the country. Hence, Campbell County is treated uniquely, as outlined in Appendix B of the Supplementary Material.

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Table 2. *Decline in U.S. coal activity and costs of lost wages from associated employment changes relative to the 2014 counterfactual*

		Labor market costs from the decline of coal in the U.S.					
Economic sector	Impacts variable	2015	2016	2017	2018	2019	Five-year total
Utility	Capacity (GW)	−9.54	−31.8	−44.7	−52.2	−68.3	−207[A]
	Generation (TWh)	−234	−342	−377	−433	−620	−2,010
	Annual jobs[B]	−2,600	−1,860	−816	−819	−2,390	−8,490
	Job–years[C]	−2,600	−4,460	−5,280	−6,100	−8,490	−26,900
	Wages (billion $)	−0.30	−0.51	−0.61	−0.71	−1.00	−3.14
Mining	Contracts (count)	−399	−527	−674	−696	−690	−2,990[A]
	Sales (million short tons)	−70.5	−202	−210	−253	−290	−1,030
	Annual jobs[B]	−5,470	−4,010	−2,130	−1,350	−773	−13,700
	Job–years[C]	−5,470	−9,470	−11,600	−13,000	−13,700	−53,200
	Wages (billion $)	−0.48	−0.82	−1.03	−1.15	−1.22	−4.71
Coal sector total	Annual jobs[B]	−8,070	−5,870	−2,950	−2,160	−3,170	−22,200
	Job–years[C]	−8,070	−13,900	−16,900	−19,100	−22,200	−80,200
	Wages (billion $)	−0.78	−1.33	−1.65	−1.86	−2.22	−7.84

Sources: Capacity, generation, contracts, and sales changes are derived using data from the EIA (U.S. EIA, 2023*b*, *d*).
Notes: [A]Totals represent *variable*-years (e.g., a one GW decrease in 2015 cumulates to a five GW-year decrease from 2015 to 2019). [B]Annual jobs are job changes compared to the previous year. [C]Job-years are cumulative lost working years compared to 2014, assuming no re-employment. Wages are state- and year-specific. For coal variable data from 2014 to 2019, see Supplementary Table B20. For expanded versions of Table 2, see Supplementary Tables B21 (employment) and B23 (wages). See Supplementary Tables B22 and B25 for lower and upper estimates of coal employment and wage changes, respectively.

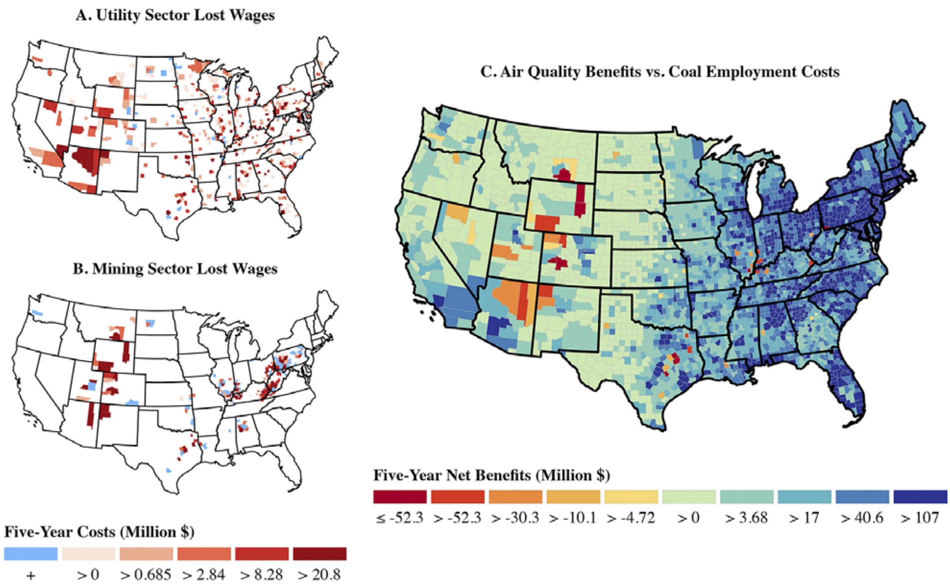

Figure 2. *Five-year costs and net benefits from coal's decline in the U.S. by county. Notes: Benefits and costs are five-year cumulative totals (2015 to 2019 vs. 2014) in 2020 U.S. dollars. Panel (A) shows lost wages in the utility sector from jobs associated with coal capacity and generation. Panel (B) shows lost wages in the mining sector from jobs associated with mining contracts and quantity of coal sales. Panel (C) shows air quality benefits (coal decline benefits minus added natural gas damages from Figure 1) minus coal employment costs, from panels (A) and (B). For panels (A) and (B), color scale divides county-sector costs into five equally sized groups; county-sector gains (i.e., added wages) are shown in blue. For panel (C), color scale divides counties with net costs and net benefits each into five equally sized groups. See Supplementary Figures B8 and B9 for costs per capita and net benefits per capita, respectively.*

Figure 2C shows that over 98% of U.S. counties experienced net benefits. This includes 410 counties that saw losses in the coal industry. Many of the 54 counties with net costs saw substantial losses in the mining sector, which accounted for 84% of foregone wages across these counties (see Supplementary Table B27 for the benefits and costs of counties with the greatest net losses). Especially evident in Figure 2C are net losses in counties in western coal mining states. A critical factor driving this pattern is the low level of air quality benefits in the West, as shown in Figure 1. This is further evident when normalizing net benefits by county populations (see Supplementary Figure B9).

We conclude this section by highlighting the potential for wage replacement and other policies to achieve a Pareto improvement. The cumulative avoided air pollution benefits clearly exceed the cumulative wage losses experienced from 2015 to 2019. Hence, the "winners" could compensate the "losers" at the level of lost wages, and society overall would still come out far ahead, with more than $290 billion in net benefits. This is a start but may fall short for localities faced with an existential threat from the changing energy economy; a more robust approach is warranted. To reinvigorate these coal-dependent communities, policies could replace the approximate $4.7 billion in lost tax revenue, estimated using tax

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revenue data from Raimi *et al.* (2022) and the five-year losses of 2.01 thousand TWh and 1.03 billion short tons of coal from Table 2 (see Supplementary Tables B29 and B30). Moreover, the federal government could invest an amount equal to indirect wage losses (on the order of tens of billions of dollars – see Supplementary Tables B31 and B32) toward vocational training, educational programs, or place-based policies for coal communities.

Notably, the air quality benefits modeled in this article are external to markets; communities that enjoy improved air quality do not receive actual cash benefits. Rather, the value associated with less $PM_{2.5}$ exposure reflects the collective willingness to pay to avoid mortality risk embodied in the VSL. Thus, such policy interventions that compensate coal-dependent communities would need to procure revenue to enact such a transfer. Legislation is one funding vehicle; the Inflation Reduction Act (IRA) authorized hundreds of billions of dollars in federal funding for climate and energy investments over the next decade (Rep. Yarmuth, 2022). In fact, recent funding guidance specifies how coal communities can claim clean energy-related tax credits through the IRA (USDT, 2023). While likely to face political opposition, regulations designed to derive revenue from economic activity that produces negative externalities (such as oil and gas extraction or even fossil fuel-fired power production itself) would enhance efficiency while generating funds to support public policy solutions for coal communities during the energy transition.

3.3. Future damages and buyout policies

Our damage forecasts predict the U.S. will incur \$694 (\$89.4 to \$4,330)[23] billion in damages from its coal-fired power plants through 2035. Damages from CO_2 experienced abroad comprise an additional \$558 (\$91.4 to \$2,940) billion. Assuming natural gas substitution (offsetting GHG gains entirely and criteria air pollution gains by an amount consistent with average emission rates) attenuates the benefit estimate to \$589 (\$81.8 to \$3,670) billion. On the cost side of the ledger, at \$650 thousand per MW, the net book value of the 271 GW in the coal fleet is \$176 billion. Given these estimates, a buyout of the entire coal fleet in 2020 would have produced \$413 billion in net benefits, amounting to a 235% ROI. That said, such a policy would have removed slightly more than a fifth of total U.S. capacity (U.S. EIA, 2023*b*) and a forecasted 13.6 (8.62 to 23.2) thousand TWh of electricity projected through 2035. Fully replacing this coal capacity with natural gas generators, costing about \$1.12 million per MW, would cost about \$304 billion, lowering net benefits to \$286 billion and the ROI to 94% in the base case (see Supplementary Table C6).[24]

Two factors deter a complete buyout approach. First, many real-world constraints limit buyouts or replacements (e.g., power system impacts or government budget constraints). The second, however, is an efficiency-based criterion: the government should only seek to remove capacity where the marginal benefits exceed the marginal costs. We find that, in the

[23] The uncertainty intervals for future damages use both the 80% confidence intervals of forecasting results and lower and upper MD estimates; this interval covers all other assessed outcomes considering uncertain input variables. For a detailed sensitivity analysis, see Supplementary Table C5 and Supplementary Figure C3.

[24] Wind or solar capacity could replace the coal fleet for \$407 billion or \$450 billion with no added substitution damages. This becomes more complicated when considering grid operations though, as these resources depend on geographically variable natural resources and are non-dispatchable without complementary storage solutions. That said, we also point out that natural gas is worse than other fuel sources (including coal) for various reliability and resilience attributes (Ramirez-Meyers *et al.*, 2021).

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Table 3. *Avoided air pollution damages through 2035 vs. energy system losses and policy costs of optimal 2020 U.S. coal-fired power plant buyouts achieving increasing percentages of maximum net benefits*

		Portion of maximum net benefits			
Policy expenditures	Impacts variable	>25%	>50%	>75%	100%
Net book value buyouts	Lost capacity (GW)	10.4 (3.8%)	26.6 (9.8%)	58.6 (22%)	168 (62%)
	Lost generation (TWh)	972 (7.2%)	2,250 (17%)	4,400 (32%)	9,850 (73%)
	Benefits (billion $)	125 (21%)	248 (42%)	383 (65%)	562 (95%)
	Costs (billion $)	6.74 (3.8%)	17.3 (9.8%)	38.1 (22%)	109 (62%)
	Net benefits (billion $)	118 (26%)	230 (51%)	345 (76%)	452 (100%)
	Net benefits/costs	17.6	13.3	9.05	4.14
Natural gas generator replacement	Lost capacity (GW)	10.4 (3.8%)	21.9 (8.1%)	45.7 (17%)	141 (52%)
	Lost generation (TWh)	972 (7.2%)	1,840 (14%)	3,530 (26%)	8,920 (66%)
	Benefits (billion $)	125 (21%)	219 (37%)	337 (57%)	537 (91%)
	Costs (billion $)	11.6 (3.8%)	24.5 (8.1%)	51.2 (17%)	158 (52%)
	Net benefits (billion $)	114 (30%)	195 (51%)	286 (75%)	379 (100%)
	Net benefits/costs	9.77	7.93	5.58	2.40

Sources: Buyout costs consider net book value per MW (RMI, 2022). Replacement costs consider natural gas generator construction costs per MW (U.S. EIA, 2022).

Notes: Estimate is reported first. Percentage of total is reported second in parentheses. Monetary variables are in 2020 present value U.S. dollars. Buyouts and replacements are ordered by decreasing forecasted damage per unit of capacity through 2035 (see Supplementary Figure C4 for a visual). Buyouts and replacements are conducted until at least the portion of maximum net benefits specified (e.g., 25%) is achieved. Lost capacity is out of 271 GW. Lost generation is out of the forecasted 13.6 thousand TWh through 2035. Avoided damages are out of the forecasted $589 billion through 2035, which incorporates additional damage from natural gas substitution. Buyout policy costs are out of $176 billion for net book value payments, and replacement costs are out of $304 for natural gas generator construction costs. See Supplementary Table C7 for efficient buyouts considering emissions-free alternative (rather than natural gas) substitution.

case of net book value buyouts (or generator replacements), benefits exceed costs on a per MW basis for 157 (or 128) of the 250 evaluated plants (see Supplementary Figure C4). These facilities comprise 62% (or 52%) of the coal fleet's capacity and 73% (or 66%) of the forecasted net generation through 2035. They also account for 95% (or 91%) of forecasted damages. Buying out just these coal plants would result in net benefits of $452 (or $379) billion at a cost of $175 (or $158) billion.

Table 3, which shows the benefits and costs of partial buyouts that optimally achieve increasing percentages of net benefits, is designed to inform decision-makers limited by real-world constraints. The greatest ROIs can be achieved by prioritizing the removal of the most damage-intensive capacity (determined via ranking coal plants by decreasing marginal benefits). For example, decision-makers could achieve 25% of maximum net benefits by buying out or replacing just the most damaging 10.4 GW (note: removing the same group of plants achieves this goal for either policy expenditure scenario). Buying out these coal plants would yield net benefits of 17.6 times the costs; replacing them would yield net benefits of 9.77 times the costs.

Figure 3 depicts the results of the reverse auction analysis. Because an equal amount of capacity is retired each year, costs are insensitive to the different auction designs. Assuming maximum allowable bids of $650 thousand per MW (net book value) or $1.12 million per MW (generator replacement) results in maximum nominal costs of $176 or $304 billion divided over 15 years, $145 or $249 billion in present value for 2020 (see Supplementary Table C8). Figure 3A compares the forecasted annual damages each year resulting from the various auction designs and in the case of no intervention ($589 billion cumulatively). The gap between the latter and each option demonstrates avoided damages each year resulting from policy implementation. Figure 3B aggregates the benefits of each auction design (*x*-axis) and also considers the total remaining generation among remaining active plants (*y*-axis). As a reference point, the best possible outcome for avoided damages is $429 billion. This does not consider any bid adjustment factor but rather optimizes which plants exit each year to achieve the greatest avoided damages overall (see Supplementary Table C10).

While Figure 3A shows the substantial benefits of any reverse auction regardless of design, Figure 3B shows that outcomes vary considerably according to the selected bid adjustment factor. An outcome dominates another if it results in more avoided damages and retained generation: this corresponds to larger values on both axes. For example, Figure 3B shows that the German scheme of CO_2 emissions per unit of capacity results in $355 billion in avoided damages and 5.60 thousand TWh in retained generation. This is dominated by four other bid adjustment factors: those defined in terms of SO_2 emissions and monetary damages. (If emissions-free alternatives replace coal, the CO_2 per unit of capacity scheme is only dominated by the damages per unit of capacity scheme, as shown in Supplementary Figure C6B.) If policymakers prefer a balance between avoided damages and retained generation, adjustments based on either SO_2 emissions or monetary damages per unit of generation, rather than per unit of capacity, yield appealing outcomes. The policy would first target coal plants with higher impacts per unit of electricity. This offers a possible solution to a central problem with the German approach, which creates a disadvantage in the reverse auctions for older plants with typically higher emissions (and likely damages) per unit of generation (Scott *et al.*, 2022).[25]

[25] The alternative argument here is that the government should not compensate older plants that are more likely to retire without intervention. That said, there is a history of old, grandfathered coal plants in the U.S. staying online

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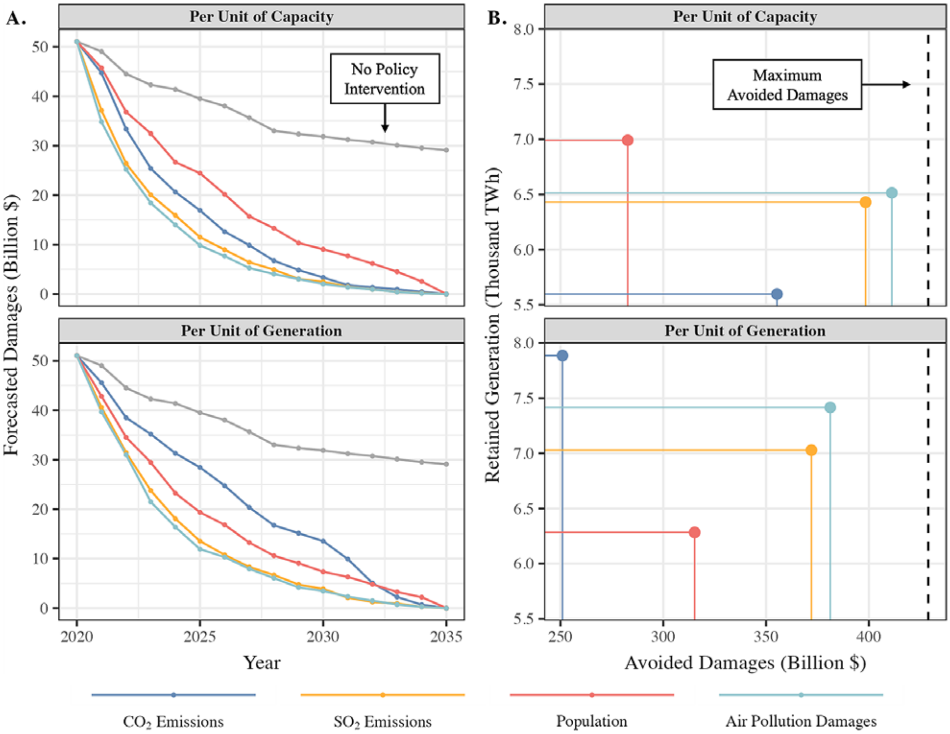

Figure 3. *U.S. coal plant reverse auction outcomes using various bid adjustment factors. Notes: Damages are in 2020 present value U.S. dollars. Approximately equal amounts of capacity are removed annually from 2020 to 2034. Forecasted (avoided) damages consider those from SO_2, NO_x, and primary $PM_{2.5}$. Forecasted (avoided) damages incorporate added damages from natural gas substitution, assuming additional SO_2, NO_x, and primary $PM_{2.5}$ consistent with average natural gas emission rates. Panel (A) shows time series of forecasted annual damages. Gray line represents no reverse auction policy. Panel (B) shows multicriteria assessments of retained generation vs. avoided damage benefits. Dashed black line shows maximum avoided damages (see Supplementary Table C10). See Supplementary Figures C5 and C6 for assessments assuming emissions-free alternative (rather than natural gas) substitution and Supplementary Tables C11 and C12 for numeric data.*

We note a few caveats to this analysis. The enactment of a long-term (through 2034) auction policy could perversely affect firms' retirement decisions. It is highly improbable that any plant would simply choose to go offline, given that it could announce an intention to stay open and earn compensation to shut down. Second, significant annual retirements through reverse auctions may induce remaining coal plants to run differently (most likely, to run more), which could increase emissions and damages. Third, we do not model the effect of auction outcomes on grid operations. We consider the cost of replacing coal capacity, but

much longer than initially expected, hindering the ability of the Clean Air Act to regulate as intended (Revesz and Lienke 2016).

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we cannot take into account the complex and dynamic nature of the U.S. energy system. Serious consideration of a reverse auction policy by decision-makers would require further work, including but not limited to an assessment of equilibrium impacts. See Appendix C of the Supplementary Material for further discussion.

4. Conclusions

This study conducts both retrospective and prospective BCAs of the decline of coal-fired power generation in the U.S. We compare retrospective avoided damages to lost coal industry wages resulting from coal's decline from 2014 to 2019. We find that the benefits ($300 billion) far exceeded the costs ($7.84 billion), indicating that wages could be replaced at a small fraction of net benefits (less than 3%). Net costs were highly concentrated in western coal mining counties, whereas benefits tended to occur in the highly populated eastern states, which are nearby and downwind from coal-fired power plants. The magnitude of the benefits compared to the costs suggests that, even after compensating workers, additional funding for other just transition policies, such as replacing the nearly $5 billion in lost tax revenue or investing the equivalent of spillover labor market costs (up to about $30 billion) to reinvigorate coal communities, would still yield positive net benefits. While the IRA subsidizes clean energy project investments in coal communities (USDT, 2023), the present analyses suggest a more robust and targeted solution, as suggested by experts and key stakeholders (Hanson, 2022; Ngo, 2023), is warranted.

Using the forecasted damages for remaining coal plants from 2020 to 2035, we find that buying out the coal fleet (at its net book value of roughly $176 billion) or replacing it with natural gas generators (at costs amounting to $304 billion) would result in large benefits ($589 billion). Buyouts (or replacements) focused on facilities where the marginal benefits exceed the marginal costs would maximize net benefits at $452 billion (or $379 billion), a 414% (or 240%) return on investment. Adopting a reverse auction program like that currently in Germany could facilitate the gradual removal of U.S. coal through a quasi-competitive process. However, we recommend bid adjustments based on SO_2 emissions or, better yet, air pollution damages. Notably, the costs of an auction-based retirement policy would likely be far less than we suggest because participating firms may be willing to accept lower bids to guarantee a payout rather than weather difficult and uncertain market conditions. Alternatively, policymakers could catalyze competition and mitigate the impacts to the U.S. energy system by using a multipronged, holistic policy approach like the German policy, including possible forced closures and sufficient capacity planning (Scott *et al.*, 2022).

The movement away from coal in the U.S. is a polarizing subject. This study demonstrates the clear case for a swift but just energy transition. We use BCA to show that society could be far better off without coal while achieving the conditions of a Pareto improvement. There are critical points to emphasize. First, in either the retrospective or the prospective case, any transfer of financial resources will depend on a federal revenue stream since actual cash benefits do not accrue to communities experiencing improved air quality. As previously discussed, one strategy to generate funds would be to tax economic activities that produce negative externalities. Second, our baseline assumption is that natural gas replaces coal capacity. We further assume a worst-case scenario in which GHG reductions from coal are entirely offset by upstream methane leakage from natural gas (Gordon *et al.*, 2023). The result of these assumptions is to attenuate benefits. This component of our analysis incorporates the costs of avoiding adverse power system impacts such as power shortages and disruptions. Specifically, we consider the costs of federally funded coal plant replacement.[26] This assumption, like many others in this research, tends to increase costs and lower net benefits. Our analysis shows that even with assumptions that tend to emphasize more costs, moving away from coal-fired power yields substantial social net benefits.

The overwhelmingly positive net benefits associated with the continued removal of coal capacity do not negate that there are families and communities whose livelihoods depend on coal. However, a cooperative path forward appears attainable. In April 2021, the United Mine Workers of America (UMWA) expressed willingness to support and participate in the transition toward a less polluting energy economy (UMWA, 2021). Crucially, the UMWA requested solutions and resources to help preserve coal communities. Our analysis can inform this discussion. We conclude by noting that our empirical estimates of both benefits and costs are provisional. However, the large and robust net social benefits associated with less coal-fired power generation suggest that carefully crafted policies can ensure a just transition for coal communities while clearing the air.

Supplementary material. The supplementary material for this article can be found at http://doi.org/10.1017/bca.2024.20.

Abbreviations. BLS, Bureau of Labor Statistics; CDC, Centers for Disease Control and Prevention; EIA, Energy Information Administration; EPA, Environmental Protection Agency; GEM, Global Energy Monitor; IWG, Interagency Working Group on Social Cost of Greenhouse Gases; NAS, National Academy of Sciences; NOAA, National Oceanic and Atmospheric Administration; NREL, National Renewable Energy Laboratory; RMI, Rocky Mountain Institute; USDT, United States Department of Treasury; UMWA, United Mine Workers of America.

Data availability statement. The datasets generated and/or analyzed for this article are available from the corresponding author upon reasonable request. Sample code developed for the study are available from the corresponding author upon reasonable request.

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[26] A federally funded replacement of the coal fleet is, candidly, superfluous. That said, assuming free markets will seamlessly substitute in for coal without considering the potential for deleterious effects is naïve. The best approach likely falls somewhere in between – for example, investment tax credits. Notably, natural gas is less damaging than coal (U.S. EPA's Clean Air Markets Division, 2022; NREL, 2023). Still, it emits excess amounts of GHGs, so our analytically conservative approach for an all-natural gas substitution should not be mistaken for an endorsement.

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