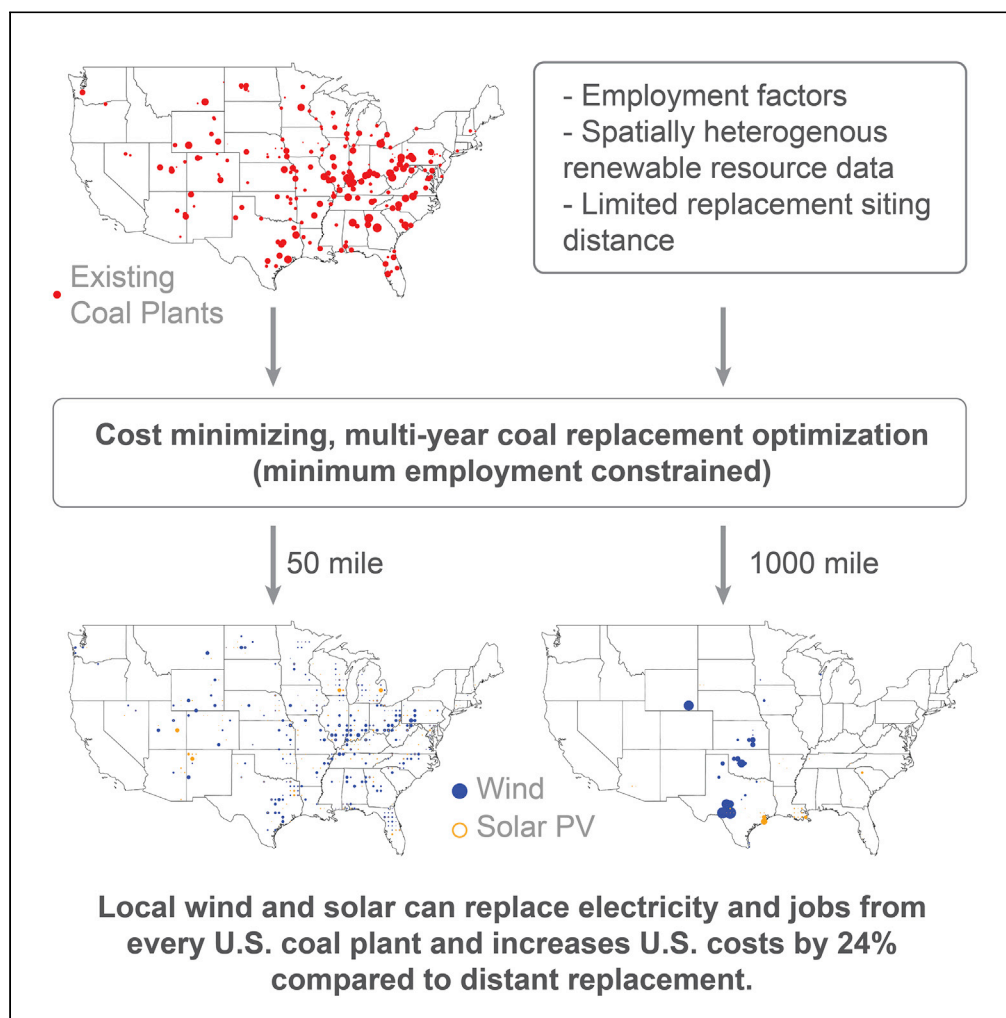


Article

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Highlights

We quantify costs of replacing coal plant with local versus distant renewable jobs

Local wind and solar can replace electricity and jobs from every U.S. coal plant

Replacing coal with local versus distant renewables increases U.S. costs by 24%

Cost increases are less than 10% for at least some coal plants in most U.S. regions

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Article

The costs of replacing coal plant jobs with local instead of distant wind and solar jobs across the United States

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SUMMARY

To further a just energy transition, jobs lost at retiring coal plants could be replaced by jobs at wind and solar plants. No research quantifies the feasibility and costs of such an undertaking across the United States. Complicating such an undertaking are workers' place-based preferences that could prevent them from moving long distances, e.g. to high renewable resource regions. We formulate a bottom-up optimization model to quantify the technical feasibility and costs of replacing coal plant jobs with local versus distant jobs in the renewables sector. For the contiguous United States, we find replacing coal generation and employment with local wind and solar investments is feasible. Siting renewables local to instead of distant from retiring coal plants increases replacement costs by 5%–33% across sub-national regions and by \$83 billion, or 24%, across the United States. These costs are modest relative to overall energy transition costs.

INTRODUCTION

Aggressively mitigating climate change will require deep, sustained reductions in carbon dioxide (CO₂) emissions (IPCC, 2018, 2014). Since electric power is the cheapest sector to decarbonize (Deep Decarbonization Pathways Project, 2015; IPCC, 2014), much of the early emission reductions have already (U.S. Energy Information Administration, 2021a; U.S. Environmental Protection Agency, 2021) and will likely continue to (Grubert, 2020; Jenkins et al., 2021) come from reductions in generating electricity using fossil fuels. Many decarbonization pathways retire most or all coal-fired power plants within the next 10–20 years (Grubert, 2020; Jenkins et al., 2021). Electricity generation from retired coal-fired power plants will need to be replaced by new low-carbon sources of electricity. Beyond CO₂ emissions, retiring coal-fired power plants has economic, environmental, and social impacts (Carley and Konisky, 2020; Mohai et al., 2009; Raimi et al., 2022; Richmond-Bryant et al., 2020). In this work, we focus on the employment dimensions of replacing electricity generation from coal-fired power plants with new low-carbon sources of electricity (Energy Futures Initiative and National Association of State Energy Offices, 2020; Jolley et al., 2019; U.S. Department of Energy, 2017a). Job losses can occur in direct, indirect, and induced jobs (Cameron and Van Der Zwaan, 2015). As of 2019, coal-fired electricity generation directly employed 79,711 workers (Energy Futures Initiative and National Association of State Energy Offices, 2020) across 43 U.S. states (U.S. Energy Information Administration, 2020).

Just and equitable energy transitions recognize historic and current inequities and injustices in electric power systems, and center these inequities and injustices in planning for a decarbonized future (Baker et al., 2019; Carley and Konisky, 2020; Jenkins et al., 2020; Sovacool and Dworkin, 2015). A just transition partly depends on how job creation and destruction is distributed across space, time, and racial demographics during the transition (Bridge et al., 2013; Healy and Barry, 2017; Mertins-Kirkwood, 2018). Employment changes will first play out in communities on the frontlines of the energy transition, including communities hosting coal-fired power plants (Carley and Konisky, 2020), the focus of our research. Diverse factors, including economics, policies, regulations, and social movements, have driven rapid and spatially heterogeneous coal plant retirements in the United States (Davis et al., 2022; Drake and York, 2021; Shrimali, 2022; U.S. Energy Information Administration, 2017). Aggressively mitigating climate change would significantly accelerate coal plant retirement timelines (Cui et al., 2019). Understanding how to achieve a just transition for coal plant workers is urgent given rapid coal plant retirements and consequent job losses in the United States and globally (Haerer and Pratson, 2015; International Renewable Energy Agency, 2018; U.S.

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[Department of Energy, 2017b](#)). Furthermore, understanding how to provide, and then providing, a just transition for coal plant workers can also enable just transitions in other frontline communities, including communities hosting other types of fossil fuel infrastructure.

Scarce research quantifies employment losses of coal plant closures and ways to compensate for those losses. Within the United States, [Patrizio et al. \(2018\)](#) quantify employment changes associated with mitigating coal-fired emissions through heat rate improvements, replacement with a natural gas plant, co-firing with forest residues, retrofit with carbon capture and sequestration (CCS), or retrofit with CCS and co-firing with biomass. Outside the United States, studies have quantified employment shifts from replacing coal plants with wind and solar power in Europe ([Kamideliwand et al., 2018](#)), India ([Sharma and Banerjee, 2021](#)), China ([Zhang et al., 2022](#)), and globally ([Pai et al., 2021](#)).

Despite rapid growth of wind and solar power in the United States, existing research has not quantified the employment consequences of replacing coal-fired generation with wind and solar generation across the United States. Complicating this analysis are strong community ties of coal plant workers in the United States, which can prevent former plant workers from moving in pursuit of new jobs ([Bridge et al., 2013](#); [Carley et al., 2018](#); [Cha et al., 2021](#)). This is particularly problematic if shifting coal plant jobs to wind and solar jobs, as wind and solar plants are dependent on spatially heterogeneous resources that might poorly align with the locations of existing coal plants. Existing research has not quantified the feasibility and consequences of replacing coal plant jobs with local wind and solar jobs.

In this research, we fill both research gaps by answering the following research question: How does replacing coal jobs with local versus distant renewable energy jobs affect system costs and investment decisions? In answering this question, we aim to contribute to a nascent just transition literature by providing new insights into replacing coal plant jobs while capturing technical, economic, and social factors.

We develop a bottom-up model that optimizes when each coal-fired power plant is retired and, to replace retired coal plants, where and when investments in wind and solar power occur. The model accounts for spatial heterogeneity in coal plant sites and wind and solar resources and capital costs. The model also includes a maximum distance constraint on where replacement wind and solar plants can be sited relative to a retiring coal plant, which we refer to as “siting limits”. To quantify the trade-offs of replacing coal plant jobs locally versus in distant locations on a plant-by-plant basis, we analyze three siting limits: 50, 500, and 1,000 miles. Given our renewable resource data resolution (see Experimental Procedures), the 50 mile limit approximates local renewable investments and associated jobs that do not require relocation. Conversely, the 1,000 mile limit allows renewable investments to occur in high-quality resource regions, generating jobs that would require relocation.

RESULTS

Renewable energy employment can fully replace coal employment

Coal plant retirements and renewable replacements will interact with one another across space and time, which we capture by running our model through 2031 for multi-state regions spanning the contiguous United States ([Table 1](#)). As each coal plant within the analyzed region retires, our model requires new renewable investments to replace that retiring coal plant’s electricity generation and employment in each year after retirement (see [supplemental information \(SI\)](#) for transition pathways). [Figure 1](#) provides annually recurring renewable employment after all coal plants retire by 2030 (see Methods). Across most regions and siting limits, annual renewable energy employment fully replaces but does not exceed coal employment. Annual renewable energy employment exceeds coal employment only at 50 mile siting limits for several regions, most notably the West and Midwest. This occurs when more renewable investment is required to replace annual coal plant generation instead of employment, i.e. when our model’s generation constraint is binding. Operations and maintenance (O&M) accounts for most (57%–92%) replacement employment at wind and solar facilities. Construction jobs play a lesser role, in part, because investments must be made each year to replace annual coal O&M jobs with renewable construction jobs. Replacement employment is also mostly from O&M jobs on a per-plant basis (see SI for distribution across plants).

Wind and solar employment contribute to replacing coal employment. However, solar employment generally exceeds wind employment, accounting for 46%–74% of replacement employment. As the siting limit tightens, wind employment O&M increases because lower quality wind resources increase installed

Table 1. Description of the eight regions into which we divide our coal plants and run through our model

Region	States	Number of coal plants	Coal capacity [MW]	Coal annual generation [TWh]	Average coal capacity factor	Coal O&M employment [job-years]	Annual coal CO ₂ emissions [million tons]
Central (CN)	KY, OH, VA, WV	38	40,930	159.43	0.44	5,730	171.27
Midwest (MW)	IL, IN, MI, WI	46	42,971	161.91	0.43	6,016	179.13
Northeast (NE)	CT, DE, MA, MD, ME, NH, NJ, NY, PA, RI	30	17,729	44.67	0.29	2,482	49.36
Northern Plains (NP)	IA, MN, ND, NE, SD	32	18,220	86.91	0.54	2,551	100.23
South Central (SC)	AR, KS, LA, MO, OK	30	27,624	107.98	0.45	3,867	119.80
Southeast (SE)	AL, FL, GA, MS, NC, SC, TN	28	41,657	125.16	0.34	5,832	134.28
Texas (TX)	TX	15	19,058	91.83	0.55	2,668	104.72
West	AZ, CA, CO, ID, MT, NM, NV, OR, WA, WY, UT	37	28,719	139.99	0.56	4,021	157.40
Total		256	236,908	917.87	0.44	33,167	1,016.19

Note that wind and solar investments can occur in locations outside each region if they are within the scenario-specific siting limit from the relevant coal plant. The map of these coal plants is shown in figure within the [STAR Methods](#) section.

capacities, which in turn increases O&M employment, in all but two regions. In those two regions, the West and Midwest, solar instead of wind O&M employment increases from 1,000 to 50 mile siting limits. This occurs due to limited wind resource availability near retiring coal plants, favoring solar over wind deployment (see SI for wind and solar resource availability maps). Replacing coal generation, though, requires significant investments in solar capacity, producing significant solar O&M employment. On a cumulative basis from 2020 through 2031, employment increases in all regions due to renewable construction employment (see SI for cumulative employment in each region).

Optimal replacement of coal plants includes wind and solar plants

In replacing coal with renewable generation and employment, our model controls where, when, and how much wind and solar investment occurs. Across regions and siting limits, retiring coal plants are replaced with a mix of wind and solar power (Figure 2). Investing in wind and solar power balances the model's regional cost minimization objective and its constraints to replace annual plant-level employment and

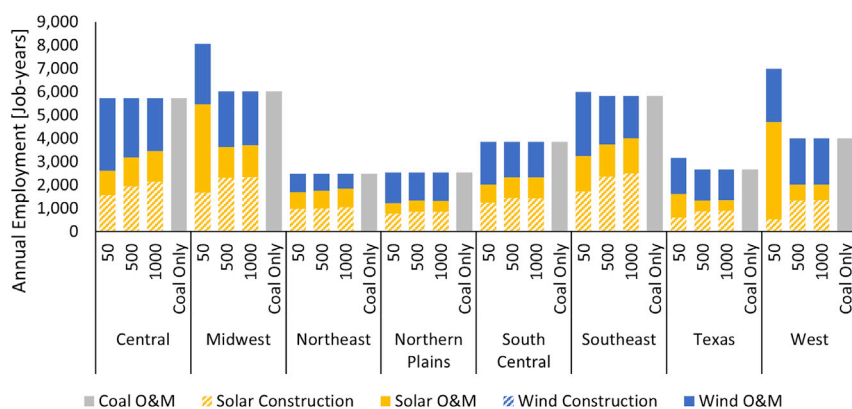


Figure 1. Renewable energy employment can fully replace coal employment

Annual construction (solid) and O&M (striped) employment (in job-years) from solar (yellow) and wind (blue) plants in 2031 at siting limits of 50, 500, and 1,000 miles. 2031 is the final year of our analysis, at which point all coal plants are retired. For comparison, O&M employment from coal plants (gray) at the beginning of our analysis (2020) is also provided. Regions are defined in [Table 2](#).

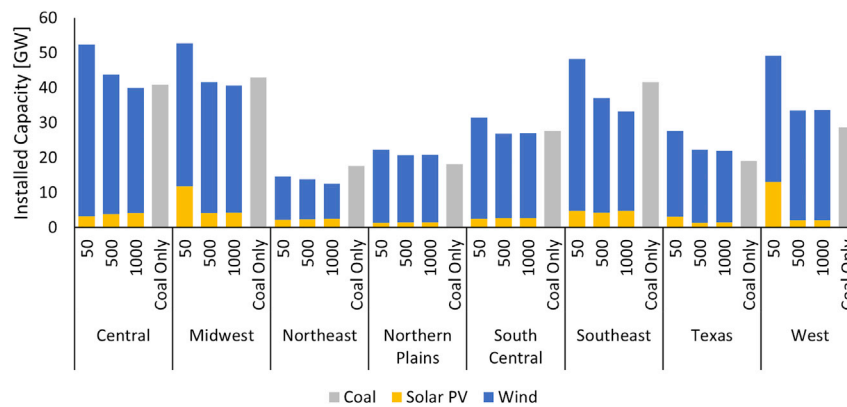


Figure 2. Optimal replacement of coal plants includes wind and solar plants

Installed wind (blue) and solar (yellow) capacity in 2031, the final year of our analysis, at 50, 500, and 1,000 mile siting limits. For comparison, initial (2020) installed coal plant capacity (gray) is also provided.

generation. Wind offers more cost-effective electricity generation in most locations, while solar offers more cost-effective employment. Across regions and siting limits, solar power constitutes 6%–27% of replacement capacity, with wind power making up the remainder. Since solar has higher employment factors than wind (Table 2), its contribution to employment (Figure 2) exceeds its contribution to total capacity (Figure 2).

Imposing siting limits shifts renewable investments and consequent employment closer to retiring coal plants

At a 1,000 mile siting limit, investments occur in the highest available wind and solar resource locations, which are largely in the central United States (Figure 3). These investments and their associated employment largely occur far from retiring coal plants within each region. Because investments exploit high-quality resources, final installed wind and solar capacity are less than initial coal-fired capacity in five regions (Figure 2). Tightening the siting limit from 1,000 to 50 miles eliminates the ability of the model to concentrate investments in high resource locations. Instead, investments must occur within 50 miles of retiring coal plants, resulting in wind and solar investments and associated jobs distributed throughout each region (Figure 3). Because sites nearby coal plants often have poor wind and solar resources, final installed wind and solar capacity exceeds initial coal-fired capacity at a 50 mile siting limit in all regions except New England (Figure 2). Solar investments do not vary substantially with tightening siting limits except for the West and Midwest regions, where tightening the siting limit from 1,000 to 50 miles increases installed solar capacity from 2 to 13 and 4 to 12 GW, respectively, due to limited availability of wind resources near coal plants (see SI for wind and solar resource availability maps).

Imposing siting limits increases regional system costs by up to 33%

Changes in renewable investments caused by tightening the siting limit from 1,000 to 50 miles increases total coal replacement costs by 5%–33% across regions (Figure 4). Due to the capital intensiveness of wind and solar power, 82%–84% of costs associated with wind and solar deployment are capital costs. Of those capital costs, wind dominates because wind deployment significantly exceeds solar deployment (Figure 2). Heterogeneity in regional cost increases largely reflects heterogeneity in available renewable resources. For example, in the Northern Plains, a 50 mile siting limit provides access to high-quality wind resources, resulting in a small cost increase of 5% (\$2 billion) relative to a 1,000 mile siting limit (Figure 4). Conversely, in the Southeast, tightening the siting limit from 1,000 to 50 miles shifts investments from high-quality wind resources to a mix of solar and low-quality wind resources, increasing costs by 33% (\$20 billion).

Tightening renewable siting limits modestly increases costs for many coal plants

While our model runs regionally to capture interactions between retirements and investments, it replaces employment and electricity generation on a per-retiring-coal-plant basis by mapping wind and solar investments to specific retiring coal plants. Significant heterogeneity exists in the costs of replacing retiring coal

Table 2. Construction and O&M EFs and sources for coal, wind, and solar used across our study region

	Coal	Wind	Solar
Construction EFs (job-years/MW)	N/A	0.91 (U.S. National Renewable Energy Laboratory, 2020)	6.5 (Mayfield et al., 2019)
O&M EFs (job-years/MW/year)	0.14 (Ram 2et al., 2020)	0.07 (U.S. National Renewable Energy Laboratory, 2020)	0.45 (Mayfield et al., 2019)
Decline factors for construction EFs	N/A	1.0%–4.4% (U.S. National Renewable Energy Laboratory, 2021a)	0.5%–7.2% (U.S. National Renewable Energy Laboratory, 2021a)
Decline factors for O&M EFs	0% (U.S. National Renewable Energy Laboratory, 2021a)	0.7%–0.9% (U.S. National Renewable Energy Laboratory, 2021a)	0.5%–3.8% (U.S. National Renewable Energy Laboratory, 2021a)

One job-year equals one full-time employee (FTE) for one year. Construction employment occurs in the year of investment in a wind or solar facility, whereas O&M employment occurs in each year of the facility's lifetime. Ranges reflect changing values across our study horizon, with values declining over time (see SI for all values).

plants with renewables (Figure 5). Across coal plants, replacement costs span three orders of magnitude, ranging from \$6.4 million to \$5.8 billion at a 1,000 mile siting limit and from \$6.5 million to \$8.4 billion at a 50 mile siting limit, with increasing coal plant capacity generally relating to increasing replacement costs. As these ranges indicate, tightening siting limits, e.g. from 1,000 to 50 miles, increases replacement costs at all but two coal plants. At those two coal plants, both of which are located in the Northern Plains, costs decrease by 7% from 1,000 to 50 mile siting limits because they retire significantly earlier at 1,000 than 50 mile siting limits and excellent renewable resources are available at 50 miles. At all other coal plants, cost increases from 1,000 to 50 mile siting limits range as high as 110%. All regions except the Southeast and West have coal plants with low (less than 10%) cost increases from 1,000 to 50 mile siting limits. The Southeast has particularly high per-plant cost increases from 1,000 to 50 mile siting limits due to its poor local renewable resources.

Results are robust across sensitivities

We quantify the robustness of our results to four sensitivities: limiting investments only to solar power, using lower wind employment factors (EFs), using lower and higher solar and wind costs, and using a reduced (3.5%) discount rate, respectively (Table 3). We run these sensitivities for 50 and 1,000 mile siting limits for the Central, West, Texas, and North Plains regions, which represents the diversity of results in our base case. Across non-solar-only sensitivities, wind investments dominate solar investments, as in the base case. Furthermore, cost increases from 1,000 to 50 mile siting limits are similar between non-solar-only sensitivities and the base case. The key exception is when limiting investments to only solar in the North Plains, which results in an 8-fold larger increase in costs from 1,000 to 50 mile siting limits relative to the base case. This increase largely reflects the modest cost increase in the North Plains in the base case due to high-quality wind resources nearby retiring coal plants (Figure 4). Total costs of replacing coal plants are largely similar across wind employment factors (EFs) and capital cost sensitivities (changing by less than 1% and 7%, respectively, from base case costs). When limiting investments only to solar plants, total costs significantly increase for all regions and siting limits (by 32%–82% from the base case). Overall, our results are robust to sensitivity analyses on wind EFs and wind and solar capital costs, but limiting investments only to solar would significantly change investment patterns, replacement costs, and the costs of creating local instead of distant jobs for several regions. For more results and discussion, see the SI.

DISCUSSION

To further a just transition for communities hosting coal plants, we quantified the cost and investment trade-offs of replacing electricity generation and jobs at retiring coal plants with those at local versus distant wind and solar plants. To quantify these trade-offs, we formulated an optimization model that chooses coal plant retirements and replacement renewable investments while accounting for costs, employment, generation, and the distance between retiring coal plants and replacement renewables. We then

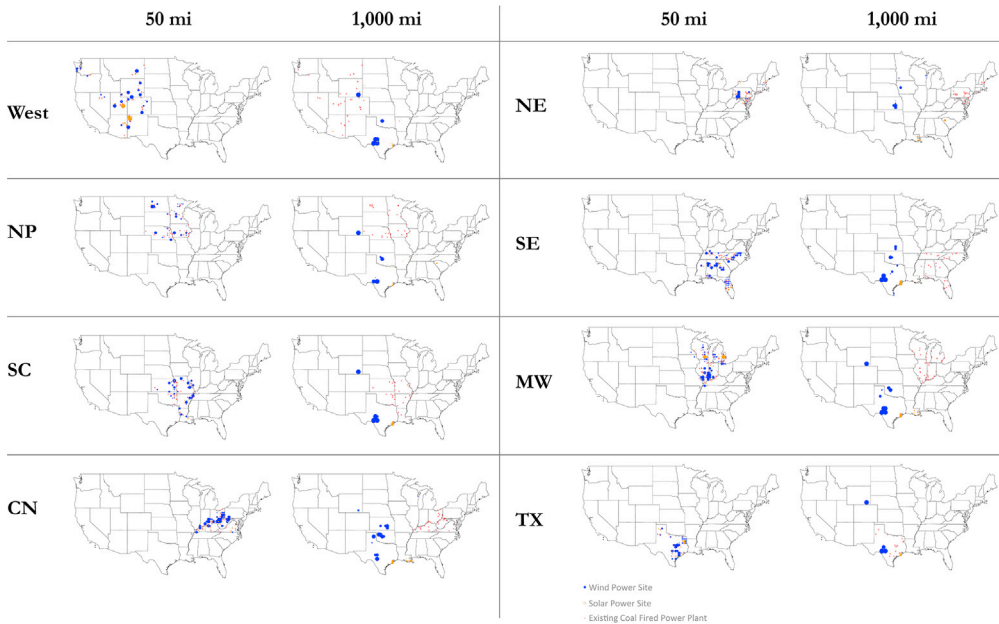


Figure 3. Imposing siting limits shifts renewable investments and consequent employment closer to retiring coal plants

Locations of existing coal plants and wind and solar plant investments that replace those coal plants by region at 50 (left columns) and 1,000 mile siting limits (right columns).

applied this model to all coal plants in the contiguous United States assuming a full phase out of coal plants through 2030.

We found investments in wind and solar plants can replace electricity generation and employment on an annual basis for each U.S. coal plant at coal-to-renewable siting limits as low as 50 miles. Siting renewables within 50 instead of 1,000 miles of retiring coal plants, which would keep employment local, would increase replacement costs for the U.S. coal plant fleet by \$83 billion, or 24%. These costs are significant in isolation, but are small relative to annual power investments (\$70 billion (U.S. Energy Information Administration, 2018a, 2018b)) and to the total costs of the energy transition (as high as \$900 billion by 2030 (National Academies of Sciences Engineering and Medicine, 2021)). Thus, our results indicate replacing lost jobs in coal

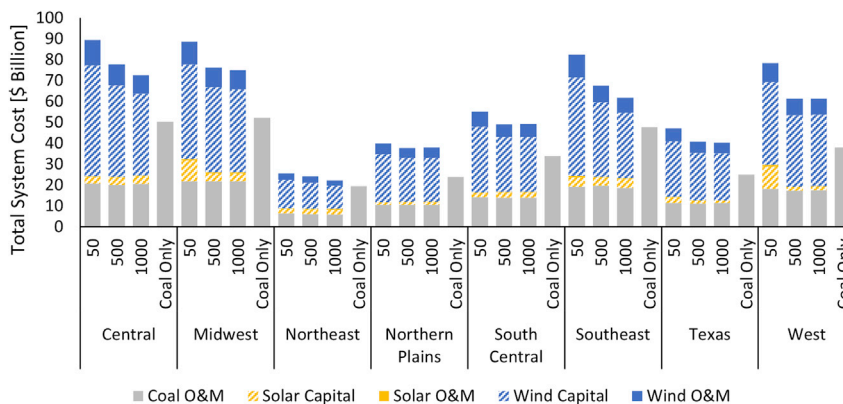


Figure 4. Imposing siting limits increases regional system costs by up to 33%

Total system costs divided into coal (gray) O&M (solid) costs and wind (blue) and solar (yellow) construction (striped) and O&M costs from 2020 through 2031 at 50, 500, and 1,000 mile siting limits for each region. For comparison, system costs assuming no coal retirements or renewable investments are also provided.

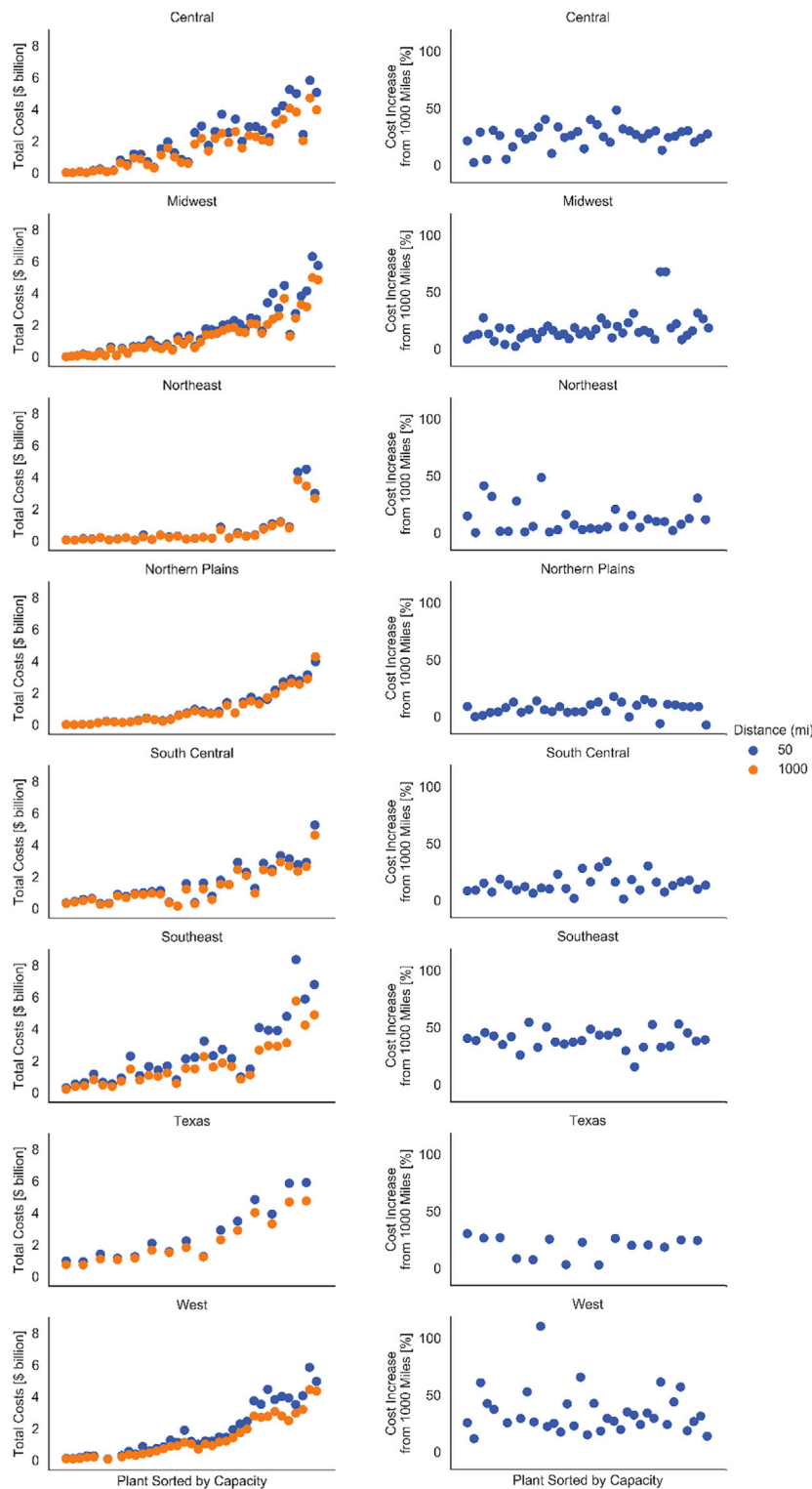


Figure 5. Tightening renewable siting limits modestly increases costs for many coal plants

Left column: Total system costs of coal plant replacement across siting limits. Right column: the percent increase in total costs from 1,000 to 50 mile siting limits. Each row corresponds to a region, and each dot represents one coal plant. Plants are sorted in order of increasing capacity, such that the order of power plants for a given region is preserved across plots.

plant communities would modestly increase overall energy transition costs while significantly furthering a just transition for one category of frontline communities. Furthermore, within most regions, coal plants exist with low-cost increases for replacing coal plants with local instead of distant renewables. While a just transition for all U.S. coal plant communities might not be feasible, ample opportunity exists for just transitions for numerous coal communities at small cost increase.

Several categories of actors can help achieve local replacement of coal with renewables. Federal policy-makers could introduce a new Investment Tax Credit (ITC) that is only applied to wind and solar projects that are located near retiring coal plants and that employ retrained coal plant workers. The current ITC defrays 10% of solar capital costs (U.S. Congressional Research Service, 2021). That same amount would overcome the cost differential of replacing coal with local instead of distant renewables for 61 coal plants, which are spread across all but two of our study regions. In states with vertically integrated utilities, public utility commissions (PUCs) must approve utility investment plans, e.g. as put forward in an Integrated Resource Plan. PUCs could consider approving additional expenses of local renewables given their social benefits.

To quantify employment impacts, we use job-year as our unit of analysis. In replacing coal plant O&M job-years with wind and solar construction and O&M job-years on an annual basis, we avoid solutions that replace long-term coal plant employment with short-term renewable employment, e.g. with large numbers of construction jobs that only last for one or two years. Jobs in coal versus wind and solar plants vary in other ways that we do not capture. Coal plant jobs might require different skills than construction and/or O&M jobs in wind and solar plants. Our analysis does not capture any consequent workforce retraining requirements for shifting coal plant workers to renewable construction or O&M. However, Louie et al. (Louie and Pearce, 2016) find 43% of coal plant workers could transition to solar jobs without retraining. Furthermore, retraining costs would not differ significantly with job relocation distance. Thus, we do not expect that accounting for retraining costs would significantly affect our results regarding cost trade-offs between replacement renewables sited in local versus distant locations. Jobs in coal, wind, and solar plants might also have different wages, benefits, and/or unionization rates. Across coal, wind, and solar plants, wages are similar by industry segment, e.g. utilities, construction, or repair and maintenance (National Association of State Energy Offices et al., 2021), indicating wages would be similar for workers that stay in the same industry segment. However, to maintain annual employment, we found ongoing construction of renewables is required to some extent in all regions, which might shift workers from higher utility wages at coal plants to lower construction wages at wind plants.

Our research quantifies the feasibility and costs of transitioning coal plant workers to renewable workers across the United States for the first time. Communities hosting coal plants are not the only frontline communities in the ongoing energy transition. Other frontline communities include communities that host other fossil assets, have historically lacked access to jobs in the energy sector, and/or bear disproportionate burdens from energy costs (Bednar and Reames, 2020; Drehobl et al., 2020) or air pollution (Mohai et al., 2009; Richmond-Bryant et al., 2020). For the former two types of communities, our approach could be expanded to inform a just transition through updated inputs and constraints for where new investments can be sited. For the latter two types of communities, our model's constraints could be expanded to account for the needs of these communities, e.g. by incorporating marginal health damages of individual coal plants in making retirement decisions.

Table 3. Sensitivity analysis names and descriptions completed in our study

Sensitivity	Alternative Wind and Solar Capital Costs	Low Wind Employment Factors	Solar Only Replacement	Reduced Discount Rate
Description	Wind CAPEX and FOPEX values increased by 10%. Solar CAPEX and FOPEX values decreased by 10%.	Wind construction and O&M EFs decreased to 0.43 job-years/MW and 0.05 job-years/MW, respectively, which correspond to 500 instead of 57 MW wind farms (U.S. National Renewable Energy Laboratory, 2020)	Only solar renewable sites are eligible for investment.	Discount rate decreased to 3.5%

Limitations of the study

Future research can expand our work in several other ways. First, coal-fired generation will likely be replaced by a combination of new renewable investments, which we capture, and increased utilization of existing natural gas plants, which we do not capture. The extent to which existing assets replace coal plant generation will reduce the extent to which renewable employment can offset coal employment. Second, we ignore cost and system consequences of sub-annual variability in wind and solar generation. Renewable integration costs are generally modest relative to capital costs and increase with renewable penetrations (Hirth et al., 2015). Under tighter siting limits, renewable investments shift from high to low renewable resource and penetration regions. Thus, accounting for integration costs would likely result in a smaller cost increase from replacing coal plant jobs with local instead of distant renewable jobs. Future research could add integration costs or capacity credits to our model or use a capacity expansion (CE) model, although CE models generally sample a small number of days per year.

Finally, coal plant workers could be transitioned to non-energy-sector jobs. However, given needed growth in renewables during the energy transition and overlapping skill sets between coal plant and renewable workforces (Louie and Pearce, 2016), transitioning coal plant workers to renewables would likely provide win-win opportunities. This is especially true if renewable employment can replace coal employment at a local level. Our analysis indicates this course of action is not only feasible, but also of modest costs for many power plants across the nation, providing a pathway for a just transition for coal plant communities.

STAR★METHODS

Detailed methods are provided in the online version of this paper and include the following:

- KEY RESOURCES TABLE
- RESOURCE AVAILABILITY
 - Lead contact
 - Materials availability
 - Data and code availability
- METHOD DETAILS
 - Coal retirement and renewable investment model
 - Data
 - Scenarios and sensitivity analyses

SUPPLEMENTAL INFORMATION

Supplemental information can be found online at <https://doi.org/10.1016/j.isci.2022.104817>.

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AUTHOR CONTRIBUTIONS

Conceptualization and resources, M.T.C.; Methodology and Software, M.V., I.B., J.F., B.R., D.S., and M.T.C.; Investigation, M.V., I.B., J.F., B.R., and M.T.C.; Writing, M.V. and M.T.C.; Visualization, M.V.; Supervision, M.T.C.

DECLARATION OF INTERESTS

The authors have no interests to declare.

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STAR★METHODS

KEY RESOURCES TABLE

REAGENT or RESOURCE	SOURCE	IDENTIFIER
Deposited data		
Coal and Renewable capital and O&M costs (2021 NREL ATB)	National Renewable Energy Laboratory	https://atb.nrel.gov/electricity/2021/data
Employment factors	This paper (see SI)	
Wind capacity factors and maximum potential installed capacities (NREL Wind Supply Curve)	National Renewable Energy Laboratory	https://www.nrel.gov/gis/wind-supply-curves.html
Solar capacity factors and maximum potential installed capacities (NREL Solar Supply Curve)	National Renewable Energy Laboratory	https://www.nrel.gov/gis/solar-supply-curves.html
Existing coal plant parameters (EIA Form 860)	US Energy Information Agency	https://www.eia.gov/electricity/data/eia860/
Historical Coal Generation (EIA Form 923)	US Energy Information Agency	https://www.eia.gov/electricity/data/eia923/
Inputs for coal retirement and renewable investment model	This paper	https://doi.org/10.5281/zenodo.6818249
Software and algorithms		
Pyomo optimization language (6.1.2)	Pyomo Development Team	http://www.pyomo.org/
CPLEX optimization solver (20.1.0)	IBM	https://www.ibm.com/analytics/cplex-optimizer
Coal retirement and renewable investment model	This paper	https://doi.org/10.5281/zenodo.6818249

RESOURCE AVAILABILITY

Lead contact

Further information and requests for resources and reagents should be directed to and will be fulfilled by the lead contact, Michael Craig (mtcraig@umich.edu).

Materials availability

This project did not generate new materials.

Data and code availability

- All data have been deposited at Zenodo and are publicly available as of the date of publication. DOIs are listed in the [key resources table](#).
- All original code has been deposited at Zenodo and is publicly available as of the date of publication. DOIs are listed in the [key resources table](#).
- Any additional information required to reanalyze the data reported in this paper is available from the [lead contact](#) upon request.

METHOD DETAILS

Coal retirement and renewable investment model

To quantify trade-offs between jobs and costs across space associated with coal retirement and renewable investment decisions, we construct a mixed integer linear program (MILP). The MILP optimizes for retirements of coal plants on a plant-by-plant basis. For each retired coal plant, the MILP optimizes investment in wind and/or solar plants (hereafter “renewable plants”). Investment and retirement decisions are driven by several key constraints, detailed below, and the model’s objective, which is to minimize fixed investment plus variable operational costs:

$$\min \sum_{c,r,y} \frac{(FOM_{c,y} \times P_c^{MAX} + VOM_{c,y} \times GEN_c) \times o_{c,y} + FOM_{r,y} \times p_{c,r,y} + OCC_{r,y} \times p_{inv_{c,r,y}}}{(1 + DR)^y}$$

where c , r , and y index coal plants, renewable sites, and years, respectively; FOM = fixed O&M costs [\$/MW]; VOM = variable O&M costs [\$/MWh]; P^{MAX} = nameplate capacity [MW]; GEN = historical annual generation [MWh]; o = binary variable indicating whether coal plant is online (1) or offline (0); p = cumulative renewable capacity investments [MW]; OCC = overnight capital costs [\$/MW]; p_{inv} = new renewable capacity investments in a given year [MW]; and DR = annual discount rate [%].

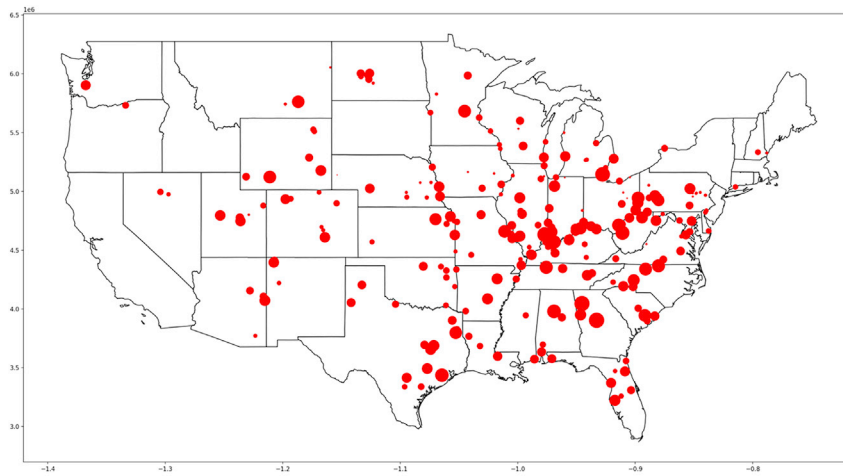
To force retirement of coal-fired power plants and to generate insights relevant to a transition away from coal-fired generation, we constrain total CO₂ emissions from all coal plants to decline linearly to zero from 2021 through 2030. While 73% of fossil fuel plants are slated for retirement prior to 2035 (Grubert, 2020), we bring the full retirement of coal plants forward to 2030 in alignment with the U.S. goal of 50% greenhouse gas (GHG) emissions reductions from 2005 levels by 2030 (Horowitz et al., 2022). Our model runs from 2020 through 2031 at annual resolution to capture this forced retirement period while also gaining insight into steady state employment effects after all coal plants retire. For each coal plant, total CO₂ emissions reflect 2019 generation levels, which we assume do not change over our study period unless the unit is retired (at which point generation and emissions become zero). This simplifying assumption is necessary absent a long-term planning optimization model for the power system, which would miss key features we examine here (e.g., retirement decisions with highly spatially resolved features). For each retired coal plant, constraints require the retired plant's generation is replaced entirely by generation from investments in renewable plants. Renewable investments' capacities and generation levels are limited by renewable energy densities and site-specific resources, respectively (see Renewable Data section). We use spatially-explicit renewable resources to calculate generation and assume, like with coal plants, renewable generation does not change over our study horizon. Renewable investments must also be less than a distance threshold from the retiring coal plant. We manipulate this distance threshold via scenario analysis (see Scenario Analysis section). Total employment across renewable investments replacing a coal plant must be greater than or equal to that coal plant's historical employment. This inequality is enforced in each year following the coal plant's retirement, and accounts for operations and maintenance (O&M) jobs at coal plants and construction and O&M jobs at renewable plants.

For our model's full formulation, see the SI. We code our model in the Pyomo optimization language (Hart et al., 2011) and solve it using CPLEX Version 20.1 (IBM, 2022).

Data

Existing coal plant data

We parameterize the existing coal plant fleet (see below figure) using 2019 data from the Energy Information Administration Form 860 (U.S. Energy Information Administration, 2020) and Form 923 (U.S. Energy Information Administration, 2021b). From Form 860, we obtain the nameplate capacity, latitude, longitude, operational status, and ORIS code for each coal plant. We identify coal plants as any plant with technology type containing the word "Coal", and further narrow our analysis to operational coal plants using operational status of "OP". For computational tractability, we aggregate generator data to the plant level by summing generator nameplate capacities. To obtain observed plant-level generation for 2019, we use Form 923 (U.S. Energy Information Administration, 2021b). We map Form 860 to Form 923 data using plants' ORIS codes. To analyze the replacement only of coal-fired electricity generation, we filter out non-coal-fired generators using fuel types from Form 923. For remaining generators at each coal plant, we sum total fuel consumption and electricity fuel consumption from Form 923 to estimate annual plant-level values. We then filter out plants that use less than 20% of their fuel consumption for electricity generation, thereby removing combined heat and power and other largely non-electricity-generating coal facilities. For remaining coal plants, we sum generator-level net generation provided by Form 923 to estimate annual plant-level net electricity generation. This plant-level net generation is replaced by generation from renewables when a coal plant is retired by our model. Using the same filtering process, we calculate annual CO₂ emissions for each facility using generator-level emissions collected by the EIA (U.S. Energy Information Administration, 2021c). From these steps, we obtain the set of coal plants operational across the contiguous United States in 2019 and their location (state, latitude, and longitude), nameplate capacity, annual generation, and annual CO₂ emissions.



Coal-fired power plants in United States

Bubbles are scaled by plant capacity, which ranges from 5 to 3,500 MW.

Wind and solar resource data

For each coal plant retired, the model must replace its generation and employment each year following retirement with investments in wind and/or solar plants. In investing in wind and solar plants, the model selects from 3,240 sites with site-specific annual capacity factors and maximum potential installed capacities. We obtain site-specific annual capacity factors and maximum potential installed capacities from the reference case of the U.S. National Renewable Energy Laboratory's wind and solar supply curves (U.S. National Renewable Energy Laboratory, 2021b, 2021c), which correspond to meteorological years 2007 through 2013. To achieve computational tractability while capturing spatial heterogeneity in wind and solar resources, we aggregate these sites via an area-weighted average into a 0.5 by 0.5° grid across the contiguous United States. These supply curves account for infrastructure, regulatory, and physical land exclusions relevant to wind and solar power, e.g. airports and public lands, and spatially-explicit wind and solar resources (Cole et al., 2021; Lopez et al., 2021). In replacing annual rather than sub-annual generation from retired coal plants, we maintain computational tractability while accounting for the fact that other resources besides from new renewable investments would contribute to system balancing.

Employment data

Two main methods exist to estimate employment or employment factors in the energy sector: input-output and survey-based methods (Cameron and Van Der Zwaan, 2015; Energy Futures Initiative and National Association of State Energy Offices, 2020; Haerer and Pratson, 2015; International Renewable Energy Agency, 2018; Llera et al., 2013; Ortega et al., 2015; Tegen et al., 2015; U.S. Department of Energy, 2017b, 2017a; Wei et al., 2010). Employment encompasses direct, indirect, and/or induced jobs. Direct jobs include construction and O&M jobs at coal or renewable plants; indirect jobs include jobs at upstream suppliers, e.g. at coal mines; and induced jobs include jobs incurred by consumption expenditures of direct and indirect jobs, e.g. at restaurants.

Given the highly variable and hard-to-measure nature of indirect and induced jobs and given our analytical focus on replacing coal plant jobs, we focus our analysis on direct jobs, i.e. on replacing coal plant O&M jobs with renewable construction and O&M jobs. In replacing coal O&M jobs with renewable construction and O&M jobs, we use job-years as our unit of analysis, which indicates full-time employment for one person for one year. Our model requires job-years from O&M jobs at each retired coal plant to be less than or equal to job-years from construction plus O&M jobs at renewable investments in the year each coal plant retires and every year thereafter. This approach differentiates construction jobs, which occur in a single year during construction, and O&M jobs, which last the plant's lifetime. We assume all renewable sites are built within one year, so all construction jobs occur within the year of renewable investment.

Even with our focus only on direct jobs, significant variability exists in the literature on coal, solar, and wind employment factors. For each technology, we quantify direct jobs using employment factors (EFs) defined as job-years per unit of installed capacity. [Table 2](#) provides the employment factors we use in our analysis. Solar EFs are for utility-scale solar and utility-scale solar additions in ([Mayfield et al., 2019](#)). Wind construction and O&M EFs are from the Jobs and Economic Development Impact (JEDI) model ([U.S. National Renewable Energy Laboratory, 2020](#)). Specifically, we use on-site job estimates (“construction and interconnection labor” for construction and “onsite labor” for O&M) for a 57 MW wind farm, the median wind farm size in the United States ([U.S. Energy Information Administration, 2020](#)). Coal O&M EFs are from ([Ram et al., 2020](#)). The above EFs are U.S.-centric, so relevant to our area of analysis; up-to-date, so reflect recent EF declines; and comparable to other literature values and employment survey data ([Cameron and Van Der Zwaan, 2015](#); [Mayfield et al., 2019](#); [Nock and Baker, 2019](#); [Pai et al., 2020](#); [Ram et al., 2020](#); [U.S. National Renewable Energy Laboratory, 2020](#); [Wei et al., 2010](#)) (see SI for review of EFs). We also capture declines in EFs over time driven by learning-by-doing and economies of scale ([Cameron and Van Der Zwaan, 2015](#); [Llera et al., 2013](#)). We approximate annual EF declines by using the annual decline in capital and O&M costs for construction and O&M EFs, respectively ([Table 2](#)), similar to the method in ([Ram et al., 2020](#)). Since we assume coal plant generation does not change unless retired over our study horizon (see above), coal plant O&M jobs do not change unless a coal plant is retired, at which point O&M jobs go to zero at that coal plant.

Coal and renewable cost data

Our model’s objective is to minimize the discounted sum of annual fixed plus variable costs. Annual fixed costs equal capital costs of renewable investments each year, while annual variable costs equal O&M costs of non-retired coal plants plus operational wind and solar plants each year. We obtain all year-specific O&M costs and wind and solar capital costs from the U.S. National Renewable Energy Laboratory Annual Technology Baseline’s moderate technology innovation scenario ([U.S. National Renewable Energy Laboratory, 2021a](#)) (see SI). To capture spatial heterogeneity in capital costs, we use county-level capital cost multipliers ([Lopez et al., 2021](#)). As with renewable resource data, we aggregate county-level multipliers to our 0.5 by 0.5° grid by averaging. Capital cost multipliers range from 0.94 to 1.34. We ignore coal plant decommissioning costs due to inadequate data. Given our model’s scope, we ignore transmission interconnection costs for renewables, which we do not expect to systematically vary between job relocation distances, and employee retraining costs, which are likely to be dwarfed by plant investment and operational costs ([Louie and Pearce, 2016](#)) (see Discussion for further justification). To discount future costs, we assume a 7% discount rate ([The White House Office of Management and Budget, 1992](#)).

Scenarios and sensitivity analyses

To answer our research question, we use scenario analysis to vary the maximum distance at which renewable investments can be sited relative from the retiring coal plant they replace. We run three such “siting limit” scenarios: 50, 500, and 1,000 miles. To maintain computational tractability while capturing interactions between retiring coal plants, we run our model for regions of coal plants ([Table 1](#)). Specifically, we run our model for each of the Western Interconnect and Texas Interconnect, thereby capturing Interconnect-level interactions. The Eastern Interconnect is not tractable in our model, so we divide it into six smaller regions, roughly reflecting geographic clusters of 40 coal plants. These eight regions define the coal plants included in our model, but wind and solar investments can occur in locations outside each region if they are within the maximum specified distance from the relevant coal plant. To quantify the robustness of our results, we rerun a subset of our analysis to alternative wind and solar capital costs; reduced wind employment factors; replacing retiring coal plants only with solar plants; and using a reduced discount rate of 3.5% ([Table 3](#)). We run these sensitivities for 50 and 1,000 mile siting limits for four regions: Central, West, Texas, and Northern Plains. These regions have large coal plant capacities and capture the diversity of results in our base case analysis.