

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

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## Abstract

US environmental policy cedes substantial authority to local governments/agencies—creating potentials for polluters to strategically export emissions. We identify such strategies among coal-fueled power plants. We document electricity generators locate near administrative borders. As water may influence borders/siting, we develop a simple, non-parametric test that demonstrates coal plants locate to reduce their downwind exposure. Natural-gas plants—facing lower regulatory pressure—do not exhibit this behavior. Using a state-of-the-art, particle-trajectory model, we illustrate coal pollution’s extreme mobility: within 6 hours, 50% of coal plants’ emissions leave their source states—99% leave their counties. These strategic responses emphasize the importance of federal oversight and transport-focused regulation.

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# 1 Introduction

Environmental regulation in the US has historically followed a decentralized, federalist approach—ceding substantial authority to state, county, and municipal governments. The US Clean Air Act (CAA), the crown jewel of US environmental regulation, is an important example of this decentralized approach. Under the CAA, local and state governments wield considerable authority for key activities in monitoring and enforcing the National Ambient Air Quality Standards (NAAQS) (US EPA, 2017d; US EPA, 2017b). For example, these sub-federal governments site air-quality monitors, permit and site polluters, monitor local air quality, designate compliance with air-quality standards, and enforce (or relax) emissions restrictions. 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).

While federalism theoretically offers certain efficiencies (Oates, 1972), federalist regulatory systems face two important challenges when governing air quality: (1) air pollution can travel long distances (i.e., crossing local and state borders) (U.S. Senate, 1963; Oates, 2002; Sergi et al., 2020) and (2) individually, local and state governments have 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). Specifically, the spatially discontinuous patchwork of local and state authorities presents opportunities for firms and/or regulators to strategically site major polluters in locations that reduce air-pollution exposure within the county/state.

This paper empirically substantiates both of these key challenges to a federalist approach to environmental policy. Namely, we identify strategic siting within a class of major air polluters in the US, and we illustrate the problems caused by the trans-boundary nature of the pollution generated by these plants. We focus on a major category of air polluters: coal-fired electricity generating units (coal EGUs). Historically, coal EGUs have accounted for a substantial share of air pollution in the US.<sup>1</sup> In addition to accounting for large shares of pollution in the US, electricity generators are required to record important emissions data—unlike most other major polluters. Thus, this setting (electricity generation) includes an empirically helpful “placebo” for coal EGUs—i.e., natural-gas EGUs.

First, we show coal EGUs tend to locate near county and state borders (57% are within 5 km of a county border; 25% are within 5 km of a state border). We then derive a simple, non-parametric statistical test and document that coal EGUs strategically locate to reduce their downwind area in their home county and state (both in absolute terms and relative to natural-gas EGUs). In addition, we show that the CAA, which attempted to arbitrate cross-state pollution, had little

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<sup>1</sup> E.g., in 2014, US coal EGUs accounted for approximately 65.7% of SO<sub>2</sub> emissions, 44.0% of mercury emissions, 39.1% of arsenic emissions, and 10.6% of NO<sub>x</sub> emissions in the United States (U.S. E.P.A., 2018).

effect on this strategic siting behavior. However, the CAA does appear to have induced more coal EGUs to locate within “interior” counties (rather than counties on states’ borders). Demand for water likely explains some of the tendency for coal EGUs to locate near borders. Still, water does not explain their tendency to choose locations that reduce the downwind area in their home counties and states.

Finally, we use HYSPLIT (a state-of-the-art particle-trajectory model developed by NOAA) to document the pervasiveness of trans-boundary air pollution. For the vast majority of coal EGUs in the US, nearly all of the plant’s pollution leaves its home *county* within 6 hours of being released. At the state level, 50%–75% of coal EGUs’ emissions leave their *state* of origin within 12 hours of release. We also show that several counties in violation of the national ambient air-quality standards (NAAQS) receive substantial amounts of NO<sub>x</sub> and SO<sub>2</sub> from coal EGUs from counties considered in compliance with the standards. Together, these results illustrate important challenges facing a decentralized, federalist approach to air-quality regulation in the US.

Our results are consistent with a growing literature on strategic responses to federalist approaches in air-quality monitoring and regulation. This nascent literature has identified three varieties of strategic responses by polluters: (1) strategic siting of polluting plants (Monogan III, Konisky, and Woods, 2017), (2) strategic production or abatement decisions (Zou, 2021), and (3) strategic siting of pollution monitors (Grainger, Schreiber, and Chang, 2018). 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, ambient 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 pollution. Broadly, this literature suggests the current implementation of federalist-inspired air-quality regulation creates opportunities for polluters to avoid regulatory oversight.

In addition, our paper relates to a large literature on the pollution-haven hypothesis (PHH). The PHH posits that polluters will tend to locate in areas with less stringent environmental regulation. Much of the literature investigates this hypothesis at the international level—focusing on how emissions-intensive production shifts towards countries with lax environmental regulation.<sup>2</sup> However, the US’s sparse network of monitors and discontinuous patchwork of local regulatory authorities (state and sub-state) also fits this hypothesis—creating variation in environmental regulation. We document that within states and within counties, coal EGUs have been strategically sited in a manner consistent with the pollution-haven hypothesis.

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<sup>2</sup> Cole (2004), Levinson (2008), Millimet and Roy (2015), and Cherniwhan, Copeland, and Taylor (2017) provide helpful overviews and discussions of the PHH literature.

This 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.<sup>3</sup> Comparing downwind area to upwind area, within the same jurisdiction, implicitly controls for the size of the jurisdiction. Monogan III, Konisky, and Woods (2017), in contrast, focus on the distance to either the “downwind border” or the “upwind 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. There appear to be no existing analyses that detect county-level strategic siting. Polluters may face incentives created by both county and state regulators/governments, causing strategic siting at either or both levels. Third, we focus exclusively on electricity generators—and specifically compare coal EGUs with natural-gas EGUs. As described above, coal EGUs account for a substantial share of local and national air pollution ( $\text{PM}_{2.5}$ ,  $\text{NO}_x$ ,  $\text{SO}_2$ , mercury, lead, ozone, and CO) and are consequently regulated and monitored closely by both federal (especially US EPA) and local (state and county) authorities.<sup>4</sup> Finally, we extend beyond Monogan III, Konisky, and Woods (2017) and the literature by including additional descriptions of the geography of power plants *and*, importantly, descriptions of the transport of coal EGUs’ emissions across the US.

Methodologically, our empirical test of strategic location overlaps with a growing literature that uses wind-direction variation 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 to upwind area within the jurisdiction to identify strategic siting among major polluters.<sup>5</sup>

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

<sup>3</sup> As we explain below, we define downwind/upwind area using 30-year averages for prevailing wind directions from NOAA (NARR, 2006).

<sup>4</sup> In addition, coal EGUs are unique in their tendency to build tall smokestacks: there are 15 smokestacks in US of at least 1,000 feet and nearly 300 chimneys of at least 500 feet (U.S. G.A.O., 2011; CAMD, 2020).

<sup>5</sup> 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).

“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 both the extent to which pollution travels and the health and policy problems posed by pollution transit.<sup>6</sup> Sergi et al. (2020) find that despite national reductions in PM<sub>2.5</sub> from point sources since 2008, approximately 26% of counties have experienced worsening health damages from pollution—noting that “around 30% of all US 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 US.<sup>7</sup> 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 extent of this problem and the damages it causes.

As our understanding of transboundary pollution has evolved, so has its regulation—from the Clean Air Acts of 1963 and 1970, to subsequent CAA amendments in 1977 and 1990, to the US EPA’s Cross-State Air Pollution Rule in 2012. This paper illustrates that despite advances in the scientific understanding of (trans-boundary) air-pollution and policy updates, (1) a class of major polluters (coal EGUs) still found it fruitful to locate near county and state borders (downwind within their county/state), and (2) the vast majority of emissions from these plants affects populations in counties and states far from the locations of the polluting plants. These observations suggest that, though helpful, current pollution regulations—in conjunction with the trans-boundary nature of the pollution from coal EGUs—may not entirely preclude strategic behavior by polluters/local governments or limit the spatial scope of the externalities caused by air pollution. By illustrating the incentives the current regulatory structure creates, we hope this paper will assist policymakers and regulators in capturing additional social benefits—be they health, environmental, and/or economic.

## 2 Institutions

**The Clean Air Act** The United States’ Clean Air Act (CAA) is often considered the *crown jewel* of environmental legislation in the US (Feldman, 2010; Browning, 2020). Established in 1963 and greatly extended in 1970, one of the primary goals of the CAA was to establish the aforementioned NAAQS standards. Local (county and state) regulators work with the federal EPA to site regulatory-grade monitors for the six “criteria” NAAQS pollutants. This sparse network of *in situ* regulatory monitors measures “local” air quality (often referred to as

<sup>6</sup> 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).

<sup>7</sup> 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.”

“county-level” air quality) across the United States.<sup>8</sup> While counties are often the initial focus for monitoring and compliance considerations, sub-county areas and/or adjoining counties can be jointly considered for compliance—often aggregating to “air regions” that resemble metropolitan areas (CRS, 2013; CRS, 2012). The CAA jointly charges states and the EPA to implement air-quality standards (US EPA, 2013a)—though states are in charge of coordinating implementation plans to abide by the NAAQS (US EPA, 2020a). Regions that fail to comply with the NAAQS are deemed *out of attainment*—also called *non-attainment areas*. Regulators often require polluters in non-attainment areas to install expensive abatement technologies and can impose emissions constraints to bring the region back into *attainment*.

The CAA recognizes cross-border air pollution is a challenge on a scale larger than neighboring counties. 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).<sup>9</sup> Further emphasizing the importance of cross-border pollution transport, in 2011 the US EPA enacted the Cross-State Air Pollution Rule (CSAPR). The CSAPR covers 27 states<sup>10</sup> in the eastern US—especially targeting power-plant emissions of SO<sub>2</sub> and NO<sub>x</sub> and their formation of fine-particulate matter (PM<sub>2.5</sub>) and Ozone (O<sub>3</sub>) (US EPA, 2020b). 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, 2020b). 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 emissions (Sanders, 2018; Volcovici, 2018; Groom, 2019).

**Siting plants** Firms’ decisions on where to site a new plant depend upon a host of variables—proximity to water,<sup>11</sup> grid/transmission availability,<sup>12</sup> access to fuel<sup>13</sup> (e.g., rail lines, pipelines,

<sup>8</sup> Grainger, Schreiber, and Chang (2018) discuss and examine the potential for strategic monitor siting.

<sup>9</sup> The CAA also allows states to petition the EPA for reviews of upwind sources (US EPA, 2013b).

<sup>10</sup> Texas, Oklahoma, Kansas, and Nebraska comprise the western edge of the CSAPR states.

<sup>11</sup> Steam-driven turbines and water-cooled plants mechanically require water. We document the distribution of plants’ proximities to water in *Strategic siting and the geography of US electricity plants* and Figure 4.

<sup>12</sup> 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.

<sup>13</sup> Preonas (2019) documents market-power-driven markups in coal-by-rail delivery to coal plants in the US.

wind/solar capacity), local regulatory oversight<sup>14</sup> (i.e., friendliness to industry), and local community characteristics,<sup>15</sup> (among others). While a substantial literature considers how local environmental regulations and enforcement affect the location of polluting firms across states and counties (see footnote 14), we are unaware of prior work that considers where firms locate at a finer scale (i.e., within state or county). However, the logic is fairly simple. If a firm reduces the area downwind from its emissions *within its own county* (or state) it may also reduce its regulation-based costs from these emissions. In terms of the modern NAAQS: A firm's emissions would be recorded by monitors in downwind areas outside of the county/state, rather than the monitors within its “home” county. Figure 1a illustrates a plant with limited downwind area (the dark purple shaded area) within its home county. The financial motivation to minimize the probability of non-attainment designation is clear to both the firm and other local businesses/regulators. When counties are deemed out of attainment, violators are often required to install costly new emission-control technology and may face a moratorium on future installations—in addition to the potential for literal fines (CRS, 2013; CRS, 2012; US EPA, 2017a). This penalty of limiting installation of additional emissions generators is especially relevant when considering local regulator's incentives, as in Grainger, Schreiber, and Chang (2018). The same incentives that cause the CAA to bind also create the potential for strategic avoidance responses.

### 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,<sup>16</sup> 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 not available). The EmPOWER CAMD data supply each EGU's daily

<sup>14</sup> 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 Shadbeginian and Wolverton (2010).

<sup>15</sup> Wolverton (2009) finds a significant negative association between plant sitings and income.

<sup>16</sup> More details can be found at [the EmPOWER website](#).

emissions of  $\text{NO}_x$  and  $\text{SO}_2$  and the EGUs' associated stacks' heights—both of which are inputs to the particle-trajectory model HYSPLIT. Panel B of Figure 4 illustrates the distribution of generators' capacities across four broad fuel categories for units operating in 2018. Figure 5 depicts the birth years for coal and natural-gas plants in the eGRID data.

**Meteorology** Our meteorologic 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, historic wind patterns in our analysis of strategic plant sitings. Specifically, we use NARR's first three pressure levels: 1000 hPa, 975 hPa, and 950 hPa. 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).

**Geography** For state borders, county borders, coast lines, and bodies of water we rely upon the US 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 US EPA's *NAYRO* file in its *Green Book* collection (US EPA, 2017c). In this paper, we focus exclusively on EGUs in the contiguous US—omitting Alaska, Hawaii, and US territories.

## 4 Strategic siting and the geography of US electricity plants

In this section, we conduct our main empirical analysis. We begin in 4.1 by documenting the fact that many EGUs are found near county and state borders. We show that there are reasons for this behavior that are *unrelated to regulatory avoidance*—we show that many 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. Finally, in 4.3 we apply this test for strategic siting and discuss its results.

### 4.1 EGUs' distances to borders and water

**Border distance** Using eGRID's plant locations, we calculate each plant's distance to the nearest county and state border.<sup>17</sup> 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*

<sup>17</sup> See appendix section A.1.1 for the details of this calculation.

*a plant* (ORIS code) are specified as the same location in eGRID. Figure 3 depicts the result—the distribution of EGUs' distances to their nearest state and county borders. We separate by the EGUs' fuel categories, as differences in EGUs' fuel types drive differences in other inputs (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).

Figure 3 demonstrates that EGUs tend to locate near county borders (Panel A) and state borders (Panel B). This tendency is particularly strong in coal-fueled and hydropower EGUs, though natural gas plants also exhibit this tendency.<sup>18</sup> 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 within 10 km of a county border. For state borders, the corresponding percentages are 18% ( $\leq 1$  km), 25% ( $\leq 5$  km), and 29% ( $\leq 10$  km). Only hydropower EGUs are more drawn to borders than coal-fueled EGUs. We formally test EGUs' distances to borders against a uniform grid covering the entire contiguous US using a Kolmogorov-Smirnov test—effectively asking whether EGUs' placements are independent of borders. All fuel types strongly reject this independence with the exception of solar/wind's distance to county borders (see Table A1). As Figure 3 and these statistics suggest, a substantial share of US coal-fueled electricity generators are sited near county and state borders—a fact that complicates regulation, regardless of its cause.

**Non-strategic explanations for EGUs' proximity to borders** As we test below, one explanation for EGUs' tendency to site near county and state borders is that it complicates monitoring and regulation—potentially reducing costs for the plant or local government. However, there are other reasons to site plants near borders. Most methods of electricity require water for steam, cooling, locomotion, and/or transportation (solar and wind are exceptions). If administrative boundaries are often formed by large bodies of water, then EGUs' need for water could explain firms' tendencies to site plants near borders.<sup>19</sup>

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*). Appendix section A.1.3 describes this operation in detail.

We find that across the contiguous US, 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 6 illustrates this heterogeneity, and Figure 7 provides four examples of the county and state borders identified as intersecting with water (in

<sup>18</sup> While natural-gas EGUs do need some water for generation, another explanation for natural-gas EGUs locating near borders is that many gas EGUs have been converted from coal EGUs—or are co-located with coal EGUs.

<sup>19</sup> This explanation also requires that the interiors of counties (and states) are disproportionately dry, relative to their borders. Otherwise, EGUs could just as easily locate in counties' interiors rather than on borders.

dark blue lines). As demonstrated by Figure 6, states in the non-coastal, western US make up the bottom 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 EGU locations featuring water and proximity to the border.

Panel A of Figure 4 confirms that EGUs do, indeed, locate near bodies of water (except wind and solar): 99% of hydropower units and 62% of coal units are within 250 meters of a body of water.<sup>20</sup> Only 48% of natural-gas units 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 on the interior of counties/states, and yet coal EGUs tend to locate near administrative borders.<sup>21</sup>

## 4.2 A test for regulatory avoidance

In this section, we develop a simple, non-parametric test to detect whether plants strategically site near borders to avoid/complicate regulatory oversight—as opposed to siting near borders coincidentally due to their demand for other inputs (e.g., water, labor, transportation networks).

Coal-fueled electricity production offers a classic example of a 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. Consequently, agents—firms or governments—can avoid the costs of pollution<sup>22</sup> by exporting their emissions to other jurisdictions soon after the emissions’ release. Locating near borders helps with this export.

With this motivation in mind, it is clear that certain borders are more advantageous than others. If a plant locates near the downwind border of its county, its emissions immediately leave the county. If the plant locates near the upwind border of its county, its emissions pass through its

<sup>20</sup> Measurement error in the latitude and longitude of generators and the Census water files likely explains why hydropower does not hit 100%.

<sup>21</sup> For example: The *interior* Catawba County in North Carolina contains the Marshall Steam Station, a 2.1-gigawatt coal plant located on Lake Norman.

<sup>22</sup> Firms face costs for their own pollution when regulators require pollution abatement technologies— incentivizing emissions export. Local governments face costs from pollution due to restricted economic activity to meet national standards, reduced amenity/property values, and internalized local health damages.

entire county. Thus, all else equal, major polluters (e.g., coal plants) and/or local governments will prefer to reduce the area in the county that is *downwind* of the plant.<sup>23</sup>

Now consider the possibility—our null hypothesis—that firms and governments do not try to export their coal pollution. Under this null, agents 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 to their emissions: this ratio is not an input to production. Put simply, 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).

Therefore, a simple, non-parametric test for strategic regulatory avoidance in the siting of coal-powered plants is to calculate the number of coal plants for whom the *downwind area* (in the county or state of residence) is less than the *upwind area*. This test is, in fact, 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

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

Because plants (and local governments) potentially face incentives to avoid regulation at both the county and state levels, we implement our test for strategic siting at both levels.

Our test offers several attractive features. First, as stated, it is simple and provides an exact  $p$ -value that does not rely upon parametric or asymptotic assumptions (Imbens and Rubin, 2015). Second, the identifying assumption is that a firm or government will only minimize a plant’s downwind area to avoid the emissions’ costs. This assumption is plausible, as 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 siting is the only real explanation for siting plants in a manner that reduces plants’ downwind exposure (relative to their area upwind). If a latent factor correlates with the ratio of 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 take into account the areas downwind or upwind

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<sup>23</sup> The same reasoning applies at the state level, i.e., plants and governments aiming to avoid regulatory oversight will site plants so as to reduce the state’s area downwind of a plant.

of a point in space—let alone their ratio. Further, natural-gas EGUs provide a convenient falsification test for this approach. Because natural-gas plants produce much fewer emissions than coal-fueled EGUs—and consequently face less regulatory pressure for their emissions—gas EGUs do not have the same incentives to reduce their downwind emissions exposure. However, natural-gas plants face similar transmission (and other unobservable) constraints to coal plants. Thus, if a latent factor is biasing our test toward detecting “strategic siting,” we should detect strategic siting for both coal EGUs and natural-gas EGUs. In short, this simple procedure generates an intuitive test for strategic siting with exact  $p$ -values and a convenient falsification test.

In addition, our test is easily extended to test whether plants locate so as to jointly reduce both 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%. Thus, the test provides simple, yet clear, evidence on whether coal plants were sited to reduce the downwind area in the plants’ home counties and states.<sup>24</sup>

To implement this test, we calculate the areas upwind and downwind of each coal and natural-gas plant in our data. 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 1 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 1a and 1b located near borders in a manner that substantially reduced the downwind area in the plant’s home county. The plants in Figures 1c and 1d were sited in parts of their county in which the downwind area is larger than the upwind area. With these calculated areas, we implement our test for strategic siting.

### 4.3 Results: Strategic plant siting

**Strategic siting: Main results** Table 1 contains the results for our test of strategically siting coal and natural-gas plants to reduce downwind area. Coal generators face the vast majority of emissions-based regulation among electricity generators and consequently have the strongest incentives to strategically locate so as to reduce the area downwind. Natural gas plants produce substantially lower emissions, face little emissions-based regulatory pressure, and thus have little incentive to locate so as to reduce their downwind areas. We separately test *coal plants* (columns 1–3) and *natural-gas plants* (columns 4–6). Table 1 contains three panels that respectively test strategic siting (a) within counties, (b) within states, and (c) within *both* counties

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<sup>24</sup> One drawback of the test’s simplicity is that it does not incorporate other dimensions of strategy, e.g., stack heights. This omission does bias the test for our specific hypothesis, but it does imply that we are testing for a specific strategy.

and states. Columns (1) and (4) test all observed plants, whereas the remaining four columns separately test plants that came online after the Clean Air Act of 1964 (columns 2 and 4) or those that came online before the CAA (columns 3 and 6).

Overall, the results in Table 1 solidly indicate strategic siting of coal plants so as to reduce 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 strategically locate to reduce their downwind areas at any level.

First consider strategic siting at the county level (**Panel a**). Among all 515 coal plants, 57.67% are sited such that the area downwind of the plant (in its county) is less than the area upwind. Under the null of no strategic siting, with 515 plants, one would observe a distribution at least this extreme (in the right tail) approximately 0.03% of the time (i.e., the *p*-value is 0.0003). For the 1,258 natural-gas plants, the corresponding share that are *strategically located* at the county level is 48.65% with *p*-value of 0.8381 (recall that under the null the expected share of strategically located plants at the county or state level is 50%). Columns (2) and (3) document that the share of strategic siting was essentially unchanged by the passage of the Clean Air Act of 1963—approximately 58% of plants sited strategically before and after the act. Strategic siting behavior for natural-gas plants was also unaffected by the CAA—remaining at 48%–49% before and after the act. At the county level, our test finds large and statistically significant evidence within the group most incentivized to strategically site (i.e., coal plants) and no evidence within the group with few incentives to do so.

The results at the state level (**Panel b**) paint a very similar picture to the county-level results. There is significant evidence of strategic siting among coal-fueled power plants (54.17% strategic with a *p*-value of 0.0321) and no evidence of strategic siting within natural-gas plants (45.71% with a *p*-value of 0.9939).<sup>25</sup> As is the case with county-level results, the state-level results also suggest that the passage of the 1963 CAA did little to affect the strategic siting of coal plants.

In **Panel c** of Table 1, we test whether plants are located strategically both within their counties and within their states. Recall that under the null hypothesis of *no strategic siting at either level*, the expected share of strategically sited plants is 25%. For the 515 coal plants, 35.34% are sited in a manner that consistent with strategic siting at both the county and state levels (*p*-value less than 0.0001). This result is, again, large and highly significant evidence that coal plants were sited to reduce downwind exposure within their counties and states. We find strong and

<sup>25</sup> 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 the same 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 replacing coal units with natural-gas units, firms may prefer to replace the poorly located units (i.e., those located with the largest downwind areas).

significant evidence of this strategic behavior both before and after the CAA (34% after the CAA; 37% before the CAA). As before, natural-gas plants show no evidence of strategic siting to reduce downwind areas when pooled (24.64%;  $p$ -value of 0.6258), after the CAA (25.03%;  $p$ -value of 0.5049), or before the CAA (23.19%;  $p$ -value of 0.7710).

Whether we consider the county level, the state level, or both levels simultaneously, we find substantial evidence that coal plants were sited to reduce the areas downwind in their counties and/or states. We also apply the same test for strategic siting to natural-gas plants—a class of plants with little-to-no incentives to strategically site. For this placebo test of natural-gas plants, we fail to detect any significant evidence of strategic siting—suggesting that our simple test is working correctly. We therefore conclude that Table 1 provides strong and statistically significant evidence that coal-fueled electricity plants strategically located to reduce the portion of their counties and/or states that are downwind of the plants. Further, this strategic siting behavior does not appear to have changed with the passage of the Clean Air Act.

**Strategic siting: Border vs. interior counties** Table 2 decomposes the main strategic-siting results for coal plants discussed above. We divide counties into two groups (*i*) counties on state borders (*border counties*, columns 1–3) and (*ii*) counties that do not touch their states' borders (*interior counties*, columns 4–6). As before, the top panel (a) of Table 2 provides county-level results, and the bottom panel (b) provides state-level results.

Of the 515 coal plants, 291 (~56.5%) are constructed in border counties. However, as Figure 5 shows, the share of coal plants constructed in border counties appears to have sharply declined around the time of the Clean Air Act of 1963. Before 1963, ~64.6% of the 229 coal plants were constructed in border counties; after 1963 exactly 50% of the 286 were constructed in border counties. The difference between these two proportions is highly significant (i.e., at the 0.1% level) and suggests that the CAA may have induced somewhat of an interior-county migration for coal plants. As Figure 5 suggests, there is no significant or appreciable evidence of an internal-county migration for natural-gas plants: prior to 1963, ~59.3% of gas plants were constructed in border counties; after 1963 ~58.5% of gas plants were constructed in border counties. This internal-county migration makes sense in light of the CAA's emphasis on interstate pollution: siting plants in border counties may have raised concerns over trans-boundary pollution in especially sensitive areas. However, this disincentive was clearly not sufficient to move all plants away from borders—strategic or otherwise.

Table 2 demonstrates that despite this internal-county migration, a large and statistically significant share of coal plants strategically sited *in border counties* (columns 1–3) before and after the CAA. The percentage of strategically sited coal plants remains fairly stable before and after the CAA: ~60.8% before the CAA and ~63.5% after the CAA ( $p$ -values of 0.0059 and 0.0006, respectively).

For *interior counties* there is a marked increase in the share of strategically located coal plants after the CAA of 1963—coinciding with the internal-county migration discussed above. However, neither this increase, nor the point estimate, are statistically significant. We are likely running into statistical power issues in this comparison having subsetted the coal plants twice (pre-/post-CAA and border/interior counties). Our test is underpowered to detect a 4.55 percentage-point deviation from the null of 50% with only 143 observations (the minimum-detectable effect with 143 observation is a 7.3 percentage-point increase—82 of 143 plants (~57.3%) would need to be strategically located for us to reject the null hypothesis at the 5% level.)

At the state level (Panel b), we find similar results but with smaller point estimates and lower statistical significance—again likely resulting from power issues after twice subsetting the coal plants. There is statistically significant evidence coal plants strategically siting in border counties with respect to *state areas* (56.01% in column 1), and the level of strategic siting again remains essentially unchanged before and after the 1963 CAA (56.08% vs. 55.94%). For interior counties we find no statistically significant evidence of state-level strategic siting. This finding is also quite plausible: a plant wishing to reduce the downwind area *in its state* will likely look to border counties rather than interior counties.

Table 3 repeats this border-interior decomposition for natural-gas plants (our placebo). Again, we find no significant evidence of strategic siting among these natural-gas plants—neither in border counties, nor in interior counties. The lack of evidence for natural-gas plants persists both at the county level and at the state level. We are fairly well-powered to detect a strategic effect among the 1,258 natural-gas plants (our test’s minimum-detectable effect with 1,258 plants is a 1.9 percentage-point increase). Yet still find no evidence among natural-gas plants.

**Strategic siting: Summary** Across all of our siting results, there is strong evidence that coal plants strategically sited to reduce their downwind areas. Across Tables 1–2, we find 55%–64% of coal plants strategically sited at the state or county level (recall that non-strategic siting should yield 50% of plants appearing to be strategic). We do not expect this number to be near 100%, as firms and governments have many other constraints when siting coal plant (e.g., water, rail, state-implementation plants for the NAAQS, and local opposition to some sites). The fact that these results persist at every level for coal plants and are entirely absent for natural-gas plants provides further evidence of strategic siting among these highly polluting and highly regulated coal plants.

It appears that this strategic siting—both at the county and state levels—is largely driven by siting behavior within states’ border counties. If plants or local governments wish to reduce their downwind exposure, a set of the state’s border counties provide ideal locations—rationalizing the observed strategic siting of major polluters. While the share of strategically sited coal plants in interior counties increased after the CAA—the same period in which the share of coal plants

in these counties also increased—we cannot reject that this increase happened by chance.

In the next section we examine how this strategic geography of coal plants, in conjunction with other key coal-EGU factors, affects the distribution of coal-plant-based emissions across the US.

## 5 Cross-border pollution and the geography of emissions

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 US 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). The strategic behaviors documented in the previous section—siting coal plants near borders while minimizing downwind areas within the sited county/county—will exacerbate this challenge. Air-quality policy in the US has recognized this transport problem since at least the 1960s (U.S. Senate, 1963; Edelman, 1966; U.S. Congress, 1968)—and recent policies have attempted to limit its extent, e.g., the Clean Air Interstate Rule (CAIR) and the Cross State Air Pollution Rule (CSAPR). Yet, the highly transportable nature of pollution (especially PM<sub>2.5</sub>, NO<sub>x</sub>, and SO<sub>2</sub>), the tall chimneys of coal plants, and the geographic/strategic distribution of coal plants themselves all continue to create regulatory challenges—as evidenced by recent lawsuits brought against the EPA for interstate pollution issues (Sanders, 2018; Volcovici, 2018; Groom, 2019).

In the subsequent sections, we demonstrate the extent of the transport problem using the particle-trajectory model HYSPLIT. We show (1) how quickly emissions leave the counties and states that house the coal plants (potentially separating plants' benefits from their externalities) and (2) many non-attainment counties receive substantial coal-based emissions from plants located in attainment counties. Alongside the previous results for strategic siting within counties and states, these results suggest that air-quality policy may need to consider much larger areas (in a similar spirit to the CSAPR).

### 5.1 HYSPLIT

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, HYbrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) (R. R. Draxler and Hess, 1998; R. Draxler 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 (A. F. Stein 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 C. M. Zigler, 2019; Henneman, Mickley, and C. 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 (Ariel F. Stein et al., 2009), volcanic ash (Stunder, Heffter, and R. R. 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 data (NARR, 2006). We then model particle trajectories for the  $\text{NO}_x$  and  $\text{SO}_2$  emissions of every coal-fueled EGU above 25 MW<sup>26</sup> in the contiguous US every day during January 2005 and July 2005. As described in *Data*, unit-level emissions releases and stack heights come from CAMD (2020).<sup>27</sup> 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 2: disperse particle paths for hundreds of particles originating at a specific EGU's longitude-latitude-height on a given date-time of release.

## 5.2 Results: Cross-boundary pollution

In Figure 2 it is clear that the two plants' emissions leave their source counties within a few hours and much of the plants' emissions leaves their source states within 24 hours of being released. This quick departure from the source counties and states occurs in both January and July. However, Figure 2 also highlights the fact that pollution transport's distance and direction may vary greatly by season (even within a plant).

**Transporting pollution away from sources** To formalize these insights, for each coal plant we calculate the share of emissions that have left the plant's county/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 ( $\text{NO}_x$  vs.  $\text{SO}_2$ ). For example, in January 2005, we calculate 32.9% of  $\text{NO}_x$  emissions from coal plant "3470" (depicted in Figure 2c) that have left the plant's county 1 hour after being release (none of these  $\text{NO}_x$  emissions have left Texas 1 hour after release). Four hours after release (still for plant 3470 in January 2005): 94.6% of  $\text{NO}_x$  emissions have the the plant's county, and 11.0% have left the plants state. As Figure 1d illustrates, plant 3470 is located upwind of much of its county and even more of its

<sup>26</sup> We choose the threshold of 25 MW as it is a common cutoff for 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.

<sup>27</sup> One shortcoming of this HYSPLIT-driven approach is that it does not model chemical reactions in the atmosphere (e.g., formation of  $\text{PM}_{2.5}$  or ozone).

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 1b is ideally located to reduce in-county emissions—most emissions leave the county nearly immediately: 1 hour after release, 69.5% of its emission have already left the county.

Figure 8 shows these results for all operating coal plants. The four subplots separate the results by administrative level (top panel (A): *county*; bottom panel (B): *state*) and pollutant (left: SO<sub>2</sub>; right: NO<sub>x</sub>). The *x*-axis gives the number of hours that have passed since the initial emissions release; the *y*-axis is the share of particles that have 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 plants for each hour—weighted by the mass of emissions.

The implications from Panel A of Figure 8 are clear: for most coal plants in the US, nearly all of the plants' pollution leaves their home counties within 6 hours of the release. This is true in both seasons, but the departure is even faster in winter months (with their, 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 have left the *state* of origin—and for many plants, this number is closer to 90% (again, particularly in the winter). Figure 8 demonstrates that pollution transport—a result of the geography of plant sitings, stack heights, and local meteorology—creates a substantial wedge between the sources of coal-based emissions and the downwind counties/states receiving the emissions.

**Decomposing the sources of local pollution** Inspired by this breadth of pollution transport, we now use HYSPLIT to separate the sources of local coal-based pollution. Specifically, we decompose the total *coal-EGU-generated pollution* within a county by the sources of that pollution (i.e., whether the sources are in-county or in-state and whether the sources are in attainment with national standards). 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. In this decomposition, we separate sources from counties that were *in attainment* of the NAAQS in 2005 vs. sources from *non-attainment* counties (i.e., violators of at least one standard in 2005). In 2005, 485 counties were out of attainment (i.e., non-attainment) for at least one of the six criteria pollutants.<sup>28</sup>

Figure 9 illustrates the results of this source-based decomposition with pollution sources separated into five groups: (1) the county's own emissions, (2) *attainment* counties within the same

<sup>28</sup> Because our HYSPLIT analysis focuses on 2005, we only consider counties' 2005 attainment status. Number of violations by standard: 422 for 8-hour O<sub>3</sub> (1997); 208 for PM<sub>2.5</sub>(1997); 49 for PM<sub>10</sub> (1987); 100 for CO (1971) 11; 10 for SO<sub>2</sub>(1971) 10; 2 for lead (1978). A county can violate multiple standards (i.e., there were 702 violations in 485 counties).

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<sub>2</sub> emissions; [Panel B](#) for NO<sub>x</sub>.

Given our previous finding that nearly all emissions leave their origin county within six hours, it is unsurprising that a very rather small share of a county's coal-EGU-based emissions comes from the county's own EGUs.<sup>29</sup> However, it is rather remarkable just how small the share of own-county emissions are relative to other coal-based EGU sources: the own-county shares (in black in Figure 9) 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 and/or presences contributing to non-attainment designations. However, on average, the vast majority of coal-EGU-based emissions in non-attainment counties appears to originate in other counties and states.

In fact, 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 9). 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 result again highlights the significance role long-distance transmission of coal-generated emissions plays in local air quality throughout the US.

A final interesting nuance in the results of Figure 9 is the difference between attainment and non-attainment counties (the left and right halves of the figure, respectively). For *non-attainment* counties, the plurality (41%–50%) of coal-based emissions comes from sources in *non-attainment* counties in other states—consistent with the EPA successfully designating many of the major pollution sources for non-attainment counties. For *attainment* counties, a larger share comes from *attainment* counties in other states (this share is particularly large for NO<sub>x</sub>). These result again emphasize the importance and regulatory challenges of trans-boundary emissions.

**Non-attainment counties and upwind emissions** Figure 9 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 4 lists the top 10 non-attainment counties in terms of the county's share of coal-based NO<sub>x</sub> 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.

<sup>29</sup> Part of this result is also driven by the fact that many counties do not have their own coal EGU.

Table 4 reveals that there are many non-attainment counties that have their own coal plants but receive a substantial share of their coal-based  $\text{NO}_x$  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  $\text{NO}_x$  emissions originate within the county, while 54.5% originate from in-attainment plants in other states. The counties in Table 4 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  $\text{NO}_x$  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*.

**Case study: Shelby County, TN** Figure 10 portrays the specific challenges of cross-boundary coal-based emissions (here,  $\text{NO}_x$ ) for the aforementioned Shelby County, Tennessee in July 2005. In 2005, Shelby County was designated non-attainment due to its violation of the 8-hour Ozone standard of NAAQS.<sup>30</sup> Panel A shows all of the coal-plant-generated  $\text{NO}_x$  emissions that eventually arrive in Shelby County during July 2005 (as estimated by HYSPLIT). We draw the paths that the emissions take to Shelby County in grey; non-attainment counties (for 2005) are cross-hashed in red. Shelby County is outlined in bright yellow. The sources of the emissions are located throughout a broad geographic stretching from Texas to Kansas to Indiana to Georgia—and including both attainment and non-attainment counties. 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. Overall, Panel A emphasizes the importance of considering potentially large regions of the country when attempting to regulate or improve local air quality.

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  $\text{NO}_x$  in 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  $\text{NO}_x$ . Remarkably, though 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) actually contributed more to Shelby County’s  $\text{NO}_x$  than did Shelby County’s own plant. Further, the coal plant in Independence County, AR (also *in attainment* in 2005) contributed approximately the same amount of  $\text{NO}_x$  emissions to

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<sup>30</sup>  $\text{NO}_x$ , which we consider in Figure 10, is a precursor of both Ozone and  $\text{PM}_{2.5}$ .

Shelby County as did Shelby County's own coal plant.<sup>31</sup> As suggested by Table 4 and illustrated in Figure 10, the vast majority of the coal-based NO<sub>x</sub> 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.

## 6 Conclusions

In this paper, we document (1) the geography of US coal plants and emissions and (2) the challenges these geographies pose to a federalist approach to air-quality regulation.

We begin by recording the tendency for electricity generators in the US to locate near county and state borders. Though proximity to water may explain part of this behavior, it cannot explain firms'/governments' preference for siting coal plants in locations that reduce the area downwind of the plant within its county and/or state. To formally test for this strategic behavior, we develop a simple, non-parametric test that compares the area downwind of the plant to the area upwind (at the county or state level). This test identifies highly significant evidence of strategic siting among coal plants. This strategic behavior is evident whether we consider plants' siting within their counties, siting within their states, or siting jointly within their counties and states. Natural-gas plants—who face much lower regulatory pressure due to their much lower emissions—provide a natural falsification test. We find no evidence of strategic siting among natural-gas plants. We also find no evidence that the Clean Air Act affected this tendency to strategically site coal plants, with one possible exception. Coal plants in states' interior counties *may* have increased strategic siting following the passage of the CAA—the same period in which the share of coal plants sited in interior counties increased.

In short, the US's federalist approach to environmental policy blankets the country in an overlapping patchwork of county and state authorities. We find significant evidence of a strategic response in an important class of major polluters: coal plants have been sited to reduce plants' downwind areas within their counties and states.

Using the particle-transport model HYSPLIT, we document just how transportable coal-based emissions are—and how quickly they leave their source counties/states. Within six hours nearly all emissions have left their source counties, and approximately 50% have left their source state. Part of this quick departure from source counties/states is attributable to plants' proximity to administrative borders. However, other forces are also at work—i.e., coal plants' tall smokestacks, meteorology, and the general transportable nature of coal plants' emissions.

These results have important implications for policy. The strategic siting behavior that we

<sup>31</sup> 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.

document is consistent with a simple model of regulatory avoidance—likely reducing regulatory efficiency. Under the current (federalism-inspired) implementation of the CAA, cross-boundary pollution requires much stronger coordination and effort than pollution that remains within its source county and state. Thus, strategic siting could render air-pollution regulation less successful or more costly (or both). Adding further complexity are (*i*) the highly transportable nature of coal-based emissions and (*ii*) the height of coal plants' smokestacks. Consequently, local and state governments face a complex challenge in monitoring and regulating these plants that strategically site near downwind borders and release highly transportable pollutants from tall smokestacks.

The shapes of some non-attainment areas reflect this complexity—knitting together whole counties with pieces of other counties and “islands” that surround major point sources. For example, consider the Huntington-Ashland non-attainment area (for the 1997 PM<sub>2.5</sub> standard) mapped in light orange in Figure 11. 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 essentially islands that each include multiple coal plants (circled, red dots). Clearly this complex non-attainment area required substantial coordination across counties and states, source-attribution modeling, and federal oversight.<sup>32</sup> Combining (*i*) our evidence of overt strategic siting, (*ii*) the large spatial scale of pollution transport, and (*iii*) the considerable complexity visible in the Huntington-Ashland non-attainment area, it is important to consider whether the potential efficiency offered by federalist air-quality policy has actually been realized.

It is *possible* that strategic siting and emitting could offer potential benefits *if* firms locate near coastal borders so that winds carry pollution out to sea.<sup>33</sup> However, the majority of coal plants are not sited in this manner. Instead, firms and governments appear to find it profitable to site coal plants near borders, and build tall stacks, to reduce the efficiency of pollution monitoring and regulation. Stronger federal (or regional) oversight could potentially diminish these incentives—effectively smoothing out the spatial patchwork of authorities. Instead, many opponents of the CAA push for a reduced federal influence.

The results of this paper suggest additional complexities in a regulatory and monitoring setting already fraught with complexity. A larger federal role may reduce the incentives that create these complexities. While we specifically document strategic siting, our results more broadly emphasize that regulators must be cautious of strategic responses to regulation—particularly for policies that are spatial in nature or create discontinuities. In short, for every policy action,

<sup>32</sup> Figure A2 provides an example of another “complex” non-attainment area contained within a single state (the Evansville, Indiana non-attainment area).

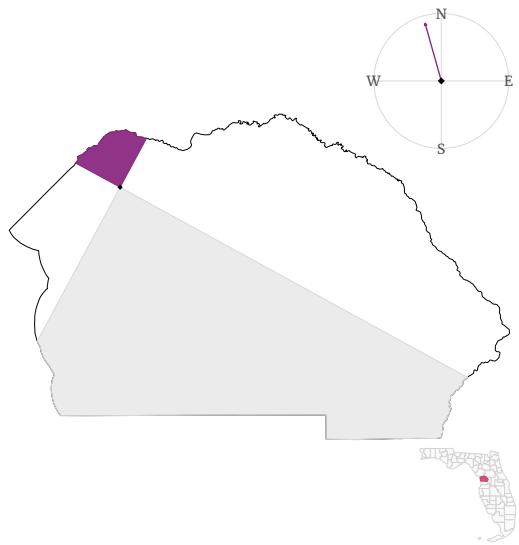
<sup>33</sup> For this outcome to be desirable, the ecological costs of blowing coal emissions out to sea would need to be less than alternative direct health costs from blowing the emissions across land and throughout cities.

we should anticipate a strategic reaction.

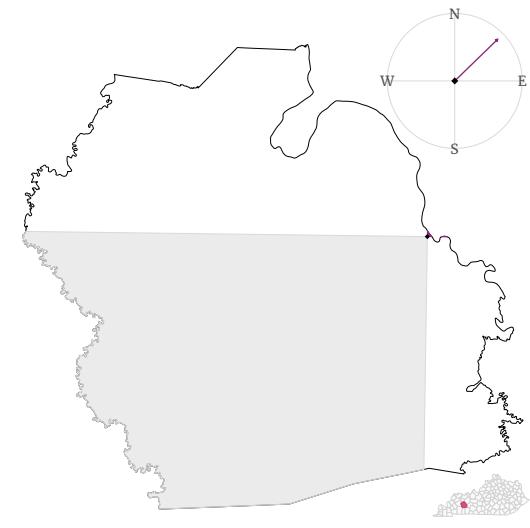
## 7 Figures

**Figure 1:** Upwind and downwind areas in “home” county relative to plants

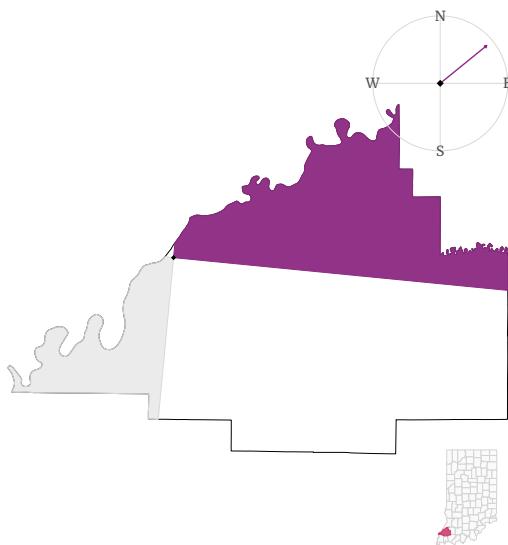
(a) Plant 628



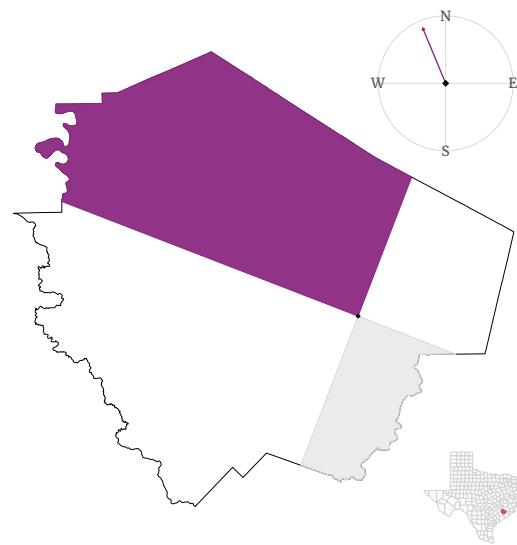
(b) Plant 1378



(c) Plant 6113



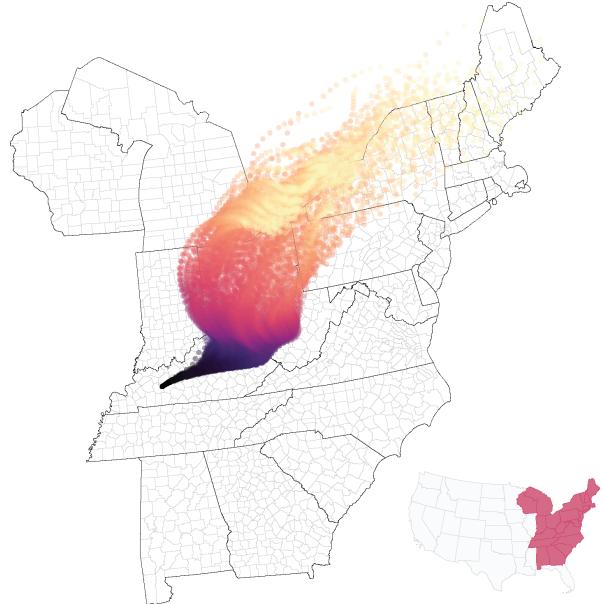
(d) Plant 3470



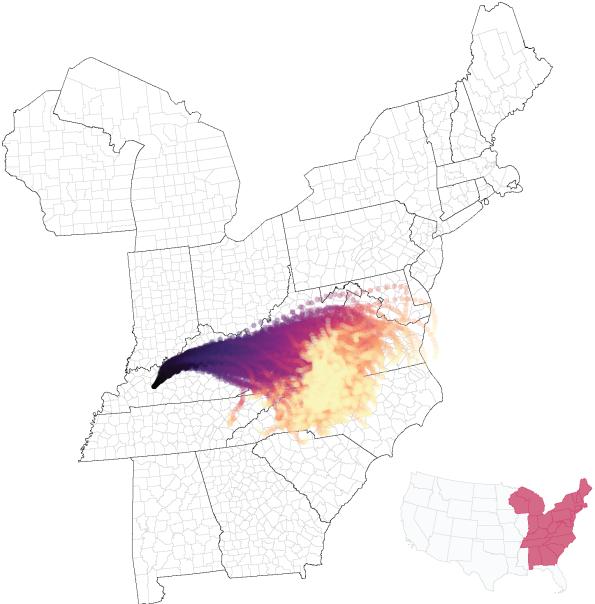
This figure demonstrates *upwind* and *downwind* areas for four coal-fueled generators. Dark, purple areas denote the 90-degree *downwind* area from the plant’s location (the small, black diamond). Light gray refers to *upwind* areas. The outlined shape depicts the plant’s county; the inset thumbnail 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 2: HYSPLIT trajectory and dispersion: Two example plants, January and July 2005**

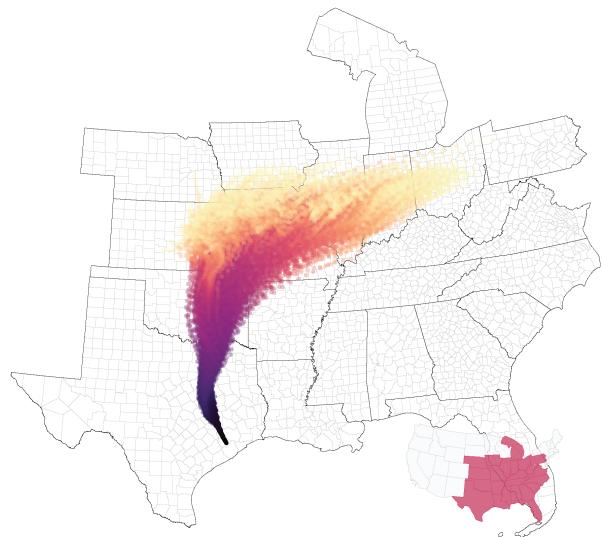
(a) Plant 1378, January 2005



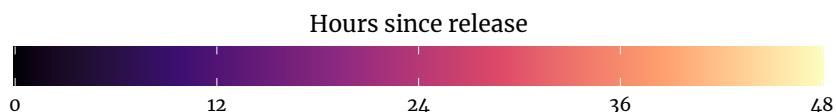
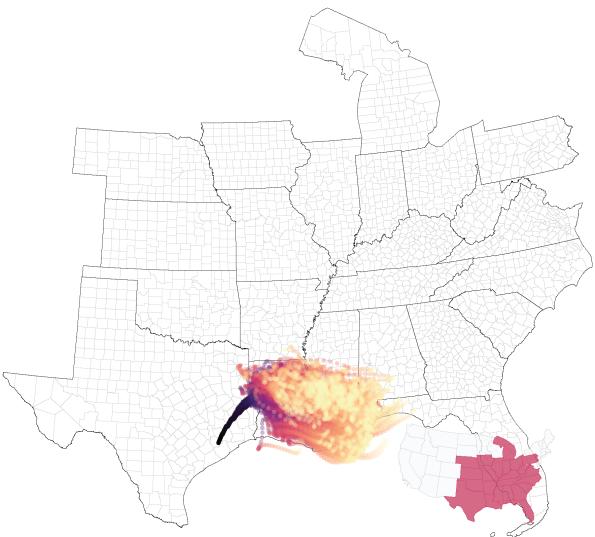
(b) Plant 1378, July 2005



(c) Plant 3470, January 2005

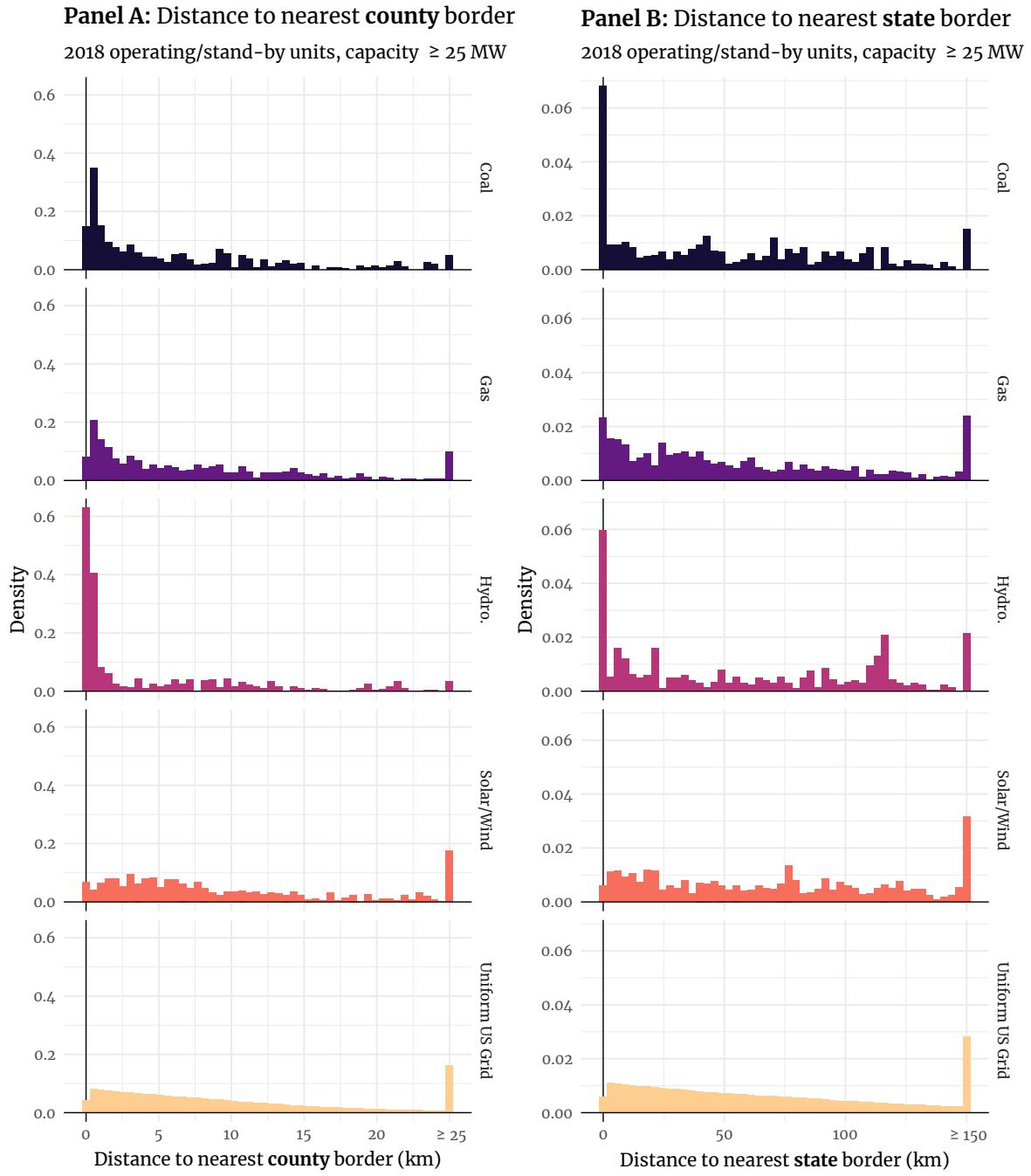


(d) Plant 3470, July 2005



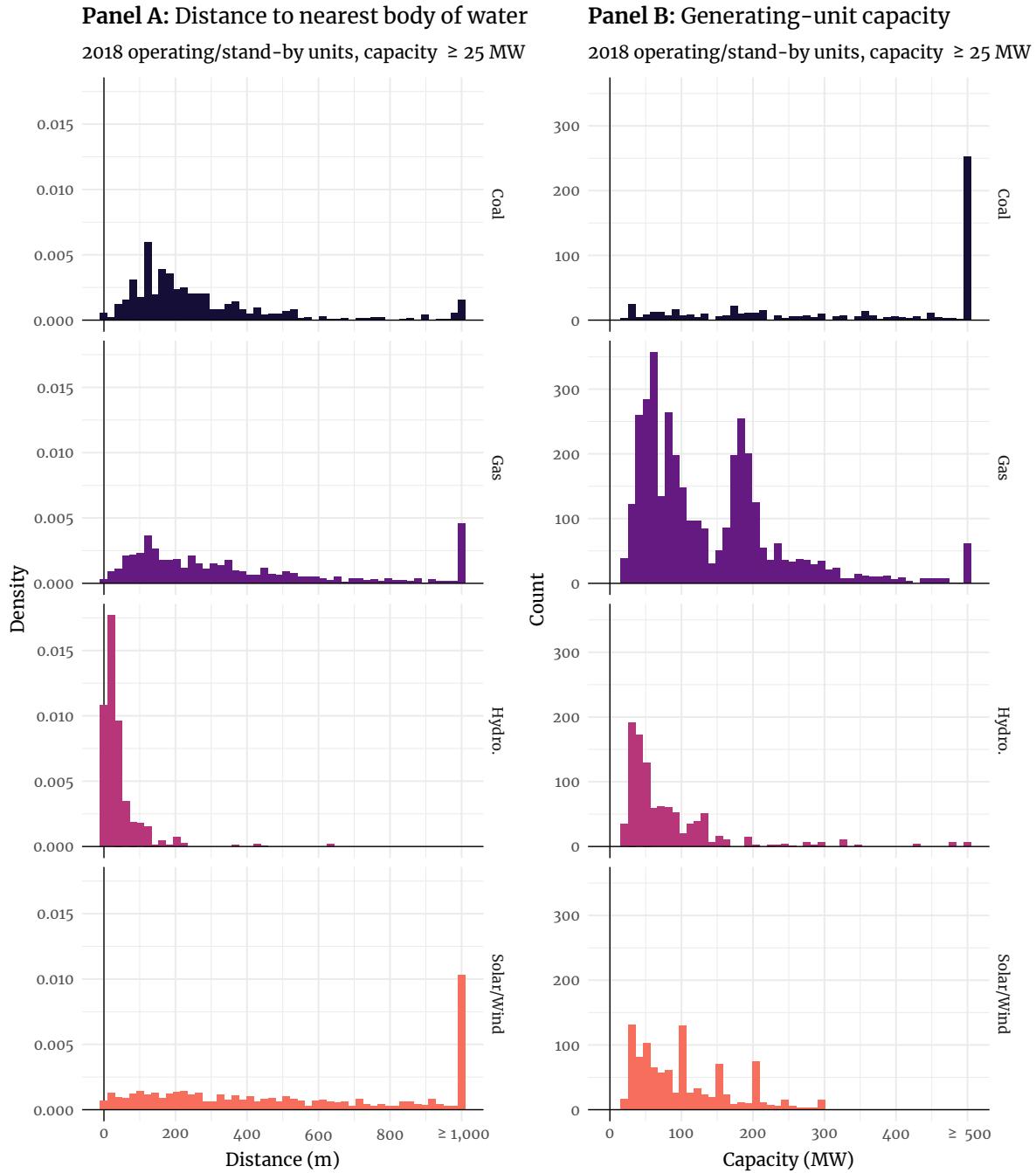
These subfigures illustrate particles' trajectories and dispersion in HYSPLIT for two plants (ORIS codes 1378 and 3470) during January 2005 and July 2005. For each day of the month, HYSPLIT models 420 particles starting at the latitude, longitude, and altitude of the plants' chimneys. We track particles for 48 hours after their initial release; particles' colors denote the number of hours since their emission. The plants correspond to Figures 1b and 1d.

**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  $\geq 25$  MW within the contiguous US 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 US.

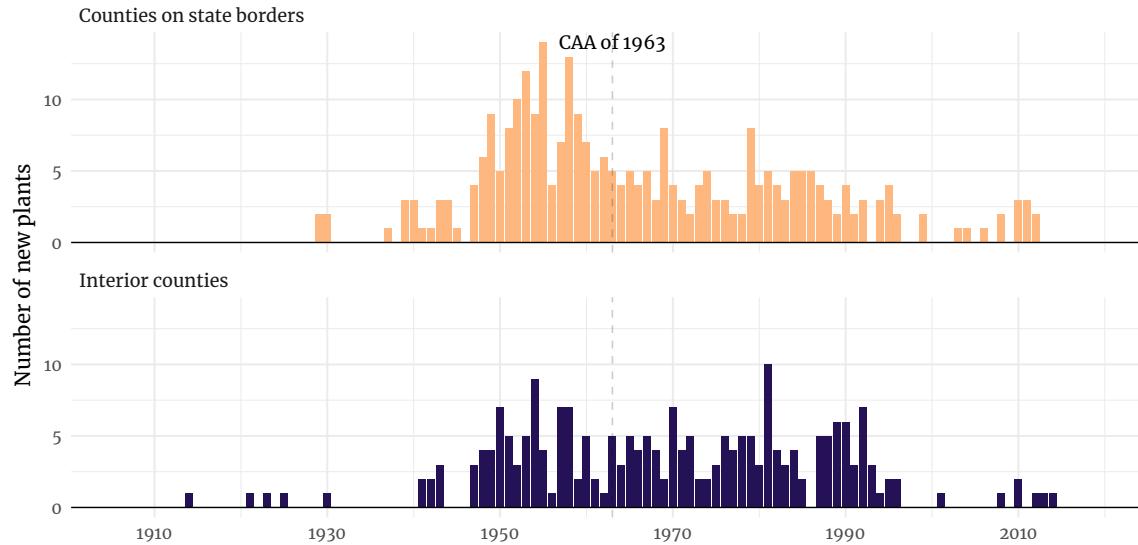
**Figure 4:** Generators' distances to water and capacities



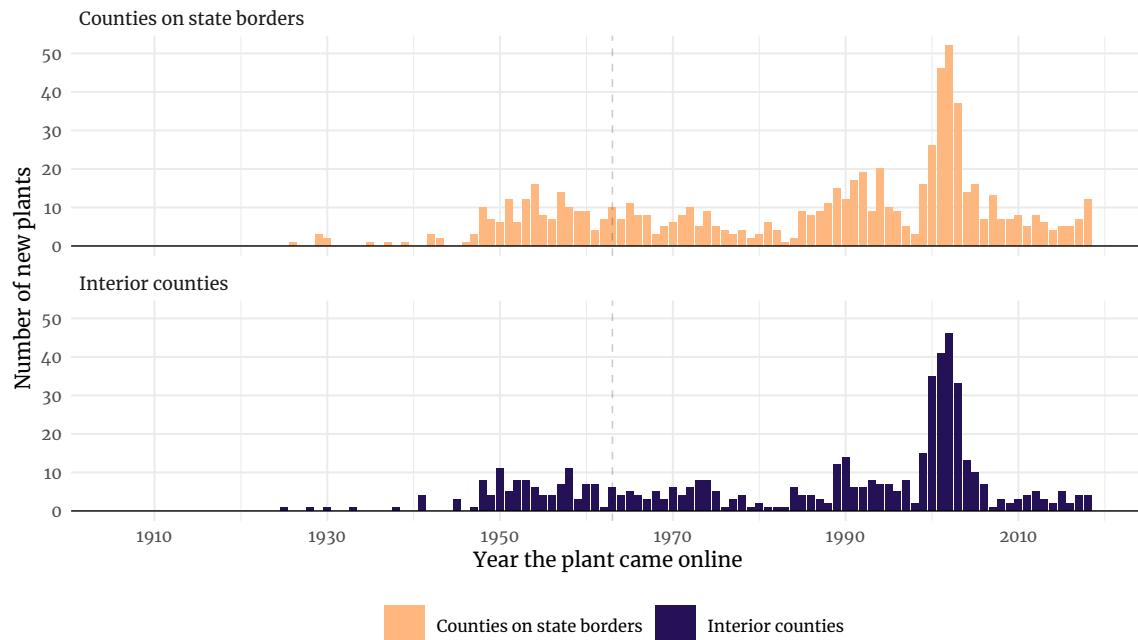
These two panels display the distributions of EGUs' distances to their nearest body of water (**Panel A**, left) and EGUs' generation capacities (**Panel B**, right) by fuel category (row and color).

**Figure 5:** Coal and natural-gas plant births by year and by border/interior county

**Panel A: Coal plant births**

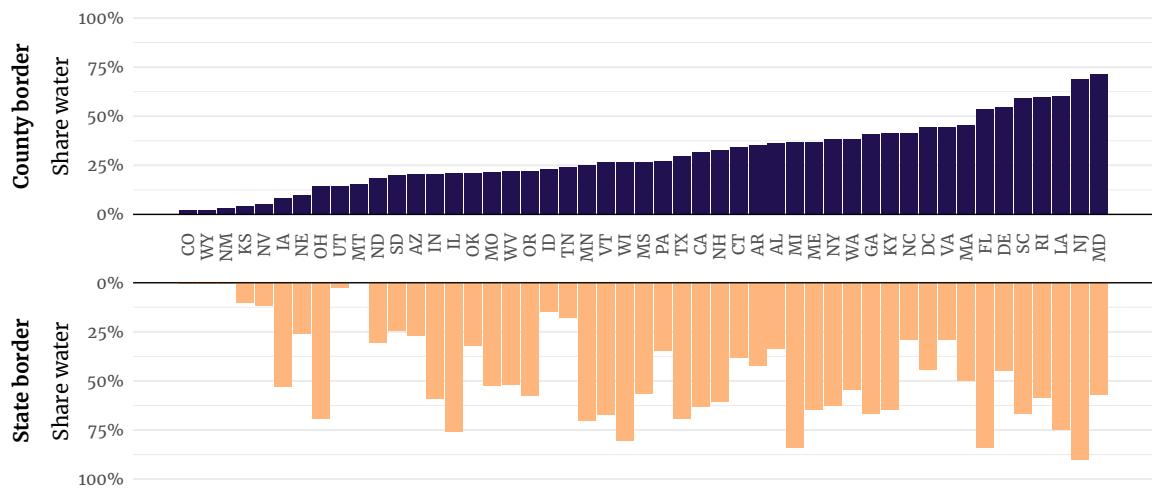


**Panel B: Natural gas plant births**



These figures plot the number of plants that came online in each year by (i) the plant's predominant fuel type (coal in **Panel A**; natural gas in **Panel B**) and (ii) whether the plant's county is on a state border (top; light orange) or is in its state's entire (bottom; dark blue). Following the Clean Air Act of 1963 (shown by the vertical, dashed line), the share of coal plants built on on state-borders decreased. The CAA of 1963 marked the beginning of increased salience of interstate air-pollution issues.

**Figure 6:** Shares of county and state borders that intersect water, by state



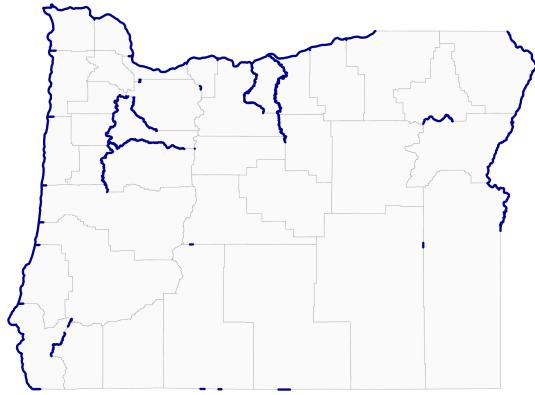
This figure illustrates the share of county borders (top) and state borders (bottom) that intersect with bodies of water, by state. The states are sorted from smallest share of county-borders intersected by water (Colorado) to largest share (Maryland). Alaska and Hawaii are excluded. Figure 7 provides four example states (LA, OR, SC, and SD) from these calculations.

**Figure 7:** Where county/state borders intersect bodies of water

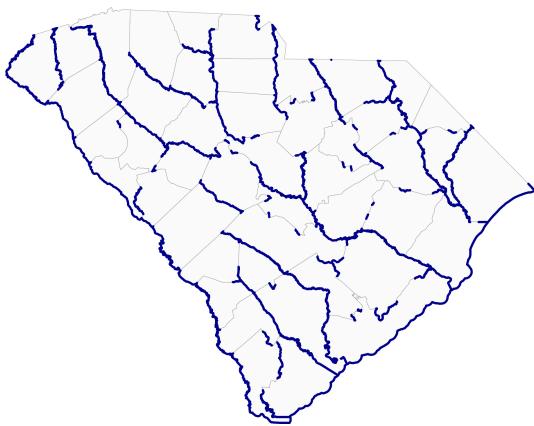
(a) Louisiana



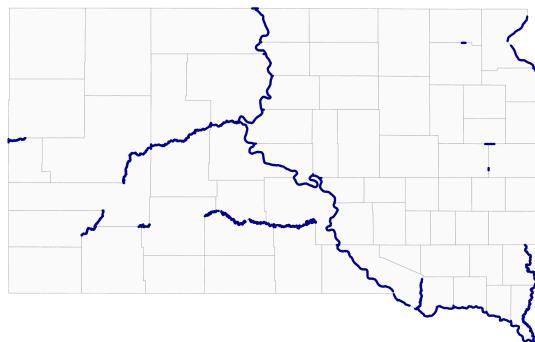
(b) Oregon



(c) South Carolina



(d) South Dakota



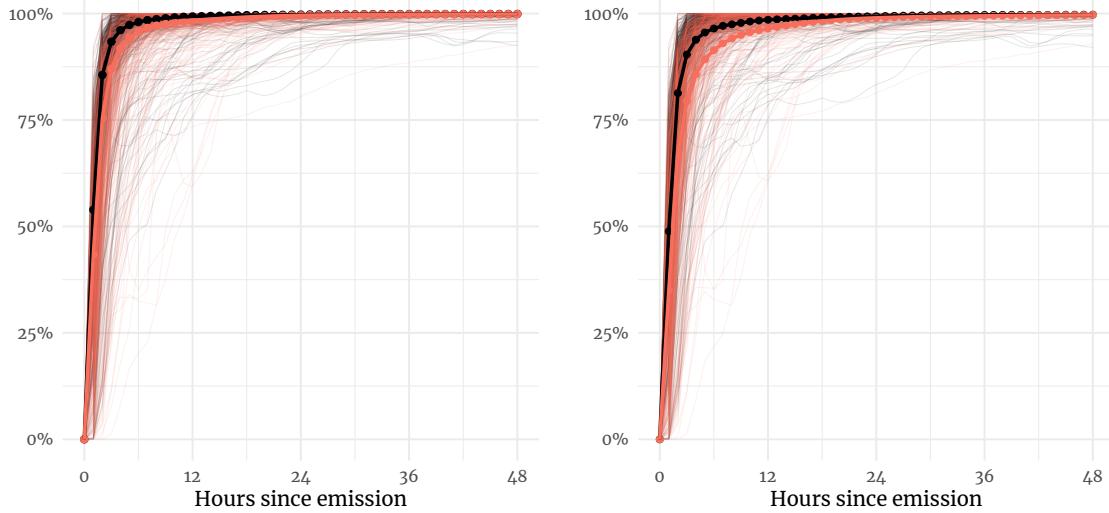
These four subfigures provide examples of the output of our calculations of county and state borders that intersect with bodies of water. Think blue lines denote administrative borders (state and/or county) that intersect with water; thin gray lines depict administrative borders that do not. Overall,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

**Figure 8:** Share of particles outside of origin county/state by hours since release

**Panel A: Percent of emissions outside of source's county—by hours since emission**

Weighted across plants by mass of SO<sub>2</sub> emissions

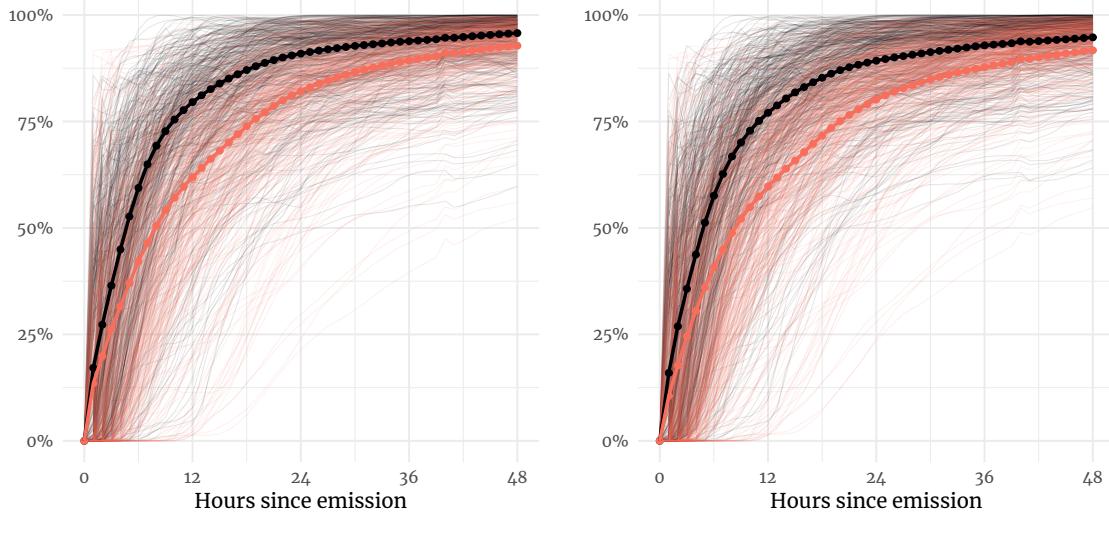
Weighted across plants by mass of NO<sub>x</sub> emissions



**Panel B: Percent of emissions outside of source's state—by hours since emission**

Weighted across plants by mass of SO<sub>2</sub> emissions

Weighted across plants by mass of NO<sub>x</sub> emissions



Month of operation — ● January — ● July

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<sub>2</sub>; the right column by NO<sub>x</sub>. Differences between the months capture seasonal differences in meteorology and in the distribution of generation. Sample: Coal-fueled generators  $\geq 25$  MW operating in Jan./July 2005.

**Figure 9:** Share of particles in a county separated by particles' sources

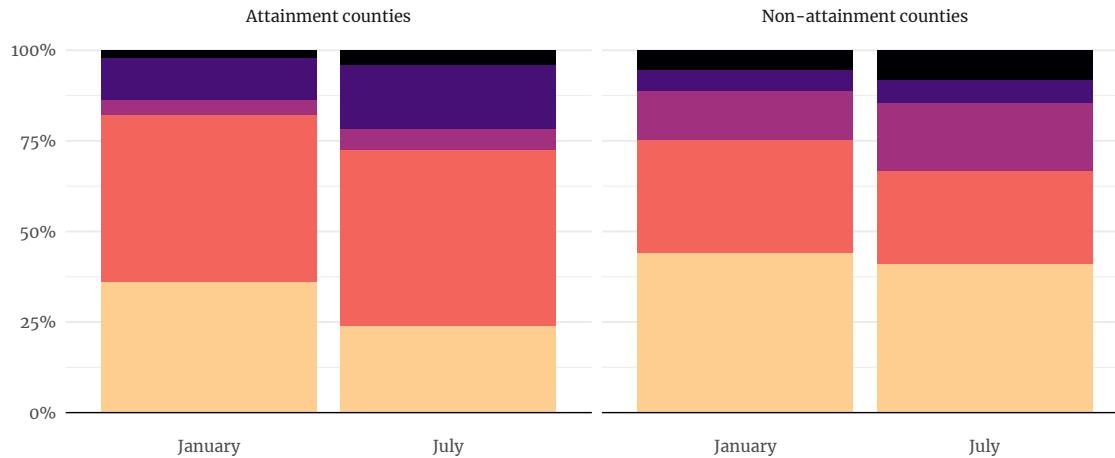
**Panel A: Sources of local coal-based particles, weighted by mass of SO<sub>2</sub> emissions**

Coal-fueled units in 2005 with capacity greater than 25 MW



**Panel B: Sources of local coal-based particles, weighted by mass of NO<sub>x</sub> emissions**

Coal-fueled units in 2005 with capacity greater than 25 MW

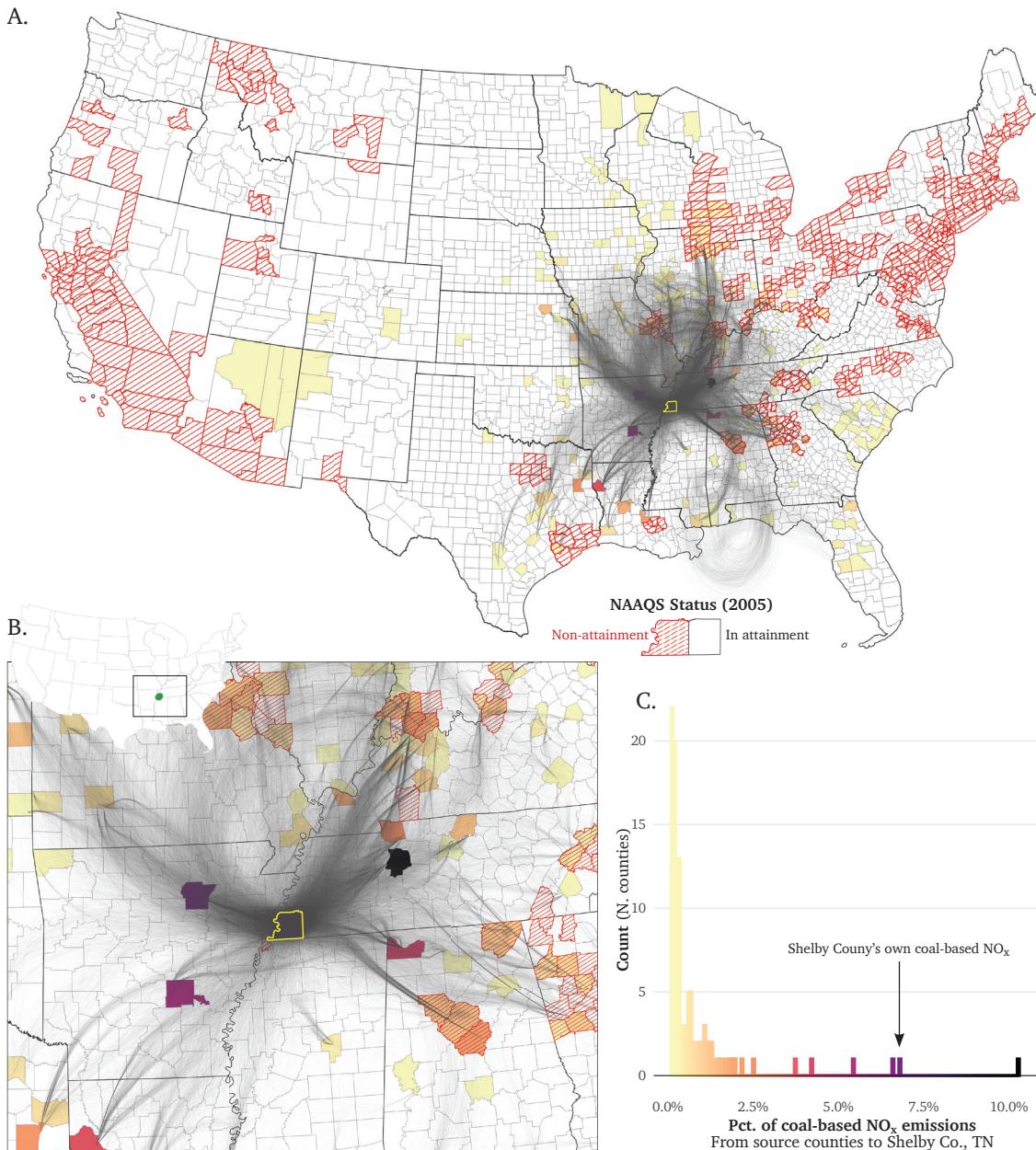


Location of emissions' source

<span style="background-color: black; color: white; display: inline-block; width: 10px; height: 10px;"></span>	Same county	<span style="background-color: purple; color: white; display: inline-block; width: 10px; height: 10px;"></span>	Other county in same state Source county: In attainment	<span style="background-color: darkviolet; color: white; display: inline-block; width: 10px; height: 10px;"></span>	Other county in same state Source county: Non-attainment
<span style="background-color: red; color: white; display: inline-block; width: 10px; height: 10px;"></span>	Other county in other state Source county: In attainment	<span style="background-color: orange; color: white; display: inline-block; width: 10px; height: 10px;"></span>	Other county in other state Source county: Non-attainment		

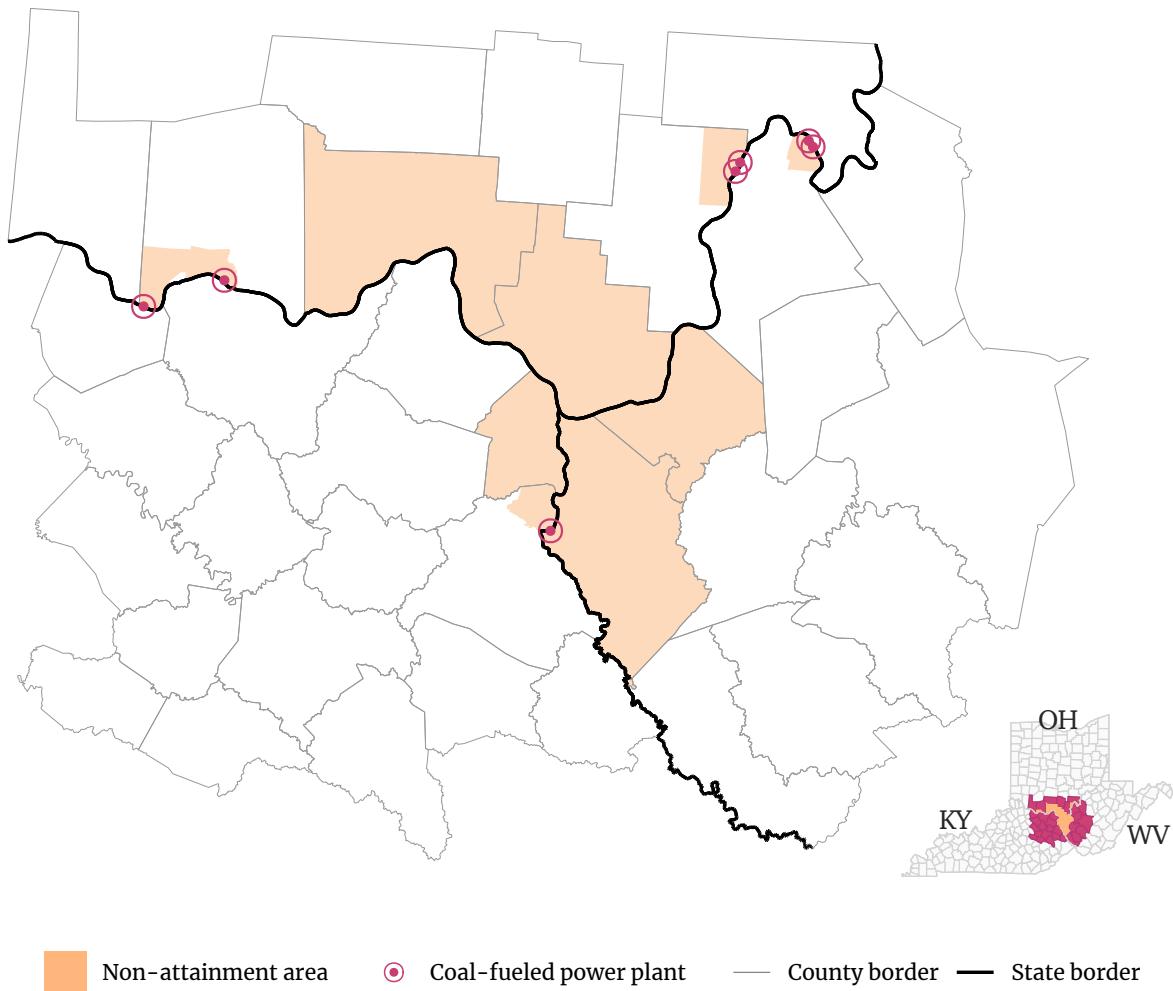
These figures illustrate the source-based decomposition of location, coal-based pollution. They described, on average, where a county's pollution come from based upon (1) the month (Jan. or July 2005), (2) the county's attainment status, and (3) the type of particle (SO<sub>2</sub> or NO<sub>x</sub>). 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<sub>2</sub> emissions; **Panel B** on NO<sub>x</sub>. Sample: Coal-fueled generators ≥ 25 MW operating in Jan./July 2005.

**Figure 10:** Illustrating the transport problem: The sources of coal-based  $\text{NO}_x$  emissions in Shelby County, Tennessee during July 2005



This figure shows the origins, paths, and shares of all coal-plant-based  $\text{NO}_x$  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 ( $\text{NO}_x$  is an Ozone precursor). Subfigure A's grey coal-based  $\text{NO}_x$  trajectories reveal that the sources of coal-based  $\text{NO}_x$  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  $\times$  600 km). Counties are colored (filled) by the share of coal-based  $\text{NO}_x$  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  $\text{NO}_x$  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  $\text{NO}_x$  emissions in Shelby County, TN during July 2005—i.e., more than Shelby County's own coal plant.

**Figure 11:** 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<sub>2.5</sub> standard. Figure A2 depicts another example of a “complex” non-attainment area (Evansville, Indiana).

## 8 Tables

**Table 1:** Testing strategic location: Comparing up- and down-wind areas for coal and natural gas plants—before and after the Clean Air Act (CAA) of 1963

	Coal-fueled plants			Natural-gas-fueled plants		
	(1) All	(2) Post-CAA	(3) Pre-CAA	(4) All	(5) Post-CAA	(6) Pre-CAA
<b>Panel a:</b> Siting strategically within <b>county</b>						
Count	515	286	229	1,258	995	263
Count strategic	297	165	132	612	482	130
Percent strategic	57.67%	57.69%	57.64%	48.65%	48.44%	49.43%
Fisher's exact test of $H_0$ : In- <b>county</b> downwind area $\geq$ upwind area						
Under $H_0$ : $E[\text{Percent strategic: County}] = 50\%$						
P-value	0.0003	0.0054	0.0122	0.8381	0.8448	0.5974
<b>Panel b:</b> Siting strategically within <b>state</b>						
Count	515	286	229	1,258	995	263
Count strategic	279	152	127	575	466	109
Percent strategic	54.17%	53.15%	55.46%	45.71%	46.83%	41.44%
Fisher's exact test of $H_0$ : In- <b>county</b> downwind area $\geq$ upwind area						
Under $H_0$ : $E[\text{Percent strategic: State}] = 50\%$						
P-value	0.0321	0.1574	0.0563	0.9989	0.9788	0.9978
<b>Panel c:</b> Siting strategically within <b>both county and state</b>						
Count	515	286	229	1,258	995	263
Count strategic	182	98	84	310	249	61
Percent strategic	35.34%	34.27%	36.68%	24.64%	25.03%	23.19%
Fisher's exact test of $H_0$ : Downwind area $\geq$ upwind area in <b>county and state</b>						
Under $H_0$ : $E[\text{Percent strategic: County} \wedge \text{State}] = 25\%$						
P-value	<0.0001	0.0003	0.0001	0.6258	0.5049	0.7710

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 1 illustrates this calculation. The columns that reference *Post-/Pre-CAA* refer to whether the plant's first year of operation was after or before the Clean Air Act of 1963. Sources: eGRID (2018) and authors' calculations.

**Table 2:** Decomposing coal plants' strategic siting by border and interior counties: Comparing up- and down-wind areas—before and after the Clean Air Act (CAA) of 1963

Counties on state borders			“Interior” counties		
(1) All	(2) Post-CAA	(3) Pre-CAA	(4) All	(5) Post-CAA	(6) Pre-CAA
<b>Panel a: Siting strategically within county</b>					
Count	291	143	148	224	143
Count strategic	181	87	94	116	78
Percent strategic	62.20%	60.84%	63.51%	51.79%	54.55%
Fisher's exact test of $H_0$ : In- <b>county</b> downwind area $\geq$ upwind area					
Under $H_0$ : $E[\text{Percent strategic: County}] = 50\%$					
P-value	<0.0001	0.0059	0.0006	0.3200	0.1578
<b>Panel b: Siting strategically within state</b>					
Count	291	143	148	224	143
Count strategic	163	80	83	116	72
Percent strategic	56.01%	55.94%	56.08%	51.79%	50.35%
Fisher's exact test of $H_0$ : In- <b>county</b> downwind area $\geq$ upwind area					
Under $H_0$ : $E[\text{Percent strategic: State}] = 50\%$					
P-value	0.0230	0.0904	0.0810	0.3200	0.5000

This table documents the differences in the siting of coal plants in counties that touch their states' borders *vs.* counties within their states interiors. As above in Table 1, 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 1 illustrates this calculation. The columns that reference Post-/Pre-CAA refer to whether the plant's first year of operation was after or before the Clean Air Act of 1963. Sources: eGRID (2018) and authors' calculations.

**Table 3:** Decomposing natural gas plants' siting by border and interior counties: Comparing up- and down-wind areas—before and after the Clean Air Act (CAA) of 1963

Counties on state borders			“Interior” counties		
(1) All	(2) Post-CAA	(3) Pre-CAA	(4) All	(5) Post-CAA	(6) Pre-CAA
<b>Panel a: Siting strategically within county</b>					
Count	738	582	156	520	413
Count strategic	342	268	74	270	214
Percent strategic	46.34%	46.05%	47.44%	51.92%	51.82%
Fisher’s exact test of $H_0$ : In- <b>county</b> downwind area $\geq$ upwind area					
Under $H_0$ : $E[\text{Percent strategic: County}] = 50\%$					
P-value	0.9786	0.9744	0.7644	0.2024	0.2455
<b>Panel b: Siting strategically within state</b>					
Count	738	582	156	520	413
Count strategic	324	262	62	251	204
Percent strategic	43.90%	45.02%	39.74%	48.27%	49.39%
Fisher’s exact test of $H_0$ : In- <b>county</b> downwind area $\geq$ upwind area					
Under $H_0$ : $E[\text{Percent strategic: State}] = 50\%$					
P-value	0.9996	0.9928	0.9960	0.7976	0.6161

This table documents the differences in the siting of gas plants in counties that touch their states’ borders *vs.* counties within their states interiors (i.e., this table replicates Table 2 but with natural gas instead of coal). As above in Table 1, 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 1 illustrates this calculation. The columns that reference Post-/Pre-CAA refer to whether the plant’s first year of operation was after or before the Clean Air Act of 1963. Sources: eGRID (2018) and authors’ calculations.

**Table 4:** Top 10 non-attainment counties by share of local coal-based NO<sub>x</sub> emissions originating from sources in external, in-attainment counties, January and July 2005

Rank	County	CBSA	Source of given county's coal-based NO <sub>x</sub> emissions				
			Own	Same-state sources	Other-state sources	Attn.	Non-Attn.
<b>Panel a: January 2005</b>							
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%
<b>Panel b: July 2005</b>							
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<sub>x</sub> 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<sub>x</sub> originating from in-attainment sources (separately for January/July 2005). These shares are based upon HYSPLIT estimates, as described in the methods.

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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 US with a uniform, hexagonal grid of points as illustrated in Appendix Figure A1. 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.<sup>34</sup> This process produced a nationally representative distribution (for the contiguous US) of distances to state and county borders using a uniform grid of approximately 7.91 million points.<sup>35</sup> 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 US. 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 US (area-wise) sits within 1 kilometer of a county border (36% within 5 km; 62% within 10 km). For state borders, only 1.1% of the US 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 US Census’s

<sup>34</sup> 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).

<sup>35</sup> For comparison, the area of the contiguous US is approximately 8.08 million km<sup>2</sup>.

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 US—with each point measuring whether the boundary substantively intersects with water.

#### A.1.4 EGUs and water

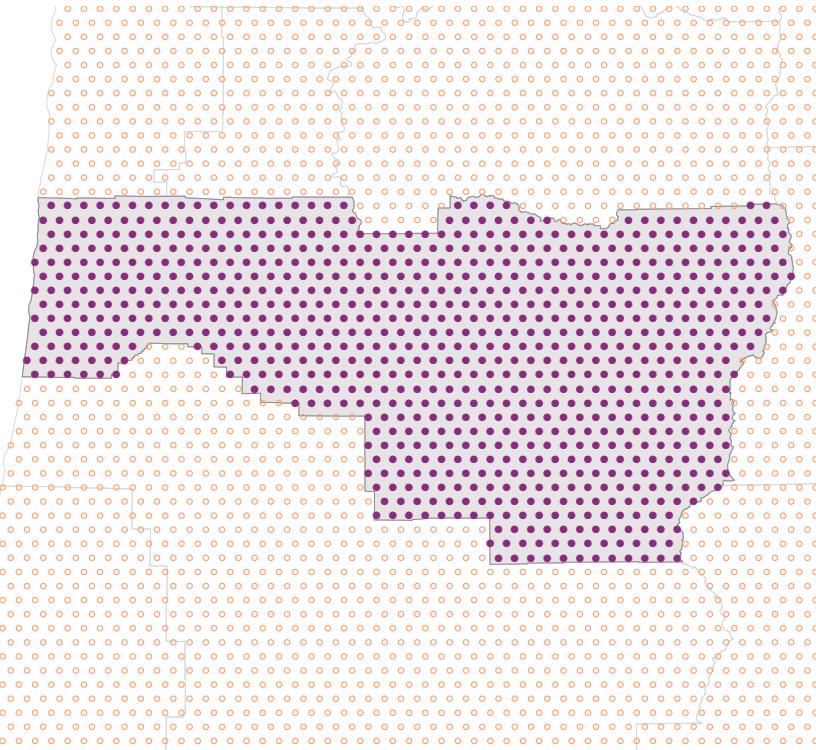
To calculate the distance to the nearest body of water, we include all bodies of water contained in the US Census’s areas of water, linear water, and coastline shapefiles, (US Census Bureau, [2016b](#)). After merging these calculated distances with eGRID’s EGU characteristics, we build the distribution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

#### A.1.5 HYSPLIT

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

## A.2 Appendix: Figures

**Figure A1:** Example of grid for distance calculation



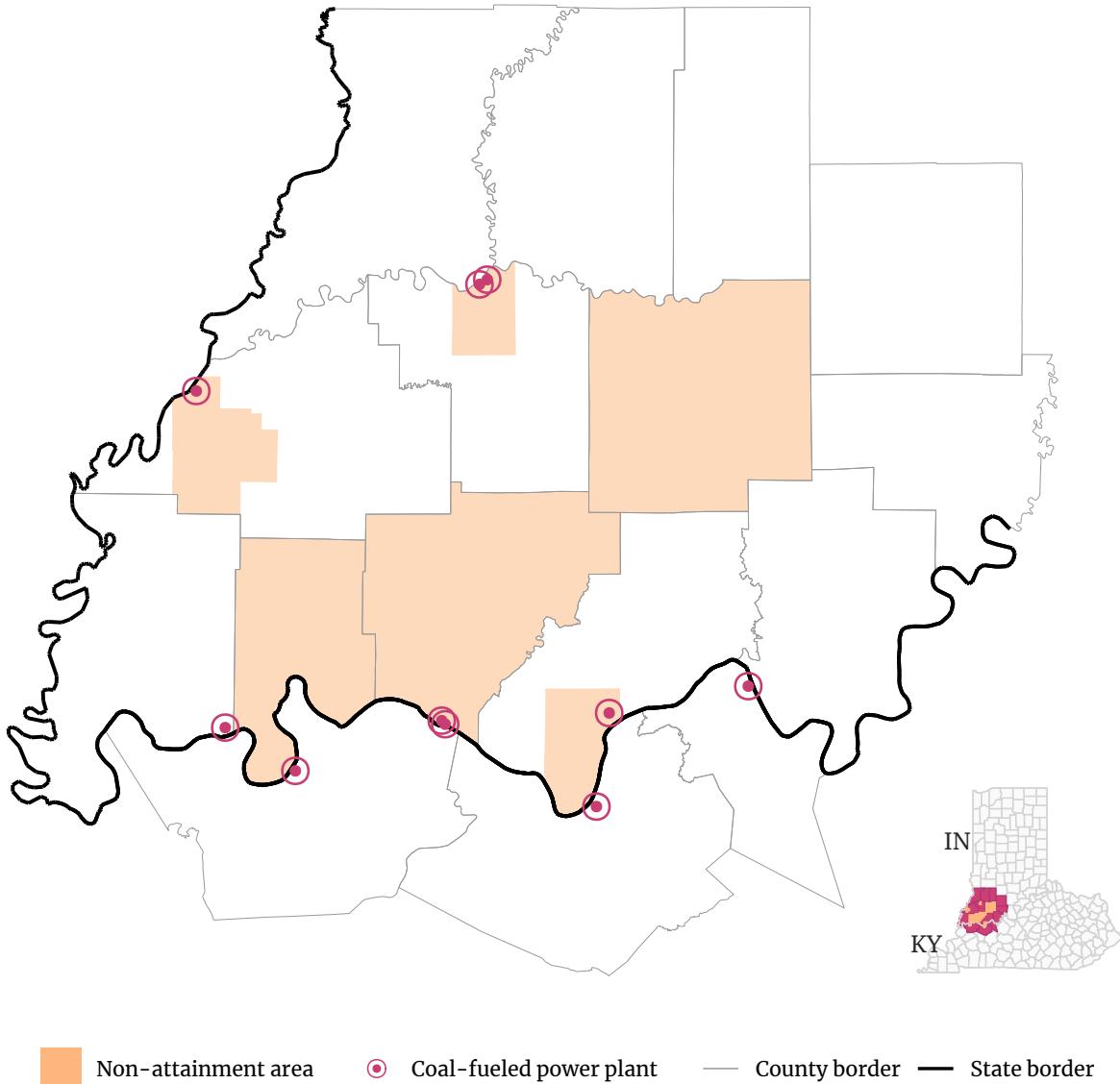
This figure illustrates the uniform grid within our nearest-border calculation. All dots (open and closed) are part of the uniform grid. Closed, dark purple dots are within Lane County, Oregon. We then calculate the shortest distance from each dot to borders of Lane County and of Oregon.

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?<sup>36</sup> 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).<sup>37</sup> The results are displayed in A1.

<sup>36</sup> Alternatively, the *two-sample* Smirnov test (sometimes called the two-sample Kolmogorov-Smirnov test) tests whether the underlying distributions of two samples statistically differ.

<sup>37</sup> We use R's base function `ks.test()`.

**Figure A2:** 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 11, the non-attainment area is for the 1997 PM<sub>2.5</sub> standard.

### A.3 Appendix: Tables

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

Fuel category	County borders		State borders	
	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.

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.