Downwind and out: The strategic dispersion of power plants and their pollution

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Abstract

In federalist systems, local governments can maximize local welfare by exporting locally-produced negative externalities. We empirically substantiate this externality-export strategy for air pollution using historical power-plant sitings, administrative borders, and prevailing wind directions. Using a simple, non-parametric test, we show that decision-makers disproportionately sited coal-fueled plants to reduce counties'/states' downwind pollution exposure. Natural-gas-fueled plants—lower polluters—did not follow this strategy. We then illustrate the extreme *exportabilitiy* of coal plants' pollution: within 6 hours, 50% of coal plants' emissions leave their source states—and 99% depart source counties. These results highlight how local strategic responses challenge federalist systems.

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1 Introduction

While federalist systems offer potential efficiencies in many settings, they also may incentivize strategic responses from local governments—whose focus tends toward providing locally enjoyed goods (Oates, 1972; Oates, 1999). For instance, local administrative units may export the negative externalities generated by locally beneficial economic activities. The extent to which the local units can export their costs—and increase *local* welfare—will depend on the degree to which the local actors can separate the externalities from the productive activities.

Consequently, federalist regulatory systems face two important challenges when governing air quality. First, local governments face few incentives to internalize the costs of pollution once it leaves their jurisdictions (Tiebout, 1956; Oates, 1972; Revesz, 1996; Monogan III, Konisky, and Woods, 2017). Second, air pollution can travel long distances (i.e., crossing city, county, and state borders) (U.S. Senate, 1963; Oates, 2002; Sergi et al., 2020). The U.S.'s spatially discontinuous patchwork of local and state authorities presents many opportunities for local decision-makers to strategically site major polluters in locations that reduce air-pollution exposure within the county/state. As a result, local governments have incentives to site polluters where the jurisdiction can simultaneously enjoy the benefits of pollution production (e.g., increased jobs and wages) while exporting the costs. This hypothesized behavior is, in a sense, a mutation of NIMBY-ism:[1] the property owner wants the activity on her property but wishes to export the negative externalities.

In two steps, we empirically substantiate this hypothesis that decision-makers attempt to capture local benefits and export their negative externalities. First, we identify strategic siting within a significant group of air polluters in the United States—demonstrating that decision-makers sited coal-fueled power plants to reduce *downwind* pollution exposure within their counties and states. Establishing this result is necessary to demonstrate strategic exporting of externalities, but it is not sufficient—externalities must be sufficiently exportable. We document the extreme mobility of the pollution generated by these plants. We (1) show that governments tend to site these major polluters near administrative units' downwind borders and (2) quantify the extent to which these polluters' emissions are carried downwind from their source counties and states. Together, these two conditions demonstrate local decision-makers' strategies to enjoy polluters' benefits without facing their costs.

We focus on coal-fueled power plants, which historically have accounted for a substantial share of air pollution in the U.S.[2] Coal-fueled electricity production offers a classic example of a

[1] NIMBY is "Not In My BackYard," as used by Gates (1980), Livezey (1980), and Mitchell and Carson (1986)—and many individuals since.

[2] E.g., in 2014, U.S. coal EGUs accounted for approximately 65.7% of SO_2 emissions, 44.0% of mercury emissions, 39.1% of arsenic emissions, and 10.6% of NO_x emissions in the United States (U.S. E.P.A., 2018)—while only contributing 39% of total electricity generation (EIA, 2021).

negative externality: The plant's operators and immediate community enjoy positive economic benefits, while counties and states downwind of the plant bear the costs of the plant's pollution. The coal EGU context provides several advantages. First, natural-gas power plants—which produce much less pollution than their coal-fired counterparts—provide a helpful 'placebo' in our empirical framework. Second, while coal and natural gas electricity generating units (EGUs) use water as an input, they do not use *areas downwind or upwind* as inputs—a fact we exploit in our empirical tests. Third, electricity generators record important emissions data—unlike most other major polluters. These emissions records are advantageous when we model coal power plants' pollution transport.

We first document that electricity generators sit near administrative borders. Because water both (a) forms many administrative borders and (b) is a key input to electricity generation—affecting EGU siting—we develop a simple, non-parametric test that shows localities (states and counties) sited coal plants to reduce within-unit, downwind exposure. Natural gas EGUs do not exhibit this behavior. In other words, while water may explain coal power plants' proximity to borders, it does not explain their tendency to be sited on *downwind* borders. Our natural gas placebo test corroborates this finding. Finally, using a state-of-the-art particle-trajectory model, we illustrate the extreme *exportabilitiy* of coal plants' pollution: within 6 hours, 50% of coal plants' emissions leave their source states—and 99% depart their source counties.[3] Together, these results illustrate critical challenges facing decentralized, federalist approaches to administration and regulation. More broadly, we find significant evidence that local decision-makers strategically respond to the spatial patchwork of jurisdictions created by the U.S.'s federalist system.

Our results parallel a growing literature documenting strategic pollution-related responses in federalist systems. This nascent literature has so far identified three varieties of strategic responses by local decision-makers and polluters: (1) strategic siting of polluting plants (Monogan III, Konisky, and Woods, 2017), (2) strategic production or abatement decisions (Zou, 2021), and (3) strategic monitoring (Grainger, Schreiber, and Chang, 2018; Mu, Rubin, and Zou, 2021). Each of these strategic responses implies different costs and requires different remedies. For example, Zou (2021) provides evidence that scheduled intermittent monitoring leads to significantly lower pollution levels on monitored days (relative to unmonitored days). Consequently, air-quality levels near intermittent monitors are likely worse than monitoring data would suggest. Grainger, Schreiber, and Chang (2018) find that the siting of air-quality monitors is vulnerable to strategy—again, resulting in an underestimate of local ambient air

[3] One might wonder whether this degree of exportability of emissions makes local strategic siting irrelevant. While a plant's pollution tends to leave its county quickly, siting is still relevant within the county. For local decision-makers and residents, there is a substantial difference between (a) a plant's pollution passing through/over the county major city and (b) the plant's pollution immediately exiting the county. The same reasoning also applies at the state level.

pollution. Mu, Rubin, and Zou (2021) detect a set of monitors that appear to shut down in anticipation of high-pollution events—also biasing air-quality estimates downward. Broadly, this literature suggests that current regulatory and political structures create opportunities for polluters and local decision-makers to avoid internalizing pollution-based costs.[4]

Our paper most closely relates to Monogan III, Konisky, and Woods (2017). Like us, these authors find significant evidence that industrial facilities with large emissions systematically locate closer to states' downwind borders relative to lower-emissions industrial facilities. Our analysis differs from Monogan III, Konisky, and Woods (2017) in four important ways. First, we define "strategic siting" (within a jurisdiction, i.e., state or county) as choosing a plant location where the downwind area is less than the upwind area (in the given jurisdiction)—based upon the location's prevailing wind.[5] Comparing the area downwind to the area upwind—within the same jurisdiction—implicitly controls for the size of the jurisdiction. In contrast, Monogan III, Konisky, and Woods (2017) focus on polluters' *distance* to the state's "downwind border". Second, we study strategic siting at both the county and the state level, while Monogan III, Konisky, and Woods (2017) focus only on state-level siting. We are unaware of any existing analyses that detect within-county strategic siting. We believe both levels warrant consideration. State and county governments each potentially face incentives to mitigate pollution exposure—e.g., counties are often the most basic unit of air-quality regulation, while state agencies coordinate local responses to regulation. Beyond regulation, politicians at every level face political incentives to increase economic activity while maintaining some degree of environmental quality (producing health and amenity values). Third, we focus exclusively on electricity generators—and specifically compare coal EGUs to natural-gas EGUs. As described above, coal EGUs account for a substantial share of local and national air pollution ($PM_{2.5}$, NO_x, SO_2, mercury, lead, ozone, and CO).[6] Finally, we extend beyond both Monogan III, Konisky, and Woods (2017) and the current literature by including additional descriptions of the geography of power plants *and*, importantly, descriptions of the transport of coal EGUs' emissions across the United States.

[4] Our paper also broadly relates to a large literature on the pollution-haven hypothesis (PHH), which posits that polluters tend to locate in areas with less stringent environmental regulation. Much of the PHH literature investigates this hypothesis at the international level—focusing on how emissions-intensive production shifts towards countries with lax environmental regulation. Cole (2004), Levinson (2008), Millimet and Roy (2015), and Cherniwchan, Copeland, and Taylor (2017) provide helpful overviews and discussions of the PHH literature. Our main hypothesis—that local decision-makers site polluters to capture economic benefits while exporting pollution's costs—follows a similar line of reasoning as the PHH but focuses on within-unit spatial siting decisions (enabling the export of pollution) rather than variation in regulatory stringency.

[5] As we explain below, we define downwind/upwind area using 30-year averages for prevailing wind directions from NOAA (NARR, 2006).

[6] Consequently, coal EGUs are regulated and monitored closely by both federal (especially U.S. EPA) and local (state and county) authorities. In addition, coal EGUs are unique in their tendency to build tall smokestacks: there are 15 smokestacks in U.S. of at least 1,000 feet and nearly 300 chimneys of at least 500 feet (U.S. G.A.O., 2011; CAMD, 2020).

Methodologically, our empirical test of strategic siting overlaps with a growing literature that uses wind direction for identification. For example, Zivin et al. (2020) use the difference between upwind and downwind agricultural fires in China to identify the effect of fire smoke on cognitive test performance. Rangel and Vogl (2019) use a similar approach to estimate the effects of fire smoke on infant health at birth. Schlenker and Walker (2016) and Anderson (2019) use upwind and downwind exposure to traffic-induced pollution (from planes and automobiles, respectively) to measure the effects of pollution on local health. Our test uses the ratio of downwind area to upwind area within the jurisdiction to identify strategic siting among major polluters.[7]

We are not the first to examine the challenges that pollution transport creates—e.g., the Clean Air Act of 1963 was understood to limit federal power to cases where (1) "air pollution... originates in one state and adversely affects persons or property in another state" or (2) for "significant intrastate problems which state and local agencies are unwilling or unable to deal with" (Edelman, 1966). A host of "pollution transport" models have been developed to study the extent to which pollution travels and the health and policy problems posed by pollution transit.[8] Sergi et al. (2020) find that despite national reductions in $PM_{2.5}$ from point sources since 2008, approximately 26% of counties have experienced worsening health damages from pollution—noting that "around 30% of all U.S. counties receive 90% of their health damages from emissions in other counties." Similarly, by decomposing pollution levels by each pollutant's distance from its source, Wang et al. (2020) find that "long-range" pollution is dominant in the U.S.[9] While nearly 60 years have passed since the CAA of 1963 recognized "the transport problem" in air pollution, substantial gaps remain in our understanding of the problem's origin, extent, and damages.

More broadly, the evidence in this paper, in conjunction with the existing literature, highlights important policy challenges facing federalist systems. Local governments can export negative externalities 'abroad' when these externalities are separable from local benefits. We provide evidence of this behavior in an economically and historically important context: coal-fueled power plants. First, we show significant evidence that U.S. counties and states sited coal power plants to reduce within-county and within-state downwind exposure. We then show that these plants—their locations, in combination with prevailing wind patterns and coal plants' tall smokestacks—export pollution quickly out of the source counties and states. By documenting

[7] Many other papers use wind variation (rather than a comparison of upwind to downwind areas) for causal identification, e.g., Barwick et al. (2018), Deryugina et al. (2019), Freeman et al. (2019), Holland et al. (2019), and Sullivan (2016).

[8] Another class of pollution transport models—reduced-complexity air transport models—make simplifying assumptions concerning meteorology and atmospheric chemistry equations in exchange for large computational benefits, e.g., the InMAP model (Tessum, Hill, and Marshall, 2017).

[9] Wang et al. (2020) define "long range" as farther than 100 km from the source—reasoning that this distance "likely represents regional background and long-range transport."

this strategic behavior and illustrating the incentives that federalism's decentralization creates, our results identify areas where policymakers and regulators may capture additional social benefits.

2 Institutions: Siting Plants

Governments' and firms' decisions on where to site a new power plant depend upon a host of variables—proximity to water,[10] grid/transmission availability,[11] access to fuel[12] (e.g., rail lines, pipelines, wind/solar capacity), local regulatory oversight[13] (i.e., friendliness to industry), and local community characteristics.[14] In the rest of the paper, we will use "decision-makers" to refer to the joint government-firm decision process for siting a plant. A large literature considers how local environmental regulations and enforcement affect the location of polluting firms across states and counties (see footnote 4). However, location decisions on a finer scale—i.e., within state or county—have received far less attention.

The logic of exporting negative externalities is simple. If a local decision-maker reduces the area downwind of polluters *within its administrative boundaries*, then fewer of its citizens bear the costs of pollution.[15] As long as the polluters remain within administrative borders, the locality captures many of the plants' benefits—tax revenue, employment, economic activity/growth. In addition, by moving polluters farther downwind, the decision-maker may also complicate pollution attribution and regulation—reducing local regulatory costs associated with the emissions.[16] Broadly, this story follows a similar logic to NIMBY behavior: an actor (the local decision-maker) tries to enjoy the benefits associated with an economic activity without bearing the activity's costs. As we show, power plants can easily export their pollution (their main costs) using wind and tall chimneys. Figure 2a shows an illustrative plant with limited downwind area (the dark purple shaded area) in its home county.

[10] Steam-driven turbines and water-cooled plants mechanically require water. We document the distribution of plants' proximities to water in *Empirics* and Figure 1.

[11] In the Texas electricity market, Woerman (2020) demonstrates that grid congestion can induce market power—more than doubling firms' markups. McDermott (2020) provides a complimentary story of market power via transmission constraints within Norwegian hydropower.

[12] Preonas (2019) documents market-power-driven markups in coal-by-rail delivery to coal plants in the U.S.

[13] An abundant literature considers the effect of local pollution regulations on polluter locational choice—e.g., McConnell and Schwab (1990), Levinson (1996), Gray (1997), Mani, Pargal, and Huq (1997), Becker and Henderson (2000), Jeppesen and Folmer (2001), Jeppesen, List, and Folmer (2002), List et al. (2003), Millimet and List (2003), and Shadbegian and Wolverton (2010).

[14] Wolverton (2009) finds a significant negative association between plant sitings and income.

[15] E.g., health costs and diminished local amenities like visibility.

[16] For an example of diminished regulatory cost, consider the Clean Air Act's National Ambient Air Quality Standards (NAAQS). By reducing the area downwind of a polluter, there is (mechanically) less space to site an air quality monitor. Consequently, the pollution will only be recorded by monitors in other counties downwind of the source county. Appendix section A.2.1 elaborates on cross-boundary regulations within the Clean Air Act.

3 Data

Overview We combine several publicly available datasets that originate from a variety of federal agencies. The data fall into three broad categories: (1) electricity-generator data (i.e., power plants), (2) meteorological data, and (3) geographic data.

Electricity generators Our data on electricity generators (at both the generator and plant levels) come from two sources: (*i*) the Emissions & Generation Resource Integrated Database (eGRID, 2018) and (*ii*) the EPA's EmPOWER Air Data Challenge,[17] which provides data through the EPA's Clean Air Markets Division (CAMD, 2020). Specifically, we use the eGRID data to obtain each EGU's latitude, longitude, year of construction, fuel category (e.g., coal, gas, hydro), generation capacity, and operating status. These variables are available at the level of generator and plant. We employ eGRID data from 2010, 2012, 2014, 2016, and 2018 (the intermediate years are unavailable). The EmPOWER CAMD data supply each EGU's daily emissions of NO_x and SO_2 and the EGUs' associated stacks' heights—both of which are inputs to the particle-trajectory model HYSPLIT. Both datasets include useful data on EGU retirements and fuel conversions. Panel B of Figure 1 illustrates the distribution of generators' capacities across four broad fuel categories for units operating in 2018.

Notably, the CAMD and eGRID datasets jointly allow us to construct the *historical* distribution of power plants in the United States. Because we observe both retirements and fuel conversions, the resulting dataset reflects the spatial distribution and fuel types of power plants *at their time of construction*—the most relevant distribution to our question of strategic siting.[18]

Meteorology Our meteorological data come from NOAA's North American Regional Reanalysis (NARR) daily reanalysis data (Mesinger et al., 2006; NARR, 2006). We use the NARR meteorology data in two applications. First, we utilize NARR's long-term averages (1979–2000) for wind speed and direction to determine prevailing, historical wind patterns in our analysis of strategic plant sitings. Specifically, we use NARR's first three pressure levels (the levels nearest to the ground): 1000 hPa, 975 hPa, and 950 hPa.[19] Second, we feed the NARR data into HYSPLIT for the particle-trajectory model's meteorology. In both applications, we employ NARR's highest spatial resolution with horizontal and vertical spacing of approximately 32 km (at the lowest latitude) (NARR, 2006).

[17] More details can be found at the EmPOWER website.

[18] The repeated cross-sections of eGRID provide further confidence in constructing this historical distribution. Further, the 2010 version of eGRID precedes the vast majority of coal EGU conversions and retirements.

[19] Pressure levels (barometric pressure levels) represent the force exerted from the weight of the air. Pressure levels decrease non-linearly with height.

Geography For state borders, county borders, coast lines, and bodies of water we rely upon the U.S. Census Bureau's *TIGER/Line* shapefiles and cartographic boundaries (US Census Bureau, 2016b; US Census Bureau, 2016a). The bodies of water are subdivided into area files (i.e., polygons that enclose areas) and linear files (i.e., line-based hydrology). Finally, we integrate data on counties' non-attainment histories using the U.S. EPA's *NAYRO* file in its *Green Book* collection (US EPA, 2017). In this paper, we focus exclusively on EGUs in the contiguous U.S.—omitting Alaska, Hawaii, and U.S. territories.

4 Empirics

We now turn to our empirical analysis. Recall that the hypothesized strategic negative-externality export requires (1) decision-makers site large polluters to reduce within-unit exposure and (2) polluters' emissions are, in fact, sufficiently exportable.

We begin in 4.1 by documenting the fact that state and county decision-maker sited many EGUs very close to county and state borders. There are non-strategic reasons EGUs might locate near borders—namely, borders are composed of water, a critical input for electricity production. Next, in 4.2 we formulate a simple test for regulatory avoidance that implicitly accounts for non-strategic reasons for locating on an administrative border. In 4.3 we apply this test for strategic siting and discuss its results.

Finally, in 4.4 and 4.5, using a particle-trajectory model (HYSPLIT), we demonstrate that coal power plants' emissions are indeed highly transportable. Together, our results show decision-makers strategically sited units of an exportable externality. These results jointly satisfy sufficiency in demonstrating our hypothesized behavior: local decision-makers attempt to capture local benefits and export their negative externalities.

4.1 Power plants' distances to borders and water

Border distance We start by calculating each plant's distance to the nearest county and state border.[20] Figure 3 illustrates the result of this calculation—the distribution of EGUs' distances to their nearest state and county borders. We separate the distributions by the EGUs' fuel categories, as EGUs' fuel types drive differences in other inputs.[21]

Figure 3 demonstrates that many EGUs were sited very close to county borders (Panel A) and state borders (Panel B). Further, this tendency is particularly extreme in coal-fueled and hy-

[20] While plants are divided into generating units (e.g., boilers), latitude and longitude are constant at the plant level in the eGRID dataset—i.e., all EGUs *within a plant* (ORIS code) are specified as the same location in eGRID. See appendix section A.1.1 for the details of this calculation.

[21] E.g., coal units require access to coal—generally via rail or barge—while natural gas units typically require access to the natural-gas pipeline.

dropower EGUs—though natural gas plants also exhibit this trend. Of the 605 operating coal units in 2018 with capacities of at least 25 MW, 30% are within 1 km of a county border, 57% are within 5 km of a county border, and 77% are with 10 km of a county border. For state borders, the corresponding percentages are 18% (≤ 1 km), 25% (≤ 5 km), and 29% (≤ 10 km). Only hydropower EGUs skew more toward administrative borders than coal-fueled EGUs. We formally test whether EGUs' placements are independent of borders using a Kolmogorov-Smirnov test. This test compares EGUs' distances to borders against a null distribution of distance-to-nearest-border for a uniform grid covering the entire contiguous US. If EGU placements are independent of borders, these distributions should be similar. All fuel types strongly reject this independence except for solar/wind's distance to county borders (see Table A1). As Figure 3 and these statistics suggest, a substantial (and disproportionate) share of U.S. coal-fueled electricity generators sit near county and state borders.

Non-strategic explanations for EGUs' proximity to borders One explanation for coal EGUs' proximity to county and state borders is the strategic export of coal generation's negative externalities. However, plants may site near borders for other reasons. Most methods of electricity generation require water for steam, cooling, locomotion, or transportation (solar and wind are exceptions). If large bodies of water (rivers or lakes) form many state/county borders, then water as an input *could* explain plants' proximity to borders.[22]

We calculate the share of each county's and state's borders that intersect bodies of water by spatially joining administrative borders (both state and county borders) to the boundaries of bodies of water (using a 50-meter buffer to allow for *near misses*).[23]

We find that approximately 46.1% of state borders and 27.4% of county borders intersect bodies of water. States differ greatly in the shares of their borders (county and state) intersecting water. Figure 4 illustrates this heterogeneity, and Figure 5 provides four examples of the county and state borders identified as intersecting with water (in dark blue lines). As demonstrated by Figure 4, states in the non-coastal, western U.S. make up the lower end of the distribution with very few county or state borders intersecting water—e.g., in Colorado, Wyoming, and New Mexico, less than 1% of state borders intersect with water, and 2%–3% of county borders intersect with water. Many coastal states (including the Gulf Coast and Great Lakes) have relatively high shares of borders intersecting with water. However, some interior states also have high water shares—e.g., 65% of Kentucky's state border and 41% of its county borders intersect with large bodies of water. Thus, most states—and many counties—offer potential sites with water and proximity to the border.

[22] This explanation also requires that the interiors of counties (and states) do not contain other large bodies of water. Otherwise, EGUs could just as easily locate in counties' interiors rather than on borders.

[23] Appendix section A.1.3 describes this operation in detail.

Panel A of Figure 1 confirms that EGUs locate near bodies of water (again, except wind and solar): 99% of hydropower units and 62% of coal units are within 250 meters of a body of water.[24] For natural-gas units, 48% are within 250 meters of water. For wind and solar EGUs, only 30% of generators are within 250 meters of a body of water. Given that hydro and coal units require large amounts of water—and wind/solar units do not—these results validate the spatial calculations in the rest of the paper and confirm that water is, indeed, a binding locational constraint when siting plants. However, these results do not entirely explain the phenomenon of siting coal plants near borders. Many bodies of water exist in the interior of counties/states, yet coal EGUs tend to locate near administrative borders.[25]

4.2 Strategic plant siting: A statistical test

We now develop a simple, non-parametric test to detect whether plants were strategically sited near borders to reduce their home counties' (or states') exposure to the plants' pollution—rather than coincidentally placed near borders due to plants' demand for water.

With this motivation in mind, it is clear that proximity to certain borders is more advantageous than proximity to other borders. If a plant locates on the downwind border of its county, then its emissions immediately will leave its county (for example, the plants depicted in Figures 2a and 2b). If a plant locates near the upwind border of its county, then its emissions will pass through a substantial portion of its county (e.g., Figure 2d). Thus, all else equal, local decision-makers wishing to reduce their county's pollution exposure will prefer to reduce the area in the county that is *downwind* of the plant.[26]

Now consider the possibility—our null hypothesis—that decision-makers do not try to export their coal pollution. Under this null, decision-makers search for a location that maximizes the plant's profit, independent of emissions export. Consequently, plants' locations should be independent of the downwind vs. upwind exposure of their emissions: this ratio is not an input to production, nor is it an input to plants' inputs. In the absence of emissions export, it should be a 50-50 'flip' whether the area downwind of the plant is larger or smaller than the area upwind (within the EGU's jurisdiction of residence).[27] Simply: In the absence of strategic emissions export, there is nothing special about *downwind* water.

Therefore, a simple, non-parametric test for strategic emissions export in the siting of coal-

[24] Measurement error in the latitude and longitude of generators and the Census water files likely explains why hydropower does not hit 100%.

[25] For example: The *interior* Catawba County in North Carolina contains the Marshall Steam Station, a 2.1-gigawatt coal plant located on Lake Norman.

[26] The same reasoning applies at the state level.

[27] Using a uniform grid covering the contiguous U.S.—effectively a higher resolution version of the raster depicted in Figure A1—we confirmed that the probability a point is more upwind than downwind is, indeed, almost identical to 50 percent.

powered plants is to calculate the number of coal plants for whom the *downwind area* (in the county or state that contains the plant) is less than the *upwind area*. We operationalize this test as an implementation of Fisher's Exact Test (Fisher, 1934; Fisher, 1935; Conover, 1971; Imbens and Rubin, 2015). Under a sharp (one-sided) null hypothesis of *no strategic siting to reduce downwind area*, the test statistic n_s (the number of plants for whom downwind area is less than upwind area) is distributed as a binomial distribution with size equal to the number of plants in the sample (N_T) and probability $p = 0.5$. Under this null, the expected share of plants whose downwind area is less than its upwind area is 50%. Consequently the p-value for a given test statistic is

$$p\text{-Value}(n_s) = \mathbf{P}(X \geq n_s;\, n = N_T,\, p = 0.5) = \sum_{x=n_s}^{N_T} \binom{N_T}{x} 0.5^{N_T}$$

Because county and state decision-makers both potentially face incentives to reduce their administrative units' pollution exposure, we implement our test for strategic siting at both administrative levels.[28]

Our test offers several attractive features. First, the identifying assumption is that a decision-maker will only minimize a plant's downwind area to avoid the costs associated with the plant's pollution. This assumption is plausible because coal- and natural-gas-fueled electricity generators do not use the *areas* upwind or downwind—or their ratio—as inputs into their production or transport of electricity. Put differently, because EGUs do not use the *ratio* of downwind-to-upwind area for production or transport, strategic pollution export is the only real explanation for locating plants in a manner that reduces the county's (or state's) exposure downwind. If a latent factor correlates with the ratio of the downwind-to-upwind area at the state or county level, then our test will falsely conclude strategic siting. However, very few social, political, or physical processes consider the areas downwind or upwind of a point in space—let alone their ratio. Further supporting this assumption: when we analyze a fine, uniform grid covering the contiguous U.S., we find no evidence of a relationship between this ratio (or its inputs) and population density or population demographics.[29]

Second, this test is simple, straightforward, and provides an exact p-value that do not rely upon parametric or asymptotic assumptions (Imbens and Rubin, 2015).[30] Third, natural-gas EGUs

[28] It may be helpful to note that there is an upwind side and a downwind side for nearly every border in the U.S. (at least for borders that run orthogonal to the wind). Our test simply asks whether decision-makers disproportionately placed coal EGUs on the upwind side of the border (reducing their downwind areas).

[29] Figures A3 and A4 illustrate that there is no relationship between share of county (or state) upwind (or downwind) and population density or population demographic composition. To falsify our identifying assumption, population density (or population composition) would need to bunch near downwind borders and avoid upwind borders. The figures contain no evidence that this bunching occurs.

[30] One drawback of the test's simplicity is that it does not incorporate other dimensions of strategy, e.g., stack heights. This omission does not bias the test for our specific hypothesis. It simply means we are testing for a specific strategy.

provide a convenient falsification test for our approach. Because natural-gas plants produce substantially less pollution than coal-fueled EGUs, counties and states do not face the same incentives to reduce gas EGUs' downwind pollution exposure. However, natural-gas plants face similar transmission constraints to coal plants. Consequently, if a latent factor is biasing our test toward detecting "strategic siting," we should detect strategic siting for coal EGUs and natural-gas EGUs. In short, this simple procedure generates an intuitive test for strategic siting with exact *p*-values, a plausible identifying assumption, and a convenient falsification test.

In addition, our test easily extends to test whether decision-makers located plants jointly reduce county and state downwind areas. Under the null of no strategic siting, the expected percentage of plants whose downwind area is less than the upwind area *at the county and state levels* is 25%.[31] More generally, this non-parametric test provides simple and clear evidence of whether decision-makers sited coal plants to reduce the downwind area in the plants' home counties and states.

To implement this test, we calculate the areas upwind and downwind of each coal and natural-gas plant in our data within the plants' counties and states. For the *wind* component of upwind and downwind areas, we use NARR's long-term averages of wind direction. The *area* is defined by the county's (or state's) intersection with right triangles emanating upwind or downwind of the plant. Figure 2 provides four examples of this calculation—illustrating the direction of the prevailing wind (the dark purple triangle in the compass), the *downwind area* (shaded dark purple), and the *upwind area* (shaded light gray). The plants in Figures 2a and 2b located near borders in a manner that substantially reduced the downwind area in the plant's home county. The plants in Figures 2c and 2d were sited in parts of their county in which the downwind area is larger than the upwind area. Using these downwind and upwind areas, we implement our test for strategic siting.

4.3 Strategic plant siting: Results

Table 1 contains the results of our test for strategically sited coal and natural-gas plants. Because coal EGUs produce substantial amounts of pollution, decision-makers have strong incentives to strategically locate coal plants to reduce the area downwind of the plants. Natural-gas plants produce considerably lower emissions, giving decision-makers little incentive to site natural-gas plants strategically. We separately test *coal plants* (column 1) and *natural-gas plants* (column 2). Table 1 contains three panels that respectively test strategic siting (A) within counties,

[31] The null of no strategic siting implies that decision-makers' siting decisions are independent of the area downwind (or upwind) at the state and county levels. Under this null, the probability a plant is more downwind in the *state* is independent of the probability the plant is more downwind in the *county*. Thus, the probability of being 'downwind' at both levels is $0.25 = 0.5 \times 0.5$.

(B) within states, and (C) within *both* counties *and* states. Each of the three panels bears strong evidence of strategic siting of coal plants that reduced the downwind areas within plants' counties (Panel A), states (Panel B), and both (jointly) counties and states (Panel C). There is no evidence that natural-gas plants were strategically located to reduce their downwind areas at any level.

Panel A tests strategic siting at the county level. Among the 514 coal plants, 56.81% sit where the area downwind of the plant (in its county) is less than the area upwind. Under the null of no strategic siting, with 514 plants, one would observe a distribution at least this extreme (in the right tail) approximately 0.12% of the time (i.e., a p-value of 0.0012).[32] For the the 1,254 natural-gas plants, the corresponding share of *strategically located* plants at the county level is 49.44% with p-value of 0.6641.[33] At the county level, our test finds large and statistically significant evidence within the group most incentivized to strategically site (coal plants) and no evidence within the group with few incentives to do so (natural gas plants).

The results at the state level (**Panel B**) paint a very similar picture as the county-level results. There is statistically significant evidence of strategic siting among coal-fueled power plants (53.89% strategic with a p-value of 0.0426) and no evidence of strategic siting within natural-gas plants (45.77% with a p-value of 0.9987).[34]

In **Panel C** of Table 1, we test whether plants are strategically located both within their counties *and* within their states. Under the null hypothesis of *no strategic siting at either level*, the expected share of strategically sited plants is 25%. Across the 514 coal plants, 34.82% sit in locations consistent with strategic siting at both county and state levels (p-value less than 0.0001). With an expected value under the null of 25%, this result's level of strategic siting (34.82%) is economically significant: an additional 50 coal plants (10%) sit in locations where they can export their pollution. As before, natural-gas plants show no evidence of strategic siting to reduce the area downwind of plants (25.04%; p-value of 0.4978). Again, we find highly significant evidence that decision-makers sited coal plants to reduce exposure downwind in plants' counties and states.[35]

Whether we consider counties, states, or both levels simultaneously, we find substantial evidence that decision-makers sited coal plants to reduce the areas downwind in plants' counties

[32] We do not expect this number to be near 100%, as governments and firms face many constraints when siting coal plants (e.g., water, rail, regulation, and local opposition to some sites)—in addition to likely having heterogeneous preferences.

[33] Recall that under the null, the expected share of strategically located plants at the county or state level is 50%.

[34] If anything, natural-gas plants appear to be sited in an anti-strategic manner at the state level—i.e., where the downwind area typically exceeds the upwind area. One explanation for this behavior is that natural-gas plants may share bodies of water with coal plants, but gas plants are willing to 'take' the downwind side of the resource (the gas plants do not need the strategic location). An alternative explanation is that, when converting coal units to natural gas, decision-makers may prefer to replace less strategically located coal units with natural-gas units.

[35] These results are robust to dropping coastal counties; see Table A2.

and states. We apply the same test for strategic siting to natural-gas plants—a class of plants that local administrators should have few incentives to site strategically. We fail to detect any significant evidence of strategic siting in this natural-gas-plant placebo. Therefore, we conclude that Table 1 provides strong and statistically significant evidence that local decision-makers strategically placed coal-fueled electricity to reduce the area downwind of plants within plants' counties and states.

This result of strategic siting is necessary for our hypothesis of local strategic export of pollution from coal-fueled power plants, but it is not sufficient. In the next section, we close the loop of this hypothesis by documenting the extent of coal pollution's mobility.

4.4 Pollution mobility: Methods

To estimate the extent to which coal-fueled EGUs' emissions travel beyond the counties and states that house the EGUs, we employ a state-of-the-art particle-trajectory model known as HYSPLIT (HYbrid Single-Particle Lagrangian Integrated Trajectory) (Draxler and Hess, 1998; Draxler, Stunder, et al., 2020). Developed by NOAA's Air Resources Laboratory, HYSPLIT is a heavily vetted and frequently used tool for calculating the trajectory and dispersion of chemicals through the atmosphere (Stein, Draxler, et al., 2015). Over its 30 years of development, researchers have used HYSPLIT to model the transport and dispersion of emissions from coal-fueled EGUs (Henneman, Choirat, and Zigler, 2019; Henneman, Mickley, and Zigler, 2019; Henneman, Choirat, Ivey, et al., 2019), facility-level pollution (Grainger and Ruangmas, 2017; Hernandez-Cortes and Meng, 2020), smoke plumes from forest fires (Stein, Rolph, et al., 2009), volcanic ash (Stunder, Heffter, and Draxler, 2007), mercury (Ryaboshapko et al., 2007), and methane emissions from the Marcellus Shale (Ren et al., 2017).

HYSPLIT requires pre-generated, gridded meteorological data, for which we use the 32-km resolution NARR (North American Regional Reanalysis) data from NOAA (NARR, 2006). We then model particle trajectories for the NO_x and SO_2 emissions of every coal-fueled EGU above 25 MW[36] in the contiguous U.S. every day during January 2005 and July 2005. As described in *Data*, unit-level emissions releases and stack heights come from CAMD (2020).[37] Modeling emissions for January and July allows us to depict the differences in emissions and meteorology between winter and summer. We model particles' paths for 48 hours after their release.

We illustrate the output of HYSPLIT in Figure 6: particle paths for hundreds of particles emanating from a specific EGU's three-dimensional location (longitude-latitude-height) at a given date-time of release.

[36] Our threshold of 25 MW is a common cutoff in regulation—e.g., the Acid Rain Program, the Mercury and Air Toxics Standards (MATS), and the Cross State Air Pollution Rule each focused on EGUs of 25 megawatts or greater.
[37] One shortcoming of this HYSPLIT-driven approach is that it does not model chemical reactions in the atmosphere (e.g., formation of $PM_{2.5}$ or ozone).

4.5 Pollution mobility: Results

From Figure 6 it is clear that the two plants' emissions leave their source counties within hours—and a large amount of the plants' emissions leaves the source states within 24 hours of being released. This quick departure from the source counties and states occurs in both January and July. Figure 6 also highlights the fact that pollution transport's distance and direction may vary significantly by season (even within a plant).

4.5.1 Transporting pollution away from sources

We now formalize and generalize these insights on the export and transport of coal emissions. For each coal plant, we calculate the share of the plant's emissions that travel beyond the plant's county and state (for each hour after the initial release). We separately calculate these plant-hour shares by administrative unit (county vs. state), month (January vs. July), and pollutant (NO_x vs. SO_2). For instance, in January 2005, 32.9% of NO_x emissions from coal plant "3470" (depicted in Figure 6c) left the plant's county one hour after the initial release. None of these NO_x emissions left the plant's state (Texas) one hour after release. Four hours after release (still for plant 3470 in January 2005): 94.6% of NO_x emissions were outside the plant's county, and 11.0% were outside the plant's state. As Figure 2d illustrates, plant 3470 is located upwind of much of its county and even more of its state (Texas), so it is reasonable that it would take time for its emissions to leave both units. For plants more strategically located—e.g., plant 1378 in Figure 2b was ideally sited to reduce in-county emissions—most of the emissions immediately leave the county: one hour after release, 69.5% of its emission had already left the county.

Figure 7 displays our pollution-mobility results for all coal plants operating in 2005. The four subplots separate the results by administrative level (top panel (A): *county*; bottom panel (B): state) and pollutant (left panes: SO_2; right panes: NO_x). The x-axis shows the number of hours that have passed since the initial emissions release; the y-axis gives the share of particles that left the source's administrative unit. The thin lines in each figure depict individual coal plants' monthly averages (black for January; light red for July). The heavy lines with dots provide the average across all plants for each hour, weighted by plants' mass of emissions.

The implications of Panel A of Figure 7 are clear: for most coal plants in the U.S., nearly all of the plants' pollution leaves plants' home counties within six hours of the release. This fact holds in both seasons, but the departure is even faster in winter months (with, on average, stronger winds). Panel B paints a similar picture for emissions' departure from source states: within 12 hours of release, 50%–85% of emissions leave the *state* of origin—and for many plants, this number is closer to 90% (again, particularly in the winter). Figure 7 demonstrates that pollution transport—a result of the geography of plant sitings, stack heights, and local meteorology—

-creates a substantial wedge between the sources that export coal-based emissions and the downwind counties/states that receive the emissions.

4.5.2 Decomposing the sources of local pollution

For a complementary perspective, we use HYSPLIT to decompose the sources of local, coal-based pollution. We separate the total *coal-EGU-generated pollution* within a county by the sources of the pollution. Specifically, we classify emissions sources by (1) whether the sources are in the same county, (2) whether the sources are in the same state, and (3) whether the sources' counties are in attainment (compliance) with national ambient air quality standards (NAAQS).[38] In 2005, 485 counties were out of attainment with the NAAQS (i.e., non-attainment) for at least one of the six criteria pollutants.[39]

Figure 8 illustrates the results of a source-based decomposition with pollution sources separated into five groups: (1) the county's own emissions, (2) *attainment* counties within the same state, (3) *non-attainment* counties within the same state, (4) *attainment* counties in a different state, and (5) *non-attainment* counties in a different state. Panel A shows the results of the decomposition for SO_2 emissions; Panel B for NO_x. In each panel, we repeat the exercise by 'receptor' county attainment status (attainment on left; non-attainment on right) and season.

Given our previous finding that nearly all emissions leave their origin county within six hours, it is unsurprising that a tiny share of a county's coal-EGU-based emissions comes from the county's own EGUs.[40] However, it is rather remarkable just how small the share of own-county emissions are relative to the contributions of other sources: the own-county shares (in black in Figure 8) range from 1% to 8%. While still small, it is notable that the share of own-county emissions is much larger for non-attainment counties than for attainment counties. This finding is consistent with coal plants' emissions (or existence) contributing to non-attainment designations. However, the vast majority of coal-EGU-based emissions in non-attainment counties appears to originate in other counties and states.

Across all counties, regardless of attainment state, the vast majority of emissions originate in other states—i.e., 65% to 85% (the sum of the yellow and orange segments in Figure 8). While this result may at first seem mechanical—each county only has one *own state* and 49 *other states*—it requires substantial transmission of *other states'* emissions. Without sizable cross-boundary transmission, counties and states would pollute themselves and not others. This

[38] Note that we first sum all coal-generated emissions that HYSPLIT locates within a county. This sum ignores where the emissions originated—so long as HYSPLIT places the emissions in the given county. We then decompose this sum by the emissions' sources.

[39] Our HYSPLIT analysis focuses on 2005, so we only consider counties' 2005 attainment status. Counts of violations by standard: 8-hour O_3 (1997), 422; $PM_{2.5}$(1997), 208; PM_{10} (1987), 49; CO (1971) 100; SO_2(1971), 10; lead (1978), 2. A county can violate multiple standards (i.e., there were 702 violations in 485 counties).

[40] This result is also driven by the fact that many counties do not have their own coal EGU.

result reiterates the importance of long-distance transport of coal pollution.[41]

Coal pollution is indeed highly exportable—even at the scale of states (and beyond). Along with our previous result of strategic downwind siting, this result closes the loop on our hypothesis of strategic export of negative externalities.

5 Discussion and conclusion

In this paper, we empirically investigate the hypothesis that decision-makers historically sited a major class of polluters—coal-fueled power plants—to strategically export their negative externalities (pollution) downwind. After documenting coal EGUs' tendency to locate near borders, we formally test whether coal EGUs disproportionately sited nearer to the downwind borders of the counties and states. Our test finds large and significant evidence that decision-makers located coal EGUs to reduce the area downwind of the plants within the counties and states that contain the plants. Our placebo—natural gas EGUs—does not exhibit this behavior.

Showing that local decision-makers disproportionately located coal EGUs downwind within counties and states is a necessary condition for our strategic export hypothesis. For sufficiency, we must also show that coal-based pollution is exportable. Toward this goal, we use a particle-trajectory model (HYSPLIT) that illustrates the extreme mobility of coal-based emissions. Our results suggest that nearly all coal EGUs' pollution leaves the sour counties within six hours of the release. Within 12 hours of release, 50%–85% of emissions leave the *state* of origin—and for many plants, it is closer to 90%.

Jointly, these two pieces of evidence offer compelling evidence that many local decision-makers historically located coal EGUs to enjoy the local benefits without facing their costs.

While these results focus on historical siting decisions, they have important implications for current environmental policy. In contemporary federalist regulations—e.g., the Clean Air Act and the Cross-State Air Pollution Rule (CSAPR)—cross-boundary pollution requires more coordination and resources than pollution that remains in (and mainly affects) its source county and state.[42] Strategically sited polluters emitting highly transportable pollution from tall chimneys[43] create a complex and challenging regulatory situation.

[41] Also potentially of interest in Figure 8: the difference between the emissions sources for attainment and non-attainment counties (the left and right halves of the figure). In *non-attainment* counties, the plurality (41%–50%) of coal-based emissions originates in *non-attainment* counties in other states. For *attainment* counties, a larger share comes from *attainment* counties in other states. Appendix section A.2.2 elaborates on the topic of non-attainment counties with substantial sources of upwind emissions.

[42] To a degree, these challenges in federalist regulation of local pollutants mirror the international community's coordination failures for limiting greenhouse gases.

[43] In 2018, the average height of a chimney attached to a coal-fueled EGU in the U.S. was approximately 500 feet, and the maximum height was 1,038 feet (calculated from CAMD (2020) data).

The shapes of some non-attainment areas—areas deemed out of compliance with the Clean Air Act air-quality standards—reflect this complexity. Some non-attainment areas knit together whole counties with adjacent pieces of other counties and "islands" surrounding major point sources (often coal plants). For example, Figure 9 maps the Huntington-Ashland non-attainment area (violated the 1997 $PM_{2.5}$ standard) in light orange. The Huntington-Ashland non-attainment area—a single non-attainment area—covers nine counties (5 whole counties; 4 partial counties) across three states (Kentucky, Ohio, and West Virginia). Six of the counties form a contiguous area. The remaining three counties (two in OH; one in WV) are islands—where each island circumscribes multiple coal plants (circled, red dots). This complex non-attainment area required substantial coordination across counties and states, source-attribution modeling, and federal oversight.[44] The Huntington-Ashland non-attainment area offers a single example of the complexities that can result from federalist environmental policy.

Figure 10 depicts a related challenge created by cross-boundary coal-based emissions (here, NO_x). In 2005, Shelby County (Tennessee) was designated non-attainment due to its violation of the 8-hour Ozone standard of NAAQS.[45] Panel A of Figure 10 shows all of the coal-plant-generated NO_x emissions that eventually arrived in Shelby County during July 2005 (as estimated by HYSPLIT). We draw emissions' paths to Shelby County in grey; non-attainment counties (in 2005) are cross-hashed in red. We outline Shelby County in bright yellow. The figure illustrates that Shelby County's emissions originate throughout a broad geographic swath, stretching from Texas to Kansas to Indiana to Georgia, including attainment and non-attainment counties.[46] Overall, Panel A emphasizes the fact that large regions of the country affect one locality's air quality—a challenge for a federalist system with many small units.

Panel B of Figure 10 zooms in on the region surrounding Shelby County, Tennessee (the "zoomed" area is approximately 900 km east-west and 600 km north-south). Counties' fill color in Panel B matches their contribution (as a share) to Shelby County's coal-generated NO_xin July 2005. Panel C provides both the legend for the colors and the histogram for the distribution of counties' shares of contribution to Shelby County's NO_x. Remarkably, although Shelby County had an operating coal plant in 2005 (and was out of attainment), the coal plant in Humphreys County, TN (which was *in attainment* in 2005) contributed more to Shelby County's NO_x than did Shelby County's own plant. Further, the coal plant in Independence County, Arkansas (also *in attainment* in 2005) contributed approximately the same amount of NO_x emissions to Shelby County as did Shelby County's coal plant.[47] As illustrated in Figure 10 (and summarized by

[44] Figure A5 provides an example of another "complex" non-attainment area contained within a single state (the Evansville, Indiana non-attainment area).

[45] NO_x, which we consider in Figure 10, is a precursor of both Ozone and $PM_{2.5}$.

[46] Notably, the emissions that eventually make their way to Shelby County come from a wide range of directions—emphasizing the importance of the temporal variation in meteorology embedded in HYSPLIT.

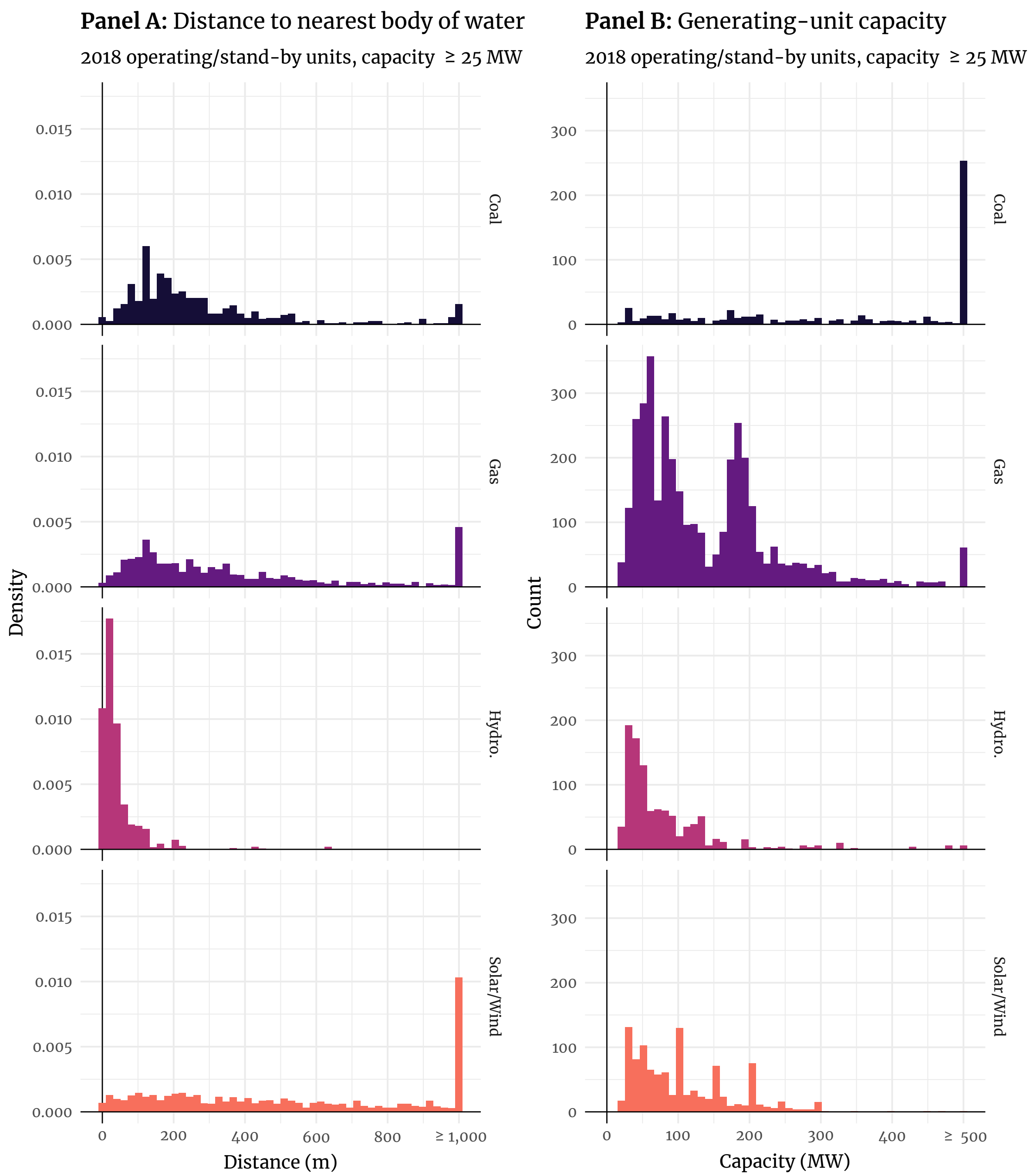
[47] Humphreys County, TN is home to the TVA's Johnsonville Fossil Plant, a 1.5-gigawatt coal power plant. Independence County, AR, houses Entergy Arkansas's 1.7-gigawatt "Independence" coal plant.

Table A3), the vast majority of coal-based NO_x emissions in Shelby County, Tennessee—a non-attainment county—came from other states, and a majority of its emissions originated from sources in attainment counties.

These two anecdotes highlight the challenges facing regulation and coordination within federalist systems. The results in our empirical section confirm that these anecdotes and their challenges are not exceptions: Facing the spatial patchwork of jurisdictions created by the U.S.'s federalist structure, local decision-makers strategically sited polluters to export pollution. More broadly, our results point to the potential for local governments' actions to erode the efficiency of federalist systems—and potentially suggest a more prominent role for the federal government when externalities are exportable.

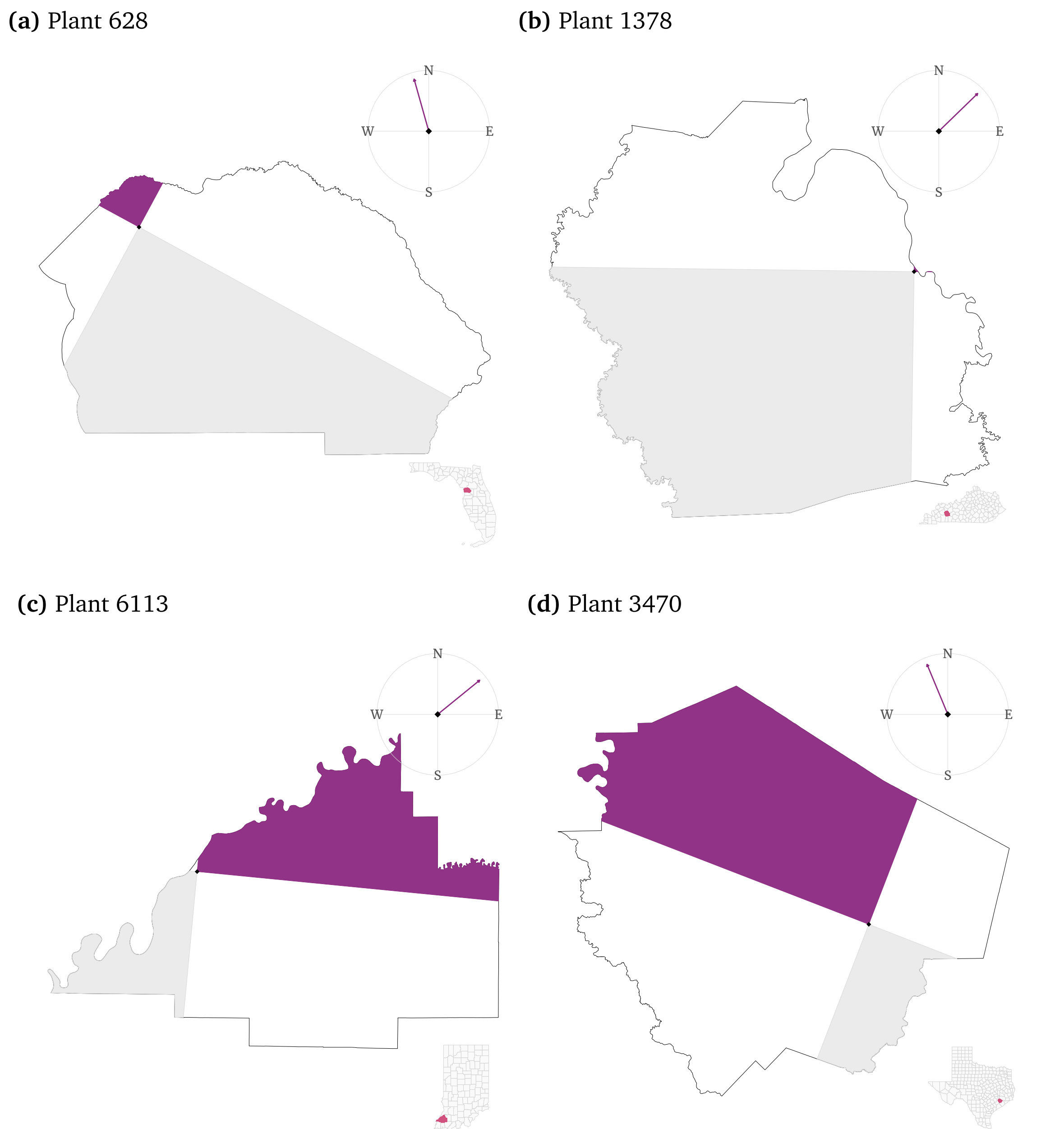
6 Figures

Figure 1: Generators' distances to water and capacities



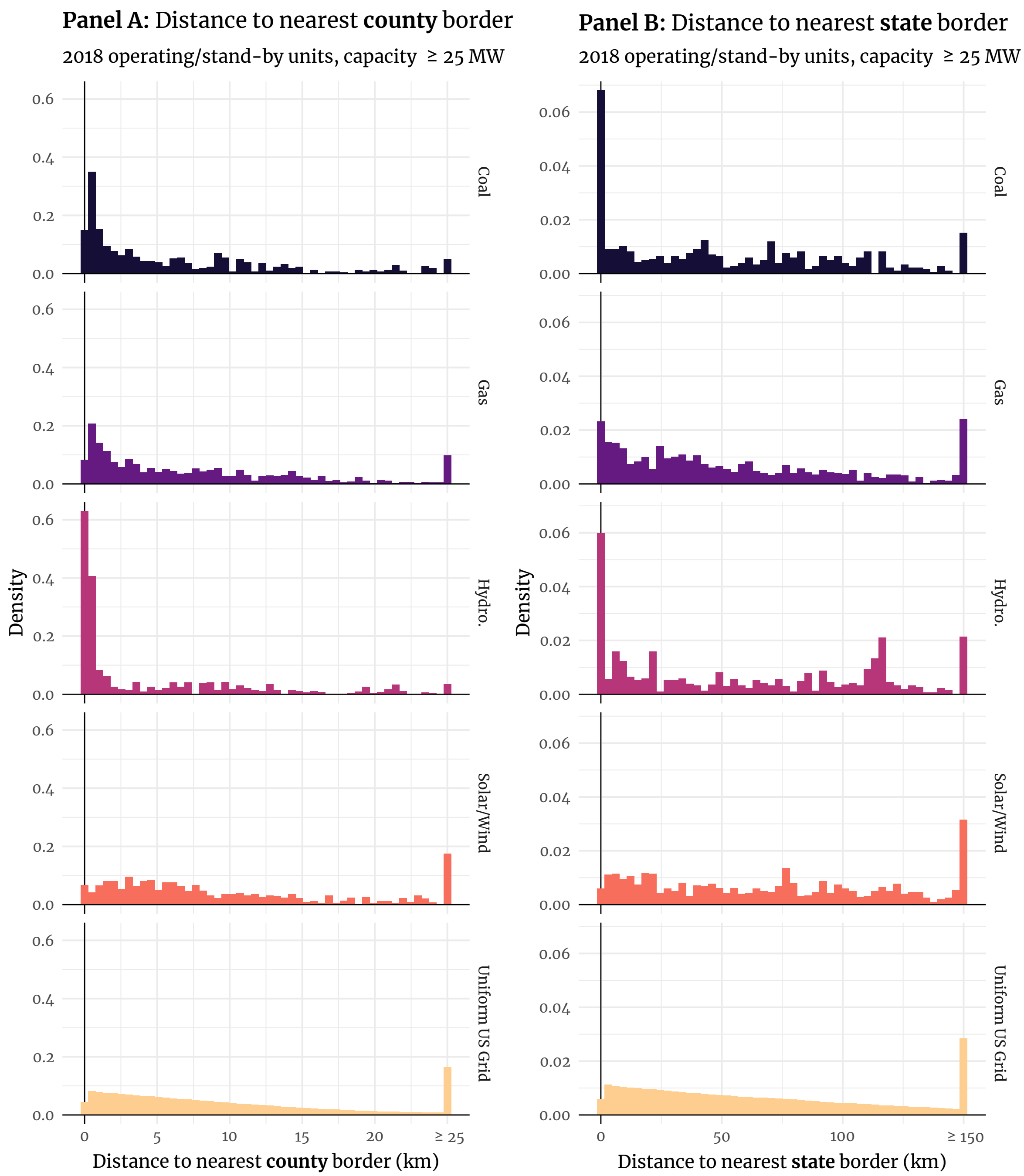
These two panels display the distributions of EGUs' distances to their nearest body of water (**Panel A**, left) and EGUs' generation capacities (**Panel B**, right) by fuel category (row and color).

Figure 2: Upwind and downwind areas in “home” county relative to plants



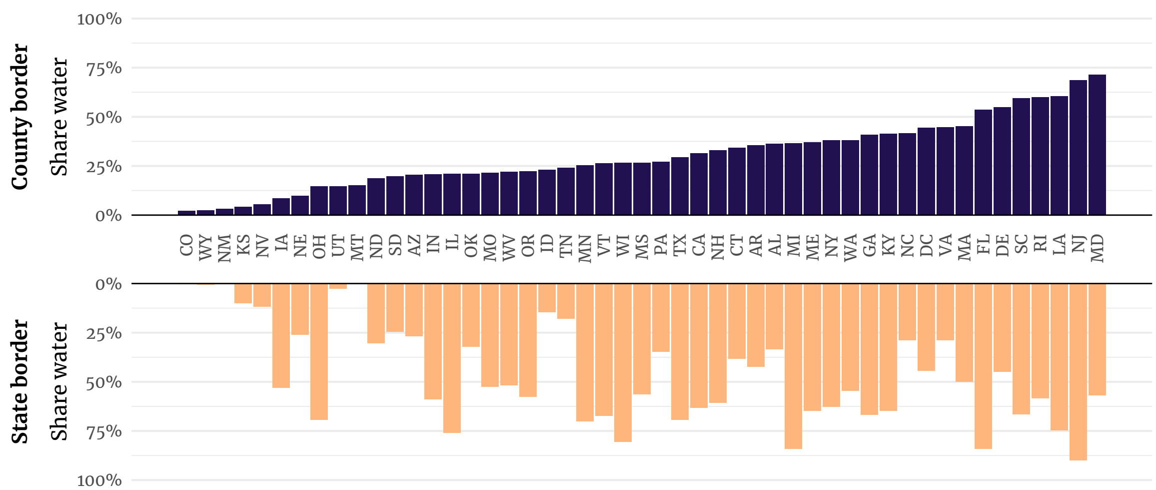
This figure demonstrates *upwind* and *downwind* areas for four coal-fueled generators. Dark, purple areas denote the 90-degree *downwind* area from the plant’s location (the small, black diamond). Light gray refers to *upwind* areas. The outlined shape depicts the plant’s county; the inset thumbnail highlights the plant within its state. The purple arrow within the compass points in the direction of the plant’s prevailing wind direction (NARR, 2006).

Figure 3: Generators' distances to county and state borders



These panels depict the empirical densities of the distributions of EGUs' distances to their nearest county (**Panel A**, left) or state (**Panel B**, right) border. The sample includes all operating and stand-by EGUs with capacities ≥25 MW within the contiguous U.S. in 2018. The first five rows of colored charts above separately produce the densities by fuel category. The final row reveals the density of *distance to the nearest border* from a uniform grid of points covering the contiguous U.S.

Figure 4: Shares of county and state borders that intersect water, by state

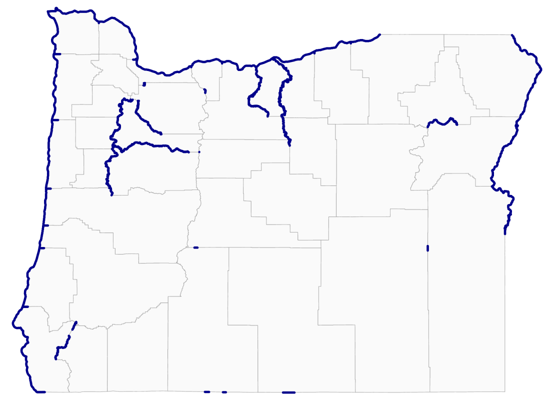


This figure illustrates the share of county borders (top) and state borders (bottom) that intersect with bodies of water, by state. The states are sorted from smallest share of county-borders intersected by water (Colorado) to largest share (Maryland). Alaska and Hawaii are excluded. Figure 5 provides four example states (LA, OR, SC, and SD) from these calculations.

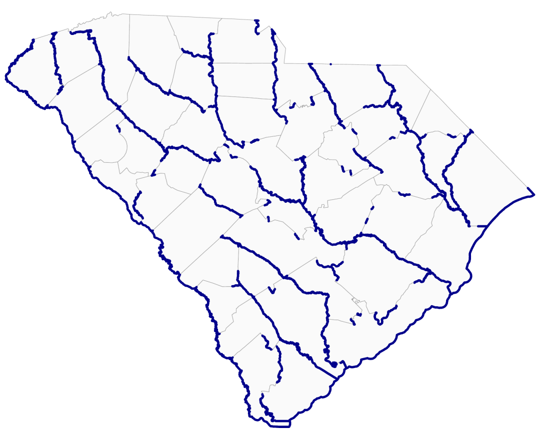
Figure 5: Where county/state borders intersect bodies of water

(a) Louisiana

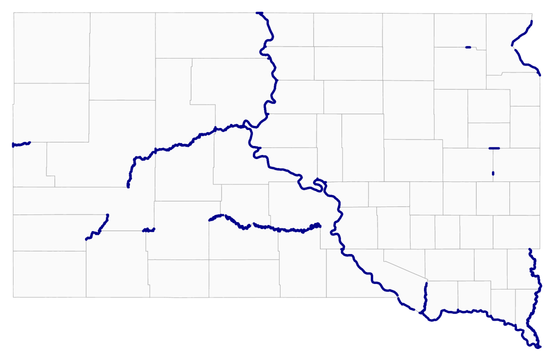
(b) Oregon



(c) South Carolina

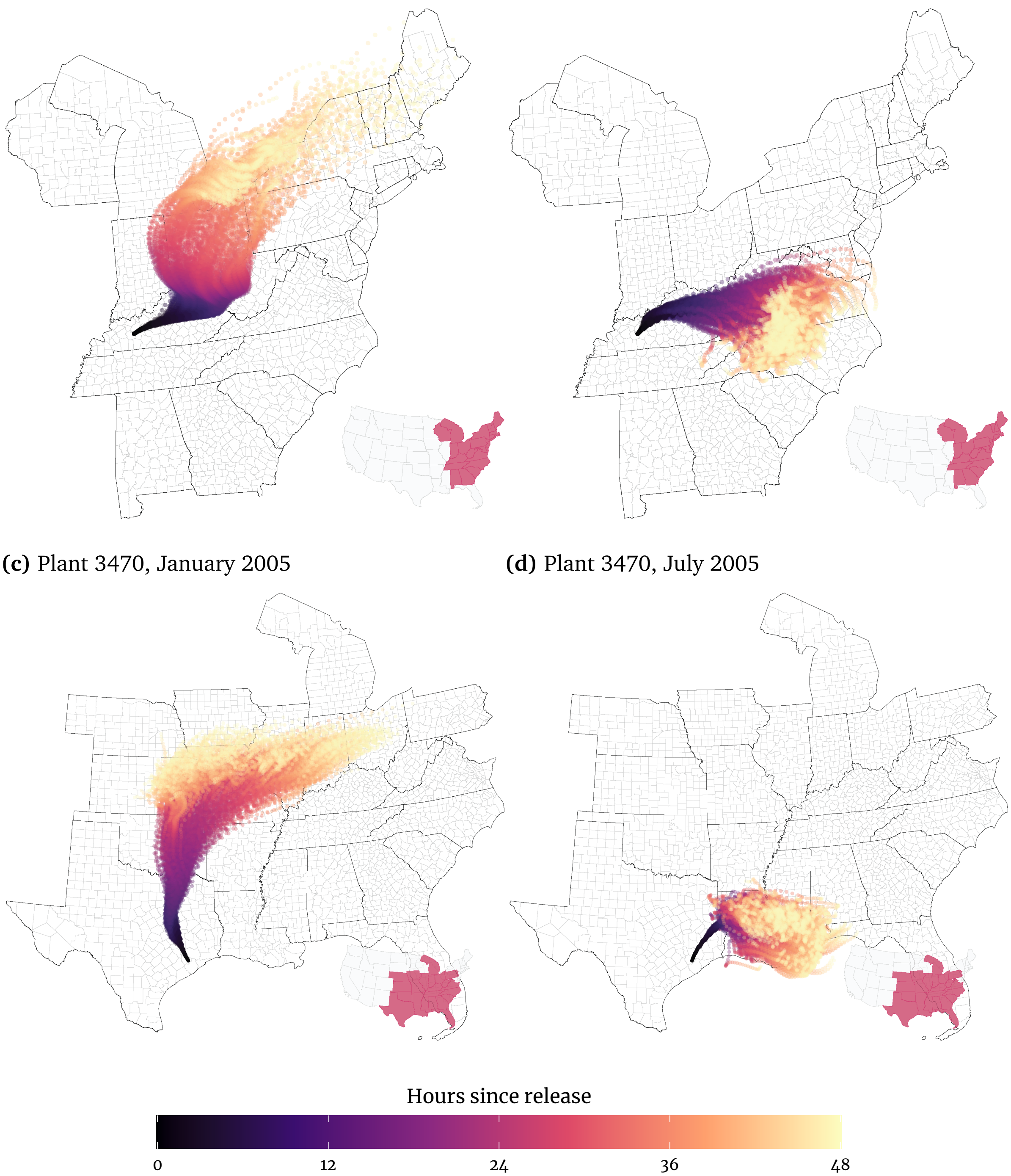


(d) South Dakota



These four subfigures provide examples of the output of our calculations of county and state borders that intersect with bodies of water. Think blue lines denote administrative borders (state and/or county) that intersect with water; thin gray lines depict administrative borders that do not. Overall, our algorithm for detecting borders' intersections with water appears to be successful.

Figure 6: HYSPLIT trajectory and dispersion: Two example plants, January and July 2005



(a) Plant 1378, January 2005

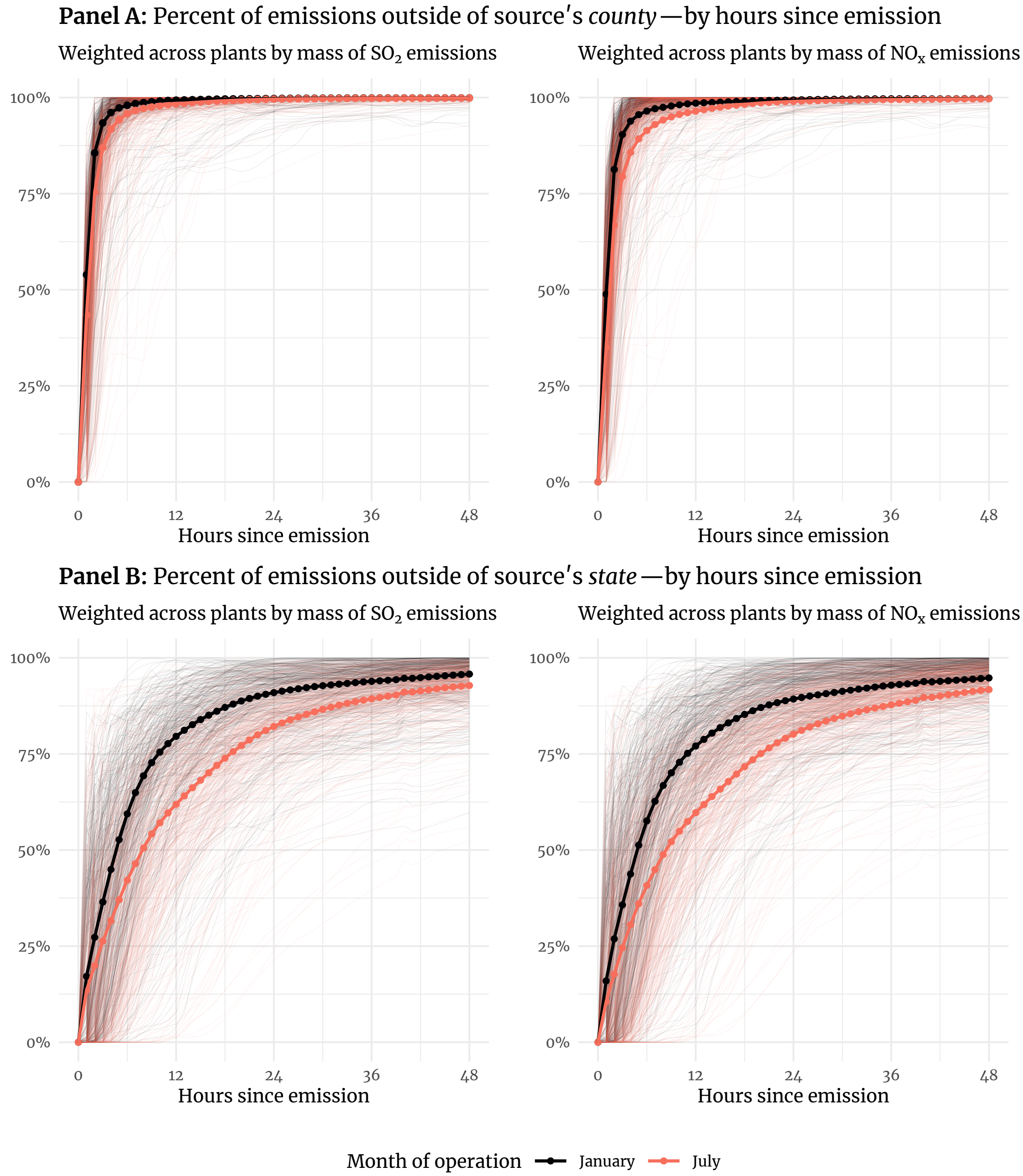
(b) Plant 1378, July 2005

(c) Plant 3470, January 2005

(d) Plant 3470, July 2005

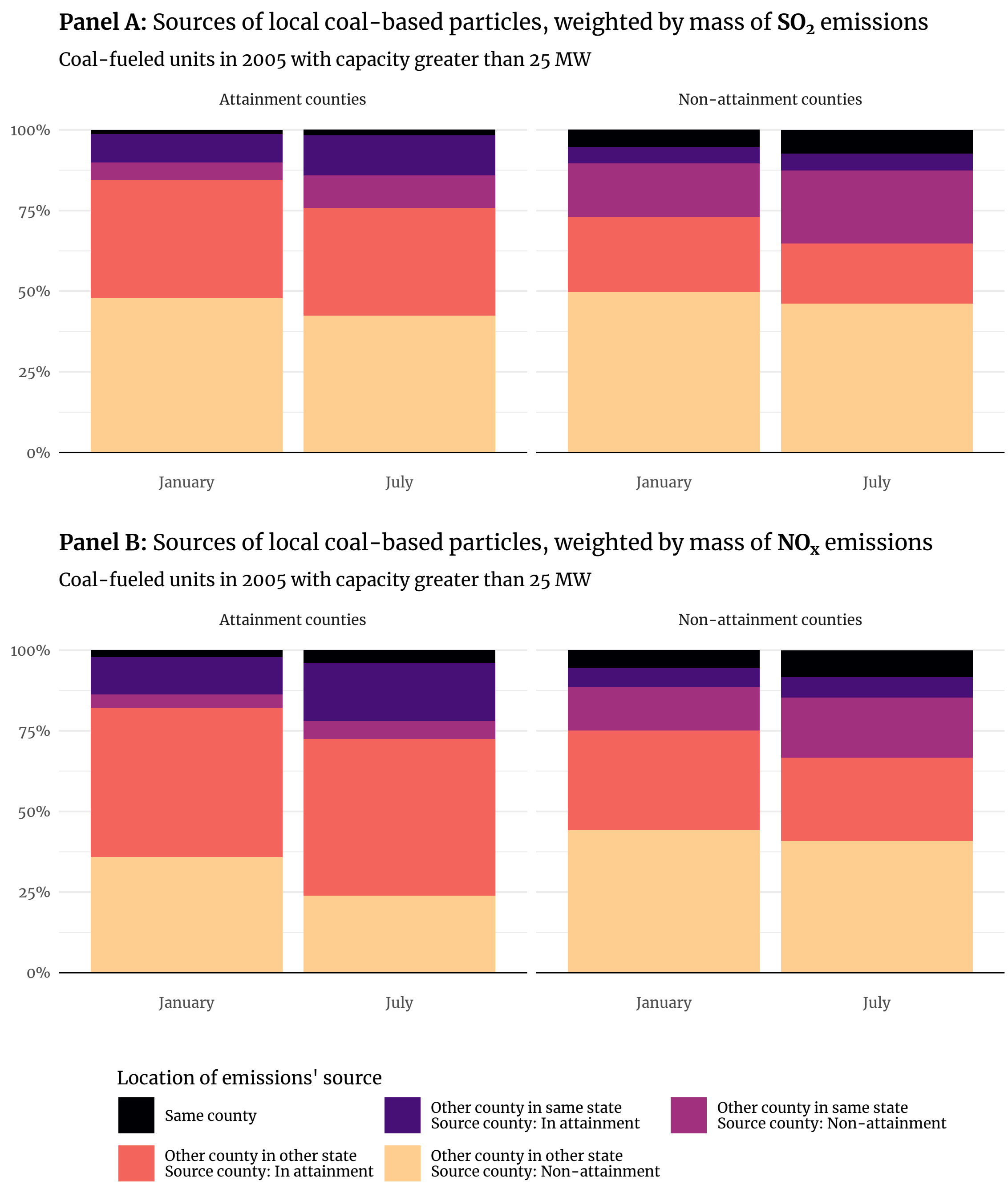
These subfigures illustrate particles' trajectories and dispersion in HYSPLIT for two plants (ORIS codes 1378 and 3470) during January 2005 and July 2005. For each day of the month, HYSPLIT models 420 particles starting at the latitude, longitude, and altitude of the plants' chimneys. We track particles for 48 hours after their initial release; particles' colors denote the number of hours since their emission. The plants correspond to Figures 2b and 2d.

Figure 7: Share of particles outside of origin county/state by hours since release



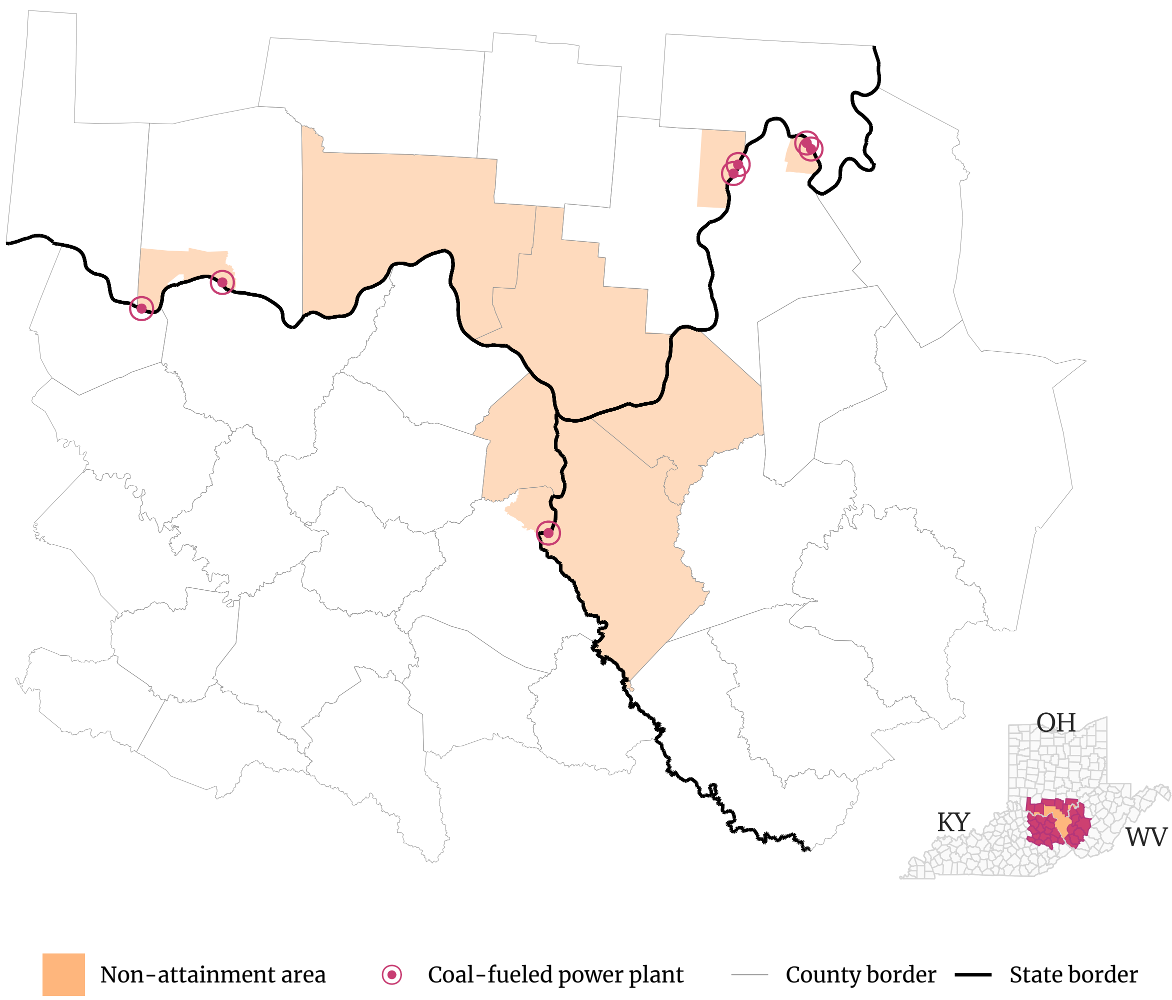
These figures portray the share of coal plants' emissions that have left plants' origin counties (top, **Panel A**) or origin states (bottom, **Panel B**) by the number of hours that have passed since the particles were released (as modeled by HYSPLIT). Each of the four subfigures contains two months of emissions: January 2005 (black) and July 2005 (light, red). Thin lines depict individual plants in a given month. Thick lines (decorated with hourly points) denote the monthly average across plants (weighted by mass of emissions). The left column weights by SO_2; the right column by NO_x. Differences between the months capture seasonal differences in meteorology and in the distribution of generation. Sample: Coal-fueled generators ≥ 25 MW operating in Jan./July 2005.

Figure 8: Share of particles in a county separated by particles' sources



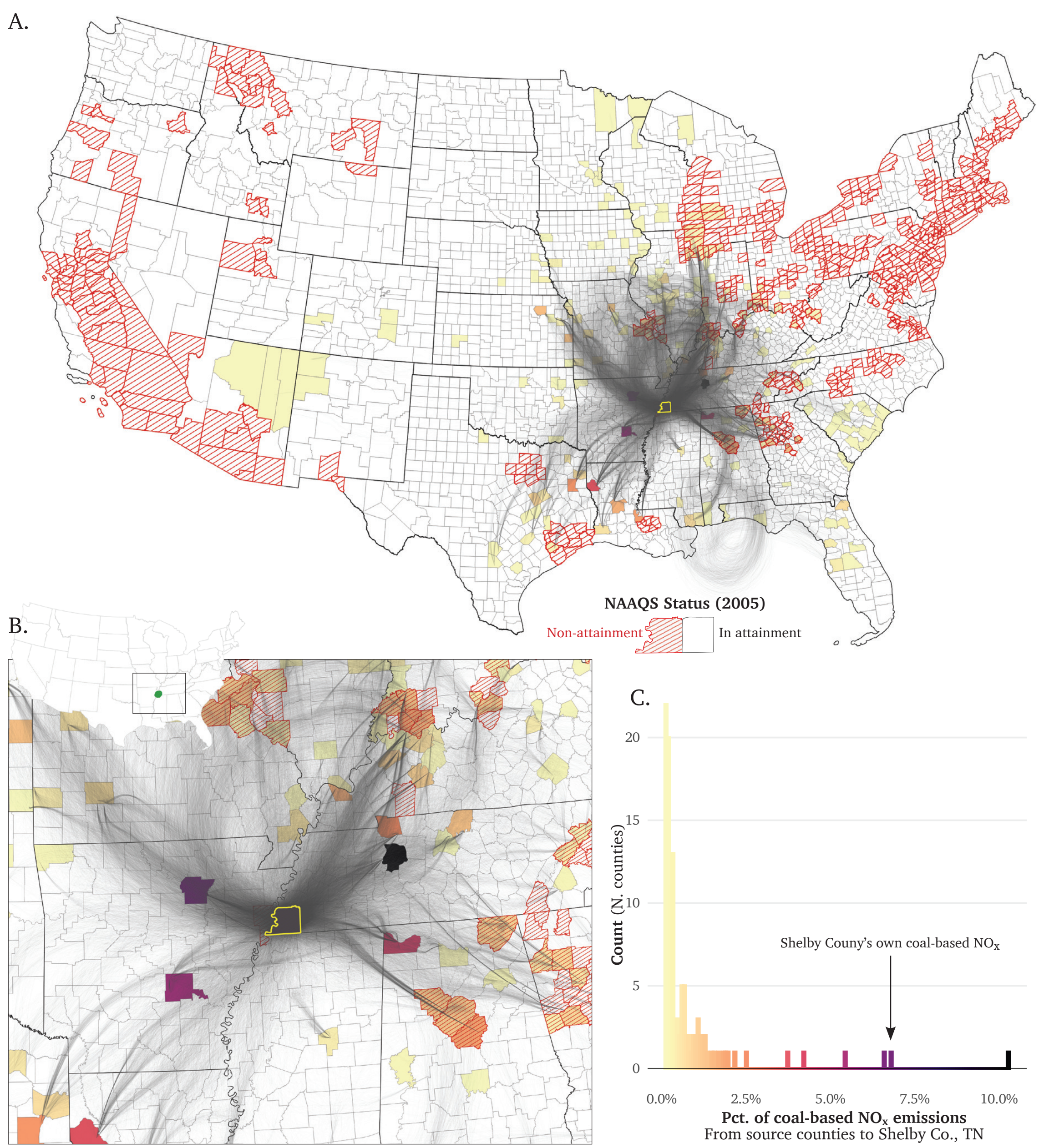
These figures illustrate the source-based decomposition of location, coal-based pollution. They described, on average, where a county's pollution *come from* based upon (1) the month (Jan. or July 2005), (2) the county's *attainment status*, and (3) the type of particle (SO_2 or NO_x). Particle trajectories come from HYSPLIT. The five colors refer to five categories of pollution sources by the EGU source's location (described in the legend). **Panel A** focuses on SO_2 emissions; **Panel B** on NO_x. Sample: Coal-fueled generators ≥ 25 MW operating in Jan./July 2005.

Figure 9: A “complex” non-attainment area: Huntington-Ashland (WV-KY-OH)



This map illustrates the complexity of the Huntington-Ashland non-attainment area (orange), which covers nine counties (5 whole; 4 partial) across three states. Six of the counties form a contiguous area. The remainder of the non-attainment area is comprised of “islands” that cover six coal plants (red-circled dots) in three different counties (two in OH; one in WV). This non-attainment area is for the 1997 $PM_{2.5}$ standard. Figure A5 depicts another example of a “complex” non-attainment area (Evansville, Indiana).

Figure 10: Illustrating the transport problem: The sources of coal-based NO_x emissions in Shelby County, Tennessee during July 2005



This figure shows the origins, paths, and shares of all coal-plant-based NO_x emissions that eventually enter Shelby County, TN during July 2005 (modeled by HYSPLIT). In 2005 Shelby County, TN was in violation of the 8-hour Ozone NAAQS (NO_x is an Ozone precursor). Subfigure **A**'s grey coal-based NO_x trajectories reveal that the sources of coal-based NO_x emissions in Shelby County include many states (from TX to GA to IL) both in attainment and non-attainment counties. Non-attainment (for any NAAQS) are hashed in red. **B** zooms in on the region surrounding Shelby County (~900 km × 600 km). Counties are colored (filled) by the share of coal-based NO_x emissions that they contribute to Shelby County, TN. **C** provides the legend for **B**'s colored shares and plots the distribution of these shares—the x axis is the share of Shelby County's coal-generated NO_x emissions that each county contributes. Despite being ~200 km from Shelby County, the black-shaded Humphreys County, TN (in attainment for all standards since 1998) accounted for the plurality of coal-generated NO_x emissions in Shelby County, TN during July 2005—i.e., more than Shelby County's own coal plant.

7 Tables

Table 1: Testing strategic siting: Upwind *vs.* downwind areas for coal and natural gas plants

	(1) Coal-fueled plants	(2) Natural-gas-fueled plants
Panel A: Siting strategically within **county**		
Count	514	1,254
Count *strategic*	292	620
Percent *strategic*	56.81%	49.44%
Fisher's exact test of H_o: In-**county** downwind area ≤ upwind area		
Under H_o: E[Percent strategic: County] = 50%		
P-value	0.0012	0.6641
Panel B: Siting strategically within **state**		
Count	514	1,254
Count *strategic*	277	574
Percent *strategic*	53.89%	45.77%
Fisher's exact test of H_o: In-**state** downwind area ≤ upwind area		
Under H_o: E[Percent strategic: State] = 50%		
P-value	0.0426	0.9987
Panel C: Siting strategically within **both county *and* state**		
Count	514	1,254
Count *strategic*	179	314
Percent *strategic*	34.82%	25.04%
Fisher's exact test of H_o: Downwind area ≤ upwind area in **county and state**		
Under H_o: E[Percent strategic: County ∧ State] = 25%		
P-value	<0.0001	0.4978

We define a plant's location as "strategic" if the downwind area *within its home county (or state)* is less than its upwind area *within its home county (or state)*. We calculate *downwind* and *upwind* areas based upon 90-degree right triangles with a vertex at the plant pointing up- or down-wind based upon the locally prevailing wind direction. Figure 2 illustrates this calculation. *Sources:* eGRID (2018) and authors' calculations.

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Appendix A

A.1 Appendix: Methods

A.1.1 Border-distance calculations

We first project the plant's location and the Census shapefiles into the plant's zone of the Universal Transverse Mercator (UTM) coordinate system. Then we calculate the distance to the plant's nearest county and state border. We use `R`'s `sf` package for these calculations (Pebesma, 2018).

A.1.2 Counterfactual grid

If the county and state borders do not impact or correlate with EGUs' locations, then EGU's distances to borders should mirror the overall national distribution of distances to borders.To build this comparison distribution, we cover the contiguous U.S. with a uniform, hexagonal grid of points as illustrated in Appendix Figure A2. The number of grid points is approximately equal to the area covered in square kilometers. We then calculate each point's distances to the nearest county border and the nearest state border.[48] This process produced a nationally representative distribution (for the contiguous U.S.) of distances to state and county borders using a uniform grid of approximately 7.91 million points.[49] This distribution represents the expected distribution of EGUs' distances to borders *if* they were sited in a manner that ignores borders and features that correlate with borders.

The last row of Figure 3 depicts the distribution of distance-to-nearest-border for the uniform grid covering the U.S. This grid's distribution demonstrates that it is *not* the case that all points in the United States are near borders. Only 8% of the U.S. (area-wise) sits with 1 kilometer of a county border (36% within 5 km; 62% within 10 km). For state borders, only 1.1% of the U.S. sits within 1 kilometer (6% within 5 km; 11% within 10 km). These numbers stand in stark contrast to the distributions of EGUs.

A.1.3 Borders and water

We calculate the share of each county's and state's borders that intersect bodies of water in four steps. First, we convert each administrative unit's linear boundaries into a series of points with 50-meter spacing. Second, we calculate the distance to the nearest body of water for each of these boundary points (if the boundary point is within a body of water, then the distance is zero). These bodies of water cover all rivers, lakes, and coastlines including in the U.S. Census's

[48] Specifically, we work in the counties' UTM zones and subset the grid points to the points *within* the county under consideration—a point's nearest border is always the border of the unit that contains that point. Again, we employ `R`'s `sf` package for these calculations (Pebesma, 2018).

[49] For comparison, the area of the contiguous U.S. is approximately 8.08 million km^2.

TIGER/Lines shapefiles discussed in *Data*. Third, we designate a boundary point as including water if the nearest body of water is less than 50 meters. This step allows for *near misses* in the Census geography files without including too many false positives. Finally, we smooth this *includes water* indicator variable using a moving-window average of all boundary points within a 2.5 kilometer radius of the given boundary point. This final step allows neighboring boundary points to *vote* on whether the boundary indeed intersects water—e.g., a single, spurious *includes water* will be overwhelmed by non-water neighbors. The final product is a series of points with 50-meter spacing covering all county and state borders in the contiguous U.S.—with each point measuring whether the boundary substantively intersects with water.

A.1.4 EGUs and water

To calculate the distance to the nearest body of water, we include all bodies of water contained in the U.S. Census's areas of water, linear water, and coastline shapefiles, (US Census Bureau, 2016b). After merging these calculated distances with eGRID's EGU characteristics, we build the distribution of distance-to-water for each fuel category.

A.1.5 HYSPLIT

The `R` packages `splitr`, `hyspdisp`, and `dispersR` were extremely helpful in developing our computational approach—as was `GNU Parallel` (Tange, 2011).

A.2 Appendix: Policy

A.2.1 The Clean Air Act and cross-border pollution

The Clean Air Act (CAA)—often called the "crown-jewel" of environmental regulation in the U.S. (Feldman, 2010; Browning, 2020))—recognizes cross-border air pollution is a challenge on a scale larger than neighboring counties. The original texts of the 1963 CAA mainly limited federal involvement to (*a*) resolving trans-boundary pollution issues—when invited by a governor—and (*b*) funding/guiding research related to air pollution (U.S. Senate, 1963; Edelman, 1966; U.S. Congress, 1968). Known as the "good neighbor" provision, section 110 of the CAA explicitly prohibits "any source or other type of emissions activity within the State from emitting any air pollutant in amounts which will (I) contribute significantly to non-attainment in, or interfere with maintenance by, any other State with respect to any such national primary or secondary ambient air quality standard" (US EPA, 2013a).[50] Further emphasizing the importance of cross-border pollution transport, in 2011 the U.S. EPA enacted the Cross-State Air Pollution Rule (CSAPR). The CSAPR covers 27 states[51] in the eastern U.S.—especially

[50] The CAA also allows states to petition the EPA for reviews of upwind sources (US EPA, 2013b).
[51] Texas, Oklahoma, Kansas, and Nebraska comprise the western edge of the CSAPR states.

targeting power-plant emissions of SO_2 and NO_x and their formation of fine-particulate matter ($PM_{2.5}$) and Ozone (O_3) (US EPA, 2020). The CSAPR links emissions-source states to recipient states—emphasizing non-attainment areas—and creates a budget-and-trading program for emissions within the covered states (US EPA, 2020). Despite this substantial infrastructure addressing cross-border pollution, disputes regarding trans-border pollution continue—e.g., in 2018 Delaware announced its intent to sue the EPA over emissions from power plants based in Pennsylvania and West Virginia, and in 2019 New York, Connecticut, Delaware, New Jersey, Maryland, Massachusetts, and NYC sued the EPA regarding upwind ozone precursor emissions (Sanders, 2018; Volcovici, 2018; Groom, 2019).

One of the complexities of monitoring and regulating air pollution from coal-fueled EGUs is the degree to which emissions can travel long distances from the initial source, polluting distant destinations. In 2018, the average height of a chimney attached to a coal-fueled EGU in the U.S. was approximately 500 feet, and the maximum was approximately 1,038 feet (calculated from CAMD (2020) data). While tall chimneys aid in dispersing high concentrations of harmful chemicals, they also substantially increase the transport of emissions to other counties and states (U.S. G.A.O., 2011).

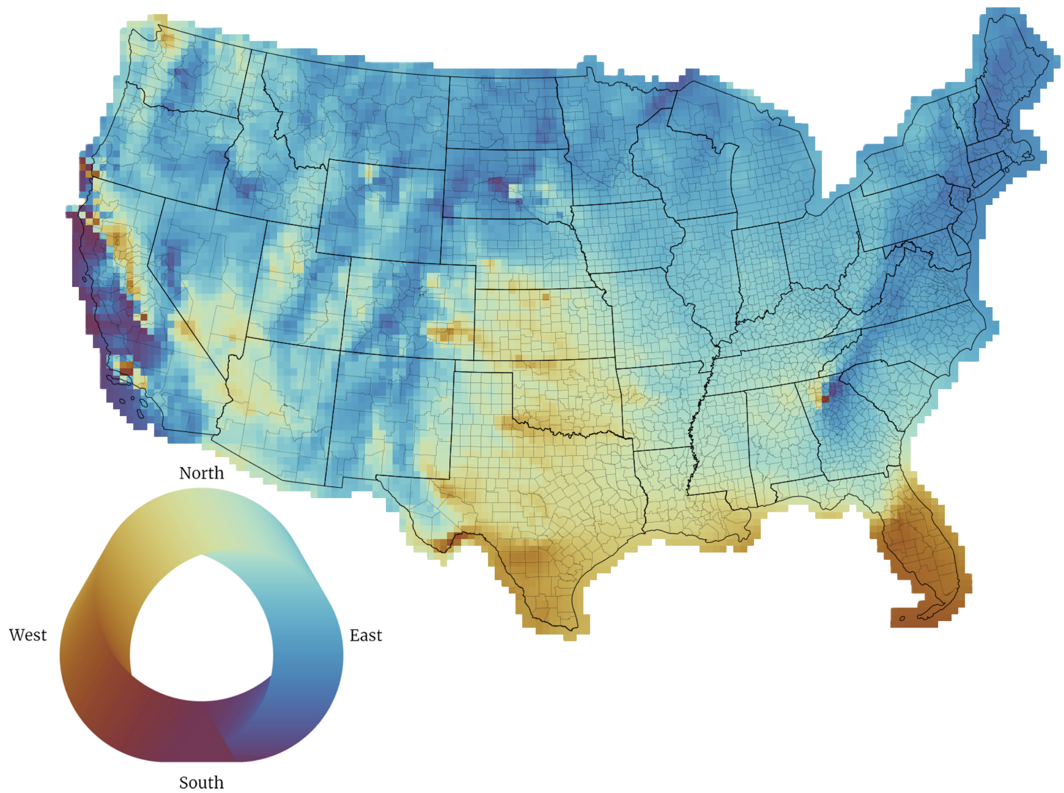
A.2.2 Non-attainment counties and upwind emissions

Figure 8 aggregates across all counties in a given category (month by NAAQS status). This aggregation is quite useful in describing average trends, but it may miss some of the nuance contained in individual counties. To document some of the underlying variation, Table A3 lists the top 10 non-attainment counties in terms of the county's share of coal-based NO_x emissions that come from in-attainment counties (including counties in the same state and in other states). We restrict the set of counties to those with operating coal plants in January and July of 2005, and we separately rank the counties for the two months.

Table A3 reveals that there are many non-attainment counties that have their own coal plants but receive a substantial share of their coal-based NO_x emissions from coal plants located within *in-attainment* counties—both in the same state and in other states. For instance, in January 2005, the coal plant in Fort Bend County in Texas (part of the Houston CBSA) only contributed only 17.8% of the county's coal-based emissions—29.3% came from in-attainment in-state sources and 48.1% came from in-attainment, out-of-state sources. For the "top" county in July of 2005—Shelby County in Tennessee (which houses Memphis)—only 6.8% of the county's coal-based NO_x emissions originate within the county, while 54.5% originate from in-attainment plants in other states. The counties in Table A3 may contribute to their own emissions problems in ways other than coal-based electricity generation—e.g., mobile sources or other major stationary sources. Regardless, it is still striking how much of these counties' coal-based NO_x emissions come from external, in-attainment sources—particularly given that these counties (1) are in non-attainment with respect to the NAAQS and (2) *house their own coal plants*.

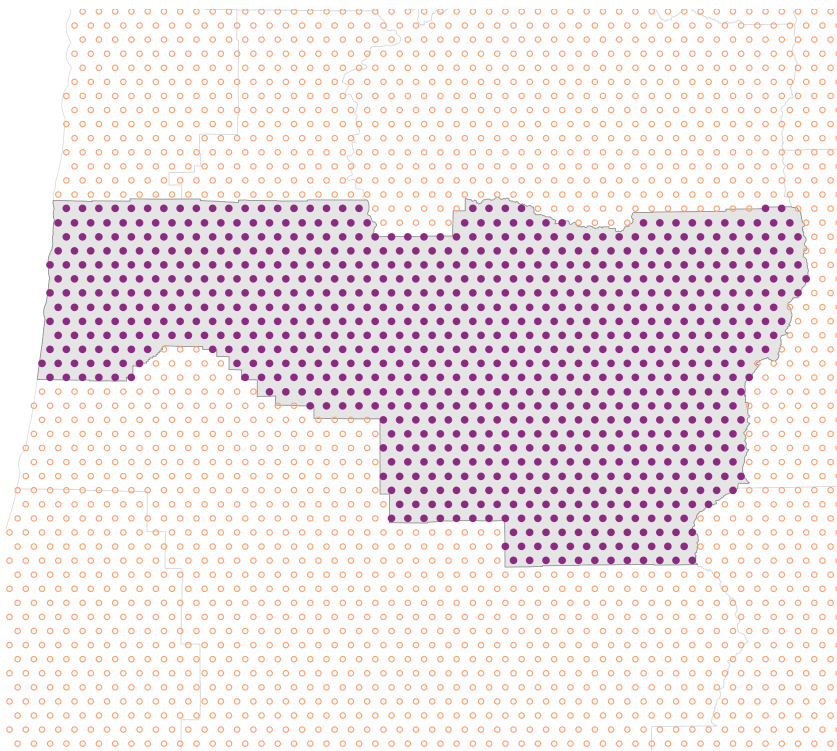
A.3 Appendix: Figures

Figure A1: NARR prevailing wind directions



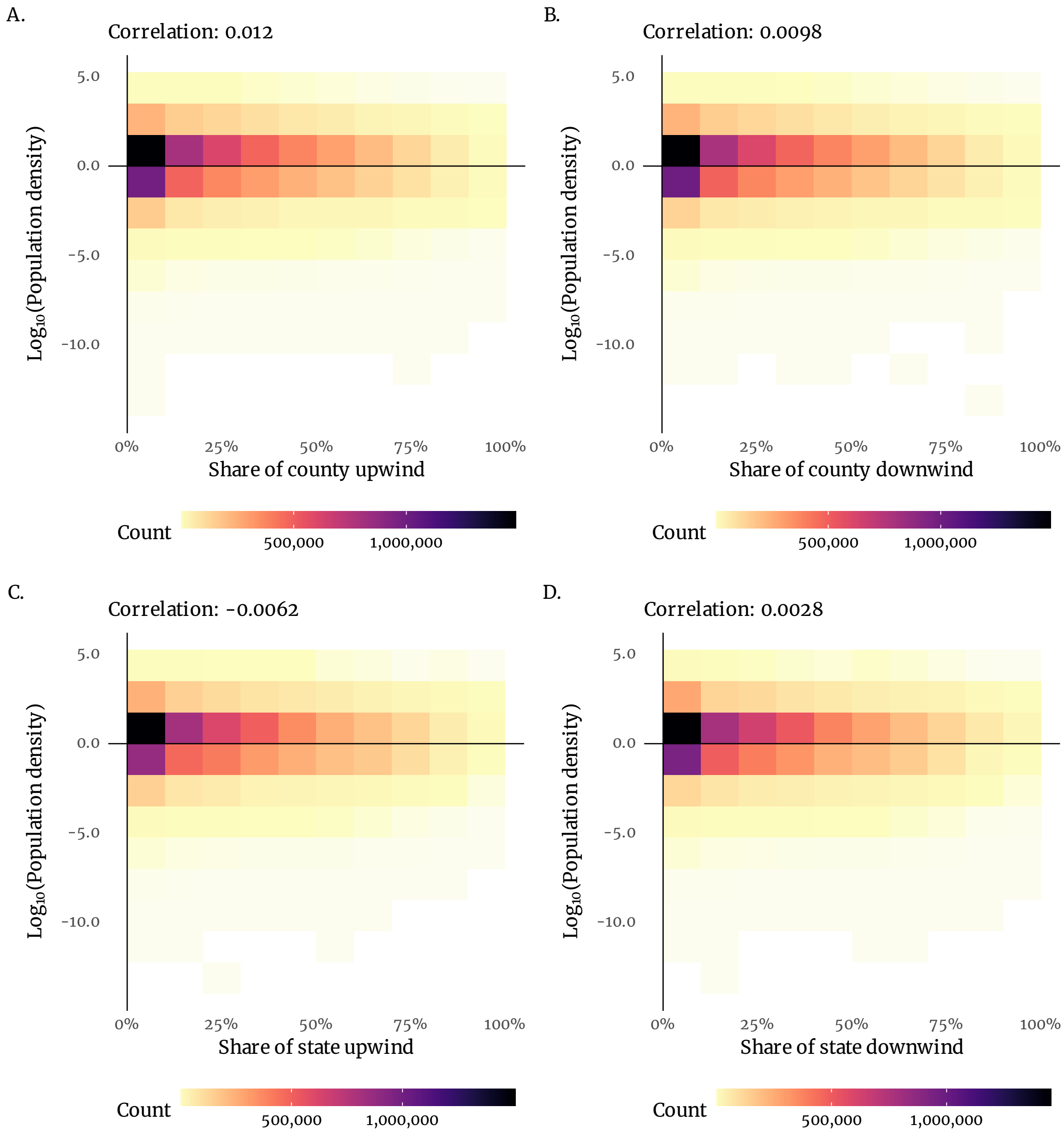
This map depicts the near-ground prevailing wind directions from NARR, 2006.

Figure A2: Example of grid for distance calculation



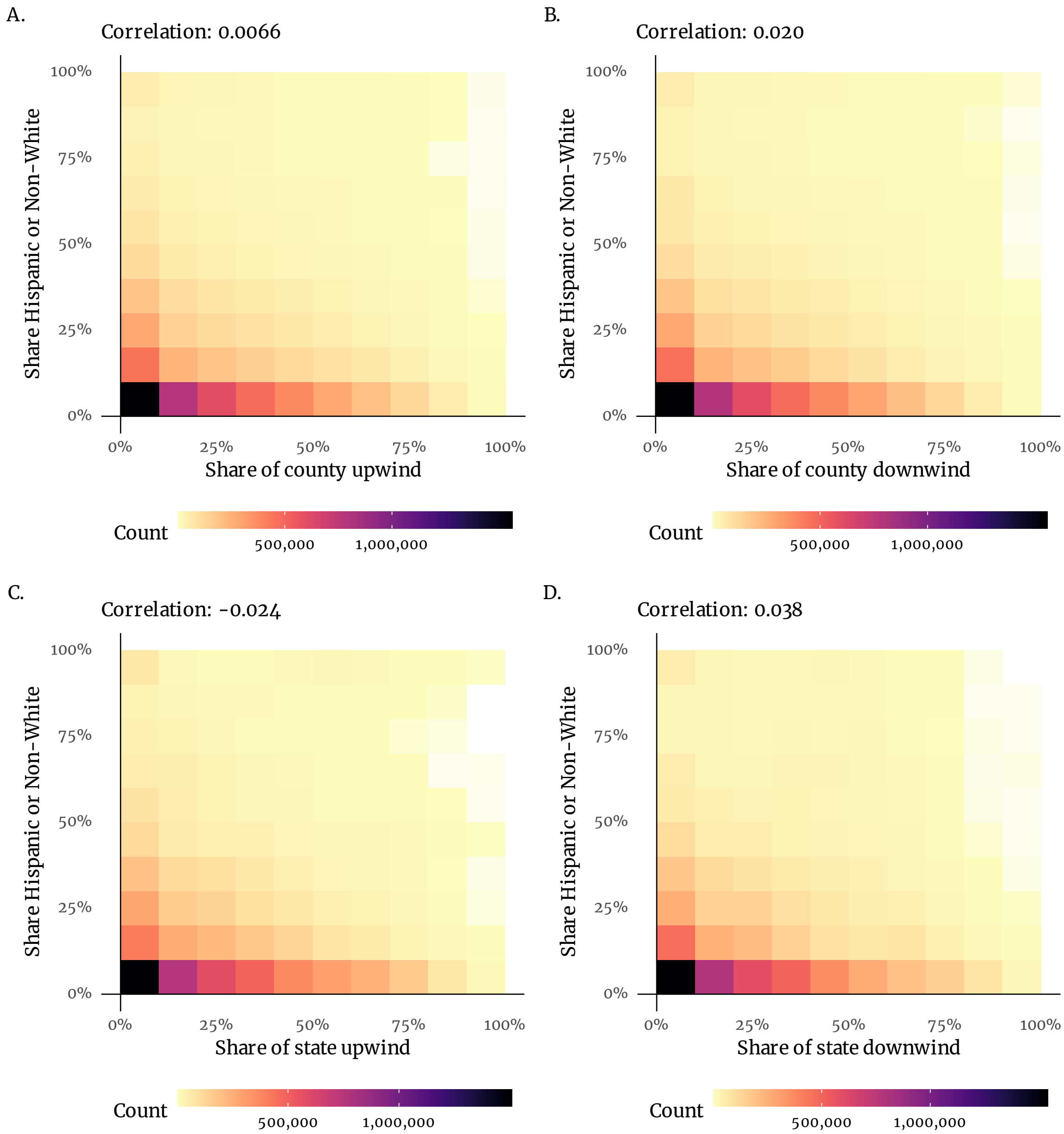
This figures illustrates the uniform grid within our nearest-border calculation. All dots (open and closed) are part of the uniform grid. Closed, dark purple dots are within Lane County, Oregon. We then calculate the shortest distance from each dot to borders of Lane County and of Oregon.

Figure A3: Population density and area down- or up-wind



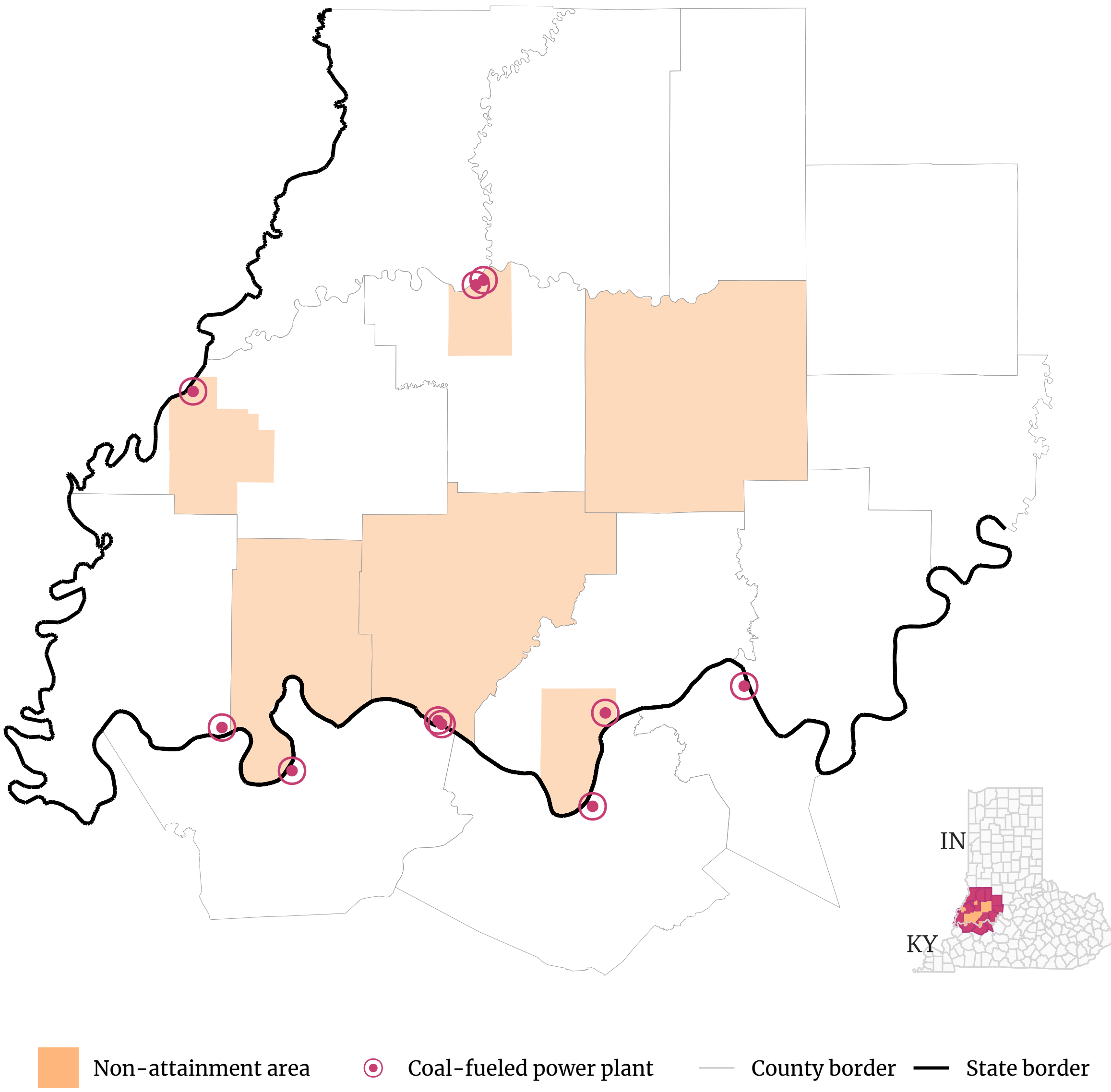
Using a uniform grid that covers the entire contiguous U.S., these figures show the relationship between (1) population density (here, transformed via base-10 log) and (2) the share of the county or state that is upwind or downwind of the grid cell. Due to the large number of grid cells, we use a heat map rather than the typical scatter plot. Note: Because we define *upwind* and *downwind* using a 90-degree triangle, very few points in the U.S. are upwind or downwind of more than 75% of their states or counties.

Figure A4: Population share that is Hispanic or non-white *vs.* area down- or up-wind



Using a uniform grid that covers the entire contiguous U.S., these figures show the relationship between (1) the share of the cell's population that is Hispanic or non-white and (2) the share of the county or state that is upwind or downwind of the grid cell. Due to the large number of grid cells, we use a heat map rather than the typical scatter plot. Note: Because we define *upwind* and *downwind* using a 90-degree triangle, very few points in the U.S. are upwind or downwind of more than 75% of their states or counties.

Figure A5: A "complex" non-attainment area: Evansville, IN



This map illustrates the complexity of the Evansville, Indiana non-attainment area (orange), which covers six counties (3 whole; 3 partial) within Indiana (along its borders with Kentucky to the south and Illinois to the west). Six of the counties form a contiguous area. The remainder of the non-attainment area is formed by islands in three counties that cover nearby coal plants (circled, red dots). As with Figure 9, the non-attainment area is for the 1997 $PM_{2.5}$ standard.

A.4 Appendix: Tables

Table A1: Testing EGUs' border distances relative to uniform US grid border distance

	County borders		State borders	
Fuel category	K-S test stat.	*p*-value	K-S test stat.	*p*-value
Coal	0.248	$< 1 \times 10^{-6}$	0.194	$< 1 \times 10^{-6}$
Gas	0.143	$< 1 \times 10^{-6}$	0.107	$< 1 \times 10^{-6}$
Hydro.	0.477	$< 1 \times 10^{-6}$	0.178	$< 1 \times 10^{-6}$
Solar/Wind	0.037	0.106	0.096	$< 1 \times 10^{-6}$

The columns labeled *K-S test stat.* contain Kolmogorov-Smirnov test statistics testing EGUs' distances to borders against the distribution of distance-to-border built by our uniform national grid. We conduct the tests by EGU fuel category (rows) and administrative level (county and state). The *p*-values correspond to the adjacent Kolmogorov-Smirnov test statistic.

To test whether the distribution of EGUs' distances to nearest borders is consistent with random sampling from the national grid we employ a simple, non-parametric, Kolmogorov-Smirnov test. The Kolmogorov-Smirnov test is designed to test whether the empirical distribution of a sample statistically differs from a known distribution, which is exactly our goal of this exercise: does the distribution of the EGUs differ from the national distribution?[52] We focus on five major fuel categories: coal, gas, hydropower, and *other renewables* (wind and solar). For each fuel category, we test whether its EGUs' distances to county (or state) borders statistically differ from the distribution of grid points' distances to borders (the grid described above).[53] The results are displayed in A1.

The K-S test resoundingly rejects that null hypothesis that the EGUs' distributions mirror the grid's distribution for each combination of administrative level (county or state) and fuel category (coal, gas, hydro, or solar/wind) with one exception. As one may guess from Figure 3, the one exception is the distance from solar and wind generators to the nearest county border. This distribution fails to reject the null with a *p*-value of approximately 0.106 (and a K-S test statistic of 0.037). Except for the solar and wind generators' distances to county borders, we observe overwhelming evidence that EGUs are disproportionately sited near county and state borders—particularly for coal and hydropower units. This observation emphasizes the complexity of monitoring and regulating emissions from EGUs.

[52] Alternatively, the *two-sample* Smirnov test (sometimes called the two-sample Kolmogorov-Smirnov test) tests whether the underlying distributions of two samples statistically differ.

[53] We use `R`'s `base` function `ks.test()`.

Table A2: Robustness to omitting coastal counties: Upwind *vs.* downwind areas for coal and natural gas plants

	(1) Coal-fueled plants	(2) Natural-gas-fueled plants
Panel a: Siting strategically within **county**		
Count	475	915
Count *strategic*	263	461
Percent *strategic*	55.37%	50.38%
Fisher's exact test of H_o: In-**county** downwind area ≤ upwind area		
Under H_o: E[Percent strategic: County] = 50%		
P-value	0.0108	0.4214
Panel b: Siting strategically within **state**		
Count	475	915
Count *strategic*	251	437
Percent *strategic*	52.84%	47.76%
Fisher's exact test of H_o: In-**state** downwind area ≤ upwind area		
Under H_o: E[Percent strategic: State] = 50%		
P-value	0.1164	0.9175
Panel c: Siting strategically within **both county *and* state**		
Count	475	915
Count *strategic*	157	230
Percent *strategic*	33.05%	25.14%
Fisher's exact test of H_o: Downwind area ≤ upwind area in **county and state**		
Under H_o: E[Percent strategic: County ∧ State] = 25%		
P-value	0.0001	0.4746

By omitting counties on the coast, this table shows the results of Table 1 are not driven by siting in coastal areas. As before, we define a plant's location as "strategic" if the downwind area *within its home county (or state)* is less than its upwind area *within its home county (or state)*. We calculate *downwind* and *upwind* areas based upon 90-degree right triangles with a vertex at the plant pointing up- or down-wind based upon the locally prevailing wind direction. Figure 2 illustrates this calculation. *Sources:* eGRID (2018) and authors' calculations.

Table A3: Top 10 non-attainment counties by share of local coal-based NO_x emissions originating from sources in external, in-attainment counties, January and July 2005

			Source of given county's coal-based NO_x emissions				
				Same-state sources		**Other-state** sources	
Rank	County	CBSA	Own	Attn.	Non-Attn.	Attn.	Non-Attn.
Panel A: January 2005							
1	Fort Bend, TX	Houston-The Woodlands-Sugar Land, TX	17.8%	29.3%	0.0%	48.1%	4.8%
2	Shelby, TN	Memphis, TN-MS-AR	18.1%	5.6%	0.4%	60.6%	15.3%
3	Randolph, IL		6.7%	22.7%	1.1%	40.8%	28.7%
4	Franklin, MO	St. Louis, MO-IL	11.2%	6.0%	8.3%	57.1%	17.4%
5	Madison, IL	St. Louis, MO-IL	2.4%	28.7%	1.7%	33.8%	33.4%
6	St. Charles, MO	St. Louis, MO-IL	7.8%	5.9%	12.0%	56.6%	17.7%
7	Jefferson, MO	St. Louis, MO-IL	1.7%	6.5%	21.0%	53.5%	17.3%
8	St. Louis, MO	St. Louis, MO-IL	6.1%	5.6%	16.1%	53.6%	18.7%
9	Sheboygan, WI	Sheboygan, WI	17.2%	10.4%	8.3%	42.6%	21.5%
10	Vigo, IN	Terre Haute, IN	14.4%	10.5%	19.8%	38.9%	16.5%
Panel B: July 2005							
1	Shelby, TN	Memphis, TN-MS-AR	6.8%	14.3%	0.4%	54.5%	24.1%
2	Pima, AZ	Tucson, AZ	19.3%	39.8%	19.6%	16.4%	4.9%
3	Franklin, MO	St. Louis, MO-IL	16.7%	5.4%	6.0%	49.9%	22.0%
4	Anderson, TN	Knoxville, TN	9.6%	19.4%	6.5%	35.0%	29.6%
5	Edgecombe, NC	Rocky Mount, NC	3.9%	17.5%	13.3%	35.4%	29.9%
6	Fort Bend, TX	Houston-The Woodlands-Sugar Land, TX	48.9%	33.7%	0.0%	17.4%	0.0%
7	Sheboygan, WI	Sheboygan, WI	12.9%	12.4%	17.2%	38.0%	19.5%
8	Catawba, NC	Hickory-Lenoir-Morganton, NC	16.0%	5.7%	5.4%	43.3%	29.6%
9	Orange, NC	Durham-Chapel Hill, NC	1.3%	8.4%	12.3%	40.2%	37.8%
10	Gaston, NC	Charlotte-Concord-Gastonia, NC-SC	16.2%	8.4%	10.4%	38.9%	26.1%

This table highlights how much coal plants in *attainment counties* may affect air quality in non-attainment counties. We decompose (and rank) each county's coal-generated NO_x emissions by the source of the emissions (same-state *vs.* other-state sources) and by attainment status of the source. *Attn.* and *Non-attn.* refer to sources in attainment and non-attainment jurisdictions, respectively. Counties in this table meet two criteria: (1) non-attainment counties (2) with non-zero coal generation in the given months. We rank counties by the share of coal-based NO_x originating from in-attainment sources (separately for January/July 2005). These shares are based upon HYSPLIT estimates, as described in the methods.