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Is Air Pollution Regulation Too Lenient? Evidence from US Offset Markets

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Abstract

This paper describes a framework to estimate the marginal cost of air pollution regulation, then applies it to assess whether a large set of existing U.S. air pollution regulations have marginal benefits exceeding their marginal costs. The approach utilizes an important yet under-explored provision of the Clean Air Act requiring new or expanding plants to pay incumbents in the same or neighboring counties to reduce their pollution emissions. These "offset" regulations create several hundred decentralized, local markets for pollution that differ by pollutant and location. Economic theory and empirical tests suggest these market prices reveal information about the marginal cost of abatement for new or expanding firms. We compare estimates of the marginal benefit of abatement from leading air quality models to offset prices. We find that, for most regions and pollutants, the marginal benefits of pollution abatement exceed mean offset prices more than ten-fold. In at least one market, however, estimated marginal benefits are below offset prices.

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A classic idea in economics is that firms may provide too much of an externality like pollution because they do not account for its full social costs. Policies addressing this market failure can maximize social welfare by regulating emissions until the marginal cost of complying with policy equals the marginal social benefit of reducing pollution emissions (Pigou 1932). In practice, designing policies to limit negative externalities involves a delicate balancing act between the costs to firms of compliance and the benefits to society of reducing externalities. For externalities including crime, innovation, and smoking, it can be difficult to estimate the total social costs and benefits of a policy, let alone the marginal costs and marginal benefits. Thus, it can be challenging to know whether existing policies maximize social welfare or are more or less stringent than economic efficiency requires.

These issues are particularly important for air pollution. Some research estimates that over five percent of premature US mortality comes from air pollution, and over a third of measured benefits of all recent federal regulations came from reducing one air pollutant, particulate matter (Fann et al. 2012; Dominici et al. 2014). Cleaning up air pollution may be costly—US air quality for some pollutants improved by over 90 percent since 1970 (Currie and Walker 2019; Shapiro 2022). The marginal cost of pollution abatement typically increases with the quantity of abatement, so these enormous pollution decreases lead to the question of when the marginal costs of increasing regulation begin to exceed its marginal benefits.

Political and economic debates have echoed these textbook questions. Two law professors, for example, summarized, "[The Environmental Protection Agency's (EPA's)] ozone standard is insufficiently stringent, not overly expensive" (Livermore and Revesz 2015). Oates (1997) disagreed:

> Existing benefit-cost studies suggest that total benefits for air pollution control have substantially exceeded the total costs in the United States, but this, of course, does not really address the question. It is still possible, and I think likely in view of the evidence, that for several of the criteria air pollutants (such as ground-level ozone), the standards have been pushed well beyond the point where the marginal benefits equal marginal cost.

Government and researchers obtain varying results, for example, on whether benefits of tightening ozone pollution standards exceed their costs (OMB 2009; Lange et al. 2018).

In part to help reconcile these disparate views, we develop a framework to estimate the marginal cost of pollution abatement separately by pollutant, county, and year. We utilize an important yet under-explored provision of the Clean Air Act that forbids increases in pollution emissions from large industrial sources in areas where pollution exceeds the National Ambient Air Quality Standards (NAAQS). Large polluting plants entering these "nonattainment areas" must offset their potential emissions by paying an incumbent polluter in the same area to permanently reduce their emissions. Entrants can spend millions of dollars purchasing such pollution "offsets." Market participants describe spending on these offsets as among the largest environmental expenditures for new or expanding facilities.

We analyze newly available offset transaction records from two states which require public disclosure of contracts, and we purchased additional data on fourteen other states plus Washington, DC, from a leading firm that advises offset transactions. Most of these data have never been analyzed or discussed in government or academia. Our data cover over 40 markets and 60 percent of economic activity from US offset trading areas. Our analysis also reflects extensive interviews with market participants, including regulators at the EPA, California Air Resources Board, and local air districts; brokers and traders active in offset markets; and environmental managers at firms that have traded offsets.[1]

Offset markets provide information about the marginal cost of air pollution regulation. A new entrant must purchase enough offsets to cover their emissions. When the market price for offsets exceeds an entrant's marginal cost of abatement, the entrant should invest in pollution abatement until its cost of abatement approaches the market price for offsets. As abatement costs begin exceeding offset prices, a profit-maximizing firm should purchase offsets for the remaining emissions. Incumbents also have an incentive to generate and sell offsets when the market price for offsets exceeds marginal abatement costs. Incumbents may generate offsets by investing in permanent, verifiable emissions reductions, which regulators certify. Canonical views of environmental markets dating back to Dales (1968) and Crocker (1966) and formalized by Montgomery (1972) suggest that emissions markets reveal marginal abatement costs via allowance prices and that efficient environmental policy equates the price of pollution offsets to the marginal social benefits of pollution

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[1] Additionally, we repeatedly attempted to contact every person listed as involved in trading offsets between 2018 and 2020 in Houston, the market where government documents provide traders' contact information.

abatement. The marginal benefits of abatement include health and other benefits from emissions reductions. These benefits differ by pollutant and location.[2]

We begin with several stylized facts on offset markets. We show that offset markets cover 60 percent of US population or economic activity, representing 180 million people or \$11 trillion in GDP. Offset prices are rapidly rising in real terms. Offset prices are related to proxies for regulatory stringency, including pollution abatement costs, emissions, economic activity in polluting industries, and nonattainment severity.

We then test policy efficiency. In markets where offset prices exceed the marginal benefits of abatement, we conclude that air quality regulation is more stringent than is efficient. In markets where the marginal benefits of abatement exceed mean offset prices, regulation is more lenient than is efficient.

We find that for most pollutants and markets with data, regulation is much less stringent than efficiency would require, though recent regulations in Houston are an exception. Nationally, mean marginal benefits of abatement for nitrogen oxides (NO_x) and volatile organic compounds (VOCs) are ten times mean offset prices. We find large benefit/cost ratios in each US region, in most markets, for one important other pollutant with limited data (particulate matter), and in sensitivity analyses. In Houston, however, the marginal benefits of abating VOCs are only half of mean offset prices.

We provide the first comprehensive empirical analysis of US air pollution offset markets. A substantial body of research analyzes the Clean Air Act. Given the importance of offset markets, it is noteworthy that empirical research has largely overlooked them. Among market-based environmental policies, economists once described Clean Air Act offsets and related policies as "by far the most important of these programs in terms of scope and impact" (Cropper and Oates 1992), but the limited existing research mentioning offset markets mostly describes legal or policy details (Dudek and Palmisano 1988; Stavins 2003; NRC 2006; Leonard 2018).

We also provide revealed preference estimates of the marginal cost of abatement that differ by pollutant, location, and year; we then compare these to corresponding marginal benefits. Since

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[2] Externalities from criteria air pollutants, like those the Clean Air Act regulates, are fairly local and larger in more densely populated areas.

the benefits of emissions reductions differ by pollutant and location, it is important for analysis of efficiency to have cost estimates that also differ by pollutant and location. Put another way, optimal regulation of externalities is more stringent in areas where marginal damages are greater.

To date, however, the literature has essentially no revealed preference estimates of marginal abatement costs that differ by pollutant and location.[3] Existing estimates of marginal abatement costs typically come from estimating structural cost functions of one industry, e.g., sulfur dioxide abatement from electricity generation (Gollop and Roberts 1985; Carlson et al. 2000). These methods require a thorough understanding of costs and production constraints and information on input prices and quantities. These methods are not ideal in settings where emissions come from many industries. In isolated settings, researchers do observe permit prices in cap-and-trade markets as a measure of abatement costs (Fowlie et al. 2012; Deschenes et al. 2017). These markets are few, geographically large, and preclude identifying costs separately for different pollutants or locations within a market.

Our focus on marginal abatement costs is useful since economic research has focused more on measuring the marginal benefits than marginal costs of air pollution policy.[4] We also contribute to an emerging literature quantifying how regulatory stringency evolves over time. Other work estimates trends in the shadow price of pollution, using models requiring strong assumptions (van Soest et al. 2006; Shapiro and Walker 2018). Tracking offset prices over time helps characterize trends in regulatory stringency nationally and by market.

Two clarifications may be useful. First, many environmental regulations govern air and water pollution, and one might wonder how these regulations affect our interpretations of the efficiency of the Clean Air Act's NAAQS. While other environmental policies create costs for firms, they do not change a plant's marginal decision—increasing expenditures on abatement decreases required expenditures on offsets. An optimizing plant should equate these costs at the margin.

Second, what can we learn from studying these markets, which can be thin? While we only

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[3] In theory, engineering models used by the EPA can provide estimates of marginal abatement costs. The data and informational requirements, however, far exceed the administrative and resource capacity available. Moreover, engineering estimates do not use revealed preference, typically ignore non-pecuniary abatement costs, and can differ substantially from revealed preference estimates (Carlson et al. 2000; Fowlie et al. 2018; Allcott and Greenstone 2023).

[4] For example, in five top general-interest economics journals, our review found 13 papers on the marginal benefits of air pollution regulation and only 3 on the marginal costs (Appendix A). The three cost studies analyzed focused settings—sulfur dioxide emissions from coal-fired power plants or vehicle environmental inspections in developing countries.

analyze entrants and incumbents trading offsets, these represent the marginal emissions decisions. Although not every incumbent trades offsets, because every incumbent can, these marginal costs provide information about all incumbents and not merely about those which trade offsets.[5] We analyze thousands of transactions, across 9 to 25 years per market, for two common pollutants, covering over 40 markets, including the seven largest US metro areas. We consider four separate air quality and valuation models, two quasi-experimental and four epidemiological estimates of the main elasticity determining benefits (the mortality-concentration response function for particulate matter), and three different estimates of the value of a statistical life. While one market or specification may be unrepresentative, and while we show important heterogeneity across markets, these estimates provide a broad picture of regulatory efficiency for the country's largest offset markets.

1 History & Design of US Air Pollution Offset Markets

The following descriptions draw on existing work (Dudek and Palmisano 1988; Fraas et al. 2017; Leonard 2018).[6]

1.1 Offset Market History

The 1970 Clean Air Act Amendments directed the EPA to set standards for ground-level ozone, particulate matter, and four other "criteria" air pollutants. The EPA monitors compliance with these standards by operating air quality monitors. If readings from a monitor violate the pollutant standard, the county enters "nonattainment" and polluting firms face stricter regulation.

Since the 1977 Clean Air Act Amendments, new or expanding facilities have been subject to New Source Review, which prohibits *net* increases in pollution emissions from stationary sources (i.e., facilities) in nonattainment areas. This provision allowed large polluting plants to enter nonattainment areas if they offset the resulting increase in pollution emissions with decreases in emissions of the same pollutants from incumbents in the same area. Hahn and Hester (1989) discuss early literature on emissions offsets and offset markets in the Clean Air Act; Appendix B provides

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[5] Similarly, plants in cap-and-trade markets may hold allowances without trading them.

[6] Formally, offsets are called "Emission Reduction Credits." We refer to sources that are new or undergoing significant modifications as entrants. We refer to stationary pollution sources as "plants."

additional background.

1.2 Offset Market Design

An incumbent in a nonattainment area may choose to permanently decrease its emissions, then receive an "offset" from regulators specifying the tons per year, pollutant, and nonattainment area. Installing more stringent abatement technology than required, closing down a plant or part of it, and decreasing total production can all generate offsets.

To generate an offset, the EPA requires that emissions reductions must be permanent, quantifiable, federally enforceable, and surplus. Surplus means "the reduction is not required by current regulations, relied on for state implementation plan planning purposes, and not used to meet any other regulatory requirement." Federally enforceable means the "reduction is enforceable through rule or permit" (USEPA 1980). Offsets and a plant's air quality permit may specify the maximum permitted hours of operation, production rate, or input rate, and ways to guarantee compliance (Gauna 1996). Quantifiable means "the actual emissions reduced are able to be calculated."[7] Permanent means the "reduction is unending or indefinite," which often requires installing or removing capital equipment, documented in photographs and records (Rucker 2018). Some offset markets, particularly for carbon dioxide, suffer from concerns that offsets are not surplus or additional. Such concerns have not been prominent for the markets we study, where states and the EPA tightly enforce requirements.

An incumbent can sell an offset to entrants, possibly in parts. Regulators typically maintain a registry of offsets and certify transactions. Offset markets are nonetheless decentralized, so buyers and sellers write bilateral offset contracts.

Some offset transactions involve brokers. Brokers help entrants find inexpensive offsets, including offsets in the process of being generated or that could be generated in the future, and provide expertise in regulation and environmental contracting. Brokers also provide confidentiality—because transactions can be a public record, a plant that trades offsets without a broker is publicly signaling its expansion or contraction plans, which may reveal sensitive business information.

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[7] Quantification may use "source tests, mass balances, or other means acceptable to the permitting agency" (Leonard 1996, p. 81). Generally, analysis must use the same method to quantify baseline and post-intervention emissions (Haddad and Palmisano 2001).

Offsets are documented in the purchaser's air quality permit, which is generally required for a polluting plant to start construction or operate. Precise rules governing offsets differ by state or air district. Appendix B.3 discusses one example offset.

What determines offset prices? The demand for offsets reflects the demand for entry or expansion of polluting firms and associated abatement costs. Offset supply reflects the availability of abatement opportunities. A few examples from market participants illustrate how supply and demand help explain offset price variability within and across markets. Los Angeles has been in nonattainment since the 1970s. Plant entry has exhausted most inexpensive abatement opportunities from incumbents. Thus, the limited *supply* of offsets produces Los Angeles' high offset prices. Conversely, in the 2010s, Houston experienced a large increase in *demand* for offsets to accommodate new refining capacity. Demand for new refining capacity stemmed from the abundance of cheap natural gas discovered in West Texas due to hydraulic fracturing. This demand outstripped supply, and offset prices rose. The Upper Green River Basin in Wyoming recently entered nonattainment and is an area with limited demand for building large polluting plants, so has low offset demand. This area also has incumbents with inexpensive abatement opportunities and low offset prices.

2 Data

This section describes data; Appendix C provides additional details.[8]

2.1 Offset Markets

We obtain offset data from several sources. For 14 states plus Washington, DC, we use records describing NO_x and VOC offset transactions from a leading emissions offset brokerage and advisor, Emission Advisors (Emission Advisors Inc, 2020).[9] These records list mean prices in each

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[8] Beyond the data discussed in this section, the analysis uses a number of additional data sets discussed in Appendix C: Arias (2014); Centers for Disease Control and Prevention (2020a,b); Federal Reserve Bank of St. Louis (2020a,b); National Bureau of Economic Research (2020a,b); Shapiro and Walker (2025); US Bureau of Labor Statistics (2023); US Census Bureau (2017, 2019, 2020a,b,c); US Environmental Protection Agency (2019b); and US Environmental Protection Agency (2019a).

[9] The 14 states are Arizona, Connecticut, Delaware, Illinois, Indiana, Maryland, Missouri, New Jersey, New York, Ohio, Pennsylvania, Virginia, Wisconsin, and Wyoming.

market×year and describe market size in four bins. We also use transaction-level records from the California Air Resources Board over 1993-2018 and the Texas Commission on Environmental Quality over 2001-2019 (California Air Resources Board 2019, 2020; Texas Commission on Environmental Quality 2019a,b). The California data list price, quantity, and the associated air quality district. The Texas data also list names of the selling and buying firms and an identifier code tracking the offset's lifecycle. We exclude intra-firm and temporary offset transactions.

Most offsets represent the permanent right to emit a ton of pollution. Most estimates of the marginal benefits of abating criteria pollution represent the marginal benefits of decreasing emissions of one ton of pollution in one year. To compare permanent offset prices and temporary pollution abatement benefits, we infer what price offset transactions would have had if the offsets only lasted one year. Appendix B.4 describes the process of converting permanent offset prices to annual prices using the ratio of short-term to permanent offset transactions. Appendix C.4 discusses how the price ratios between temporary and permanent offsets imply a discount rate for these assets of 8 to 10 percent.

2.2 Marginal Benefits of Pollution Abatement

We use estimates of the marginal benefits of pollution abatement from a leading "integrated assessment" model, AP3. Much research uses AP3 and its predecessors (e.g., Muller and Mendelsohn 2009; Fowlie et al. 2018). Using AP3, we calculate the benefit of a one-ton decrease in pollution emissions, for each county and pollutant. We use a modified version of AP3 code Nick Muller generously provided (see Appendix C.3.2); this change increases the marginal benefits of abatement by 7.5 percent. Appendix Figure 1 maps the marginal benefits of pollution abatement from AP3, which vary by pollutant and county. The marginal benefits of abatement increase with population density.

We report several sensitivity analyses. Our baseline estimates use the USEPA (2010)'s preferred VSL of \$8.8 million (2017 dollars). We consider one alternative estimate of \$3.7 million, from the OECD (2012), and an age-adjusted VSL (Murphy and Topel, 2006; Carleton et al., 2022). Our baseline estimate of the $PM_{2.5}$ concentration-adult mortality response function, which accounts for most estimated air pollution damages, is from Krewski et al. (2009). We report alternatives from the 5th and 95th percentile of the confidence interval from Krewski et al. (2009), from another epidemiological study (Lepeule et al. 2012), from a cross-sectional regression discontinuity estimate from China (Ebenstein et al. 2017), and from a panel data estimate using nonattainment designations as an instrument for pollution (Sanders et al. 2020). We also assess sensitivity to three other air quality and valuation models—InMAP, EASIUR, and AP2.

Appendix C describes additional data used for sensitivity analyses that explore the relationship between offset prices and existing measures of regulatory stringency.

3 Describing Offset Markets

We focus on the mean offset price in each market×year, for several reasons. The mean is more robust to outliers than the maximum, especially given the possibility of reporting errors, measurement error, or idiosyncratic events disproportionately impacting one offset transaction. If offset prices gradually increase as we move up the marginal abatement cost curve, using mean prices helps reflect these forces. Additionally, the data we purchased on 14 states plus DC only report the mean, so we can only analyze the median and maximum price for California and Texas. We do report sensitivity to the median and maximum price for key results in the markets for which this data exists.

3.1 Offset Market Coverage

Table 1 describes US air pollution offset markets and the markets in our data. Panel A shows that the US has several hundred offset markets that cover areas with 180 million people or $11 trillion in GDP; this represents around 60 percent of the US population, GDP, or manufacturing employment (Bureau of Economic Analysis 2020; US Bureau of Labor Statistics 2020b). Market sizes are skewed; a large share of markets represent low-population areas with few transactions. Panel B shows that during the years of our study, the US had 226 offset markets, covering 50 percent of the US population or 60 percent of economic activity. Panel C shows that our data cover 42 markets of these 226, representing 60 percent of the total population share in offset markets during this time or 63 percent of economic activity in offset markets.

Most reviews of market-based instruments mention several US environmental markets, like the

Acid Rain Program (Stavins 2003). Our analysis of offset markets represents a far larger number of distinct environmental markets than has been previously studied. The granularity and spatial diversity of these markets is also important for our study of efficiency, as regulatory stringency also differs by location, time, and pollutant.

Appendix Figure 2 maps locations of these markets. These maps show counties in states with policies that set up offset markets and that have been part of a nonattainment area at any time in 2010-2019. Panel A of Appendix Figure 2 describes markets for NO_x and VOCs, corresponding to nonattainment for ground-level ozone. More markets have existed for these pollutants than for others. Panel B shows areas with markets for other pollutants; the most common is for particulate matter, but some offset markets also cover carbon monoxide and sulfur oxides. Appendix C.2 describes other measures of market size and importance.

3.2 Trends in Offset Prices

To understand the evolution of regulatory stringency over the past 30 years, we explore trends in mean offset prices:

$$O_{mpy} = \beta y_y + \mu_{mp} + \epsilon_{mpy}$$

Here O represents the ton-weighted mean log offset price for market m, pollutant p, and year y. We regress this on a linear year trend y_y and market×pollutant fixed effects μ_{mp}, with error ϵ_{mpy}. The coefficient β represents the mean annual change in log offset prices, within a market×pollutant.

Table 2 presents estimates of β. Panel A pools pollutants and markets. Mean real offset prices increase by 5 to 8 percent per year. The pattern is similar whether we treat each offset transaction as having equal weight (column 1) or weight by tons or population (columns 2 and 3). In Panels B and C, which show each pollutant separately, the two pollutants have similar trends. Table 2 includes all years with data; limiting the sample to years 2010-2019 delivers smaller annual growth rates. The growth rate in offset prices is similar to recent rates of return in equity markets (Jorda et al. 2019). Offsets, like stocks, have short- and long-run price volatility, reflecting shifts in demand or supply.

3.3 Relationship Between Offset Prices and Measures of Environmental Compliance

We now describe relationships between offset prices and commonly-studied measures of regulatory stringency or compliance, such as county-level nonattainment severity, abatement expenditures, emission levels, and output of polluting industries (Greenstone 2002; Becker 2005; Shapiro and Walker 2018). Appendix E.1 discusses methods.

We first compare offset prices to rates of industrial spending on pollution abatement, as reported by administrative versions of the Census Bureau's Pollution Abatement Control and Expenditures Survey. Appendix Table 1 shows large and statistically significant positive relationships between offset prices and abatement expenditures. Row (1), column (1), implies that for plants that emit NO_x, a 1 percent increase in abatement operating expenditures per dollar of output is associated with a 1.8 percent increase in the NO_x offset price. Row (2) finds a larger elasticity for pollution abatement operating expenditures divided by value added. Magnitudes differ by pollutant and independent variable.

We also compare offset prices to emissions intensity, using data from the EPA's National Emissions Inventory on the tons of pollution emitted per dollar of output or dollar of value added (US Environmental Protection Agency 2020a,b,c). Appendix Table 2 suggests that regions with lower emissions intensity have higher offset prices. For example, column (1) of Panel A implies that a ten percent increase in the emissions intensity of NO_x emitting establishments is associated with a 1.69 percent reduction in the NO_x offset price. These elasticities are similar across pollutants and when looking at emissions per unit of output or emissions per unit of value added, with an elasticity around -0.14.

Discussions with market participants suggests that growing demand for offsets siphons off cheap abatement opportunities and low cost offsets. Accordingly, offset prices rise as remaining abatement opportunities become more costly. Offset market participants in our interviews often noted this phenomenon. For example, lower natural gas prices due to hydraulic fracturing (fracking) increased demand for petrochemicals production in Houston, raising offset prices. Appendix Table 3, Panel A, finds that offset prices are associated with increases in local value added from polluters. Column

(1) shows that a 10 percent increase in value added from NO_x emitting facilities is associated with a 13 percent increase in mean NO_x offset prices within an air district, or an elasticity of 1.3. Column (2) finds a slightly larger though imprecisely estimated elasticity for VOCs. Column (3) pools pollutants and shows that the average long-run elasticity is around 1.4. In Panel B the relationships between offset prices and output are weaker and statistically insignificant, compared to estimates using industry value added.

Lastly, we compare offset prices against nonattainment stringency. The 1990 Clean Air Act Amendments introduced a new ozone standard including classifications for ozone nonattainment severity. Depending on ambient ozone levels, areas could be classified into five nonattainment classifications: Extreme, Severe, Serious, Moderate, and Marginal. Increasing nonattainment stringency can affect offset markets for ozone precursors, NO_x and VOC, for two reasons. First, under more stringent nonattainment classifications, the EPA broadens the set of polluting facilities that must purchase offsets. Second, as nonattainment severity increases, facilities become required to purchase proportionally *more* offsets than they emit depending on severity-specific trading ratios. These trading ratios range from 1-to-1 for marginal nonattainment to 1.5-to-1 for extreme nonattainment. Appendix Table 4 finds that more stringent nonattainment classifications have higher offset prices. Column (1) shows that counties in moderate nonattainment have 16 percent higher offset prices than counties in marginal nonattainment, though this difference is not statistically significant at conventional levels. Offset prices increase monotonically with nonattainment stringency. Offset transactions in extreme nonattainment areas sell for nearly five times higher prices per ton than offsets in marginal nonattainment areas.[10] Columns (2) through (4) obtain similar results from adding fixed effects for years, pollutants, or pollutant×year combinations.

4 Efficiency: Comparing Offset Prices to Marginal Benefits of Abatement

Table 3 compares the marginal benefits of pollution abatement to offset prices, pooling data from 16 states plus Washington, DC, over years 2010-2019. Columns (1) and (2) describe NO_x; columns

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[10] We calculate this from $exp(1.725) - 1 \approx 4.6$

(3) and (4) describe VOCs. Columns (1) and (3) weight across markets by tons of pollution, and columns (2) and (4) weight by population. Panel A pools markets. Panels B through E describe each US Census Region. Within a panel, row 1 shows mean marginal benefits of abatement divided by mean offset prices, row 2 shows the p-value for the hypothesis test that this ratio equals one, row 3 describes mean marginal benefits of abatement, and row 4 describes mean offset prices. Under the interpretation that mean offset prices equal marginal abatement costs, row 1 represents the ratio of marginal benefits to marginal costs of pollution abatement. Appendix Tables 5 and 6 present estimates using the maximum offset price and median offset price within a district, respectively.

Table 3 shows that national mean marginal benefits of abatement substantially exceed offset prices. This provides our main result that air pollution regulation is typically less stringent than economic efficiency would require. This conclusion is statistically significant at greater than 99 percent confidence for most pollutants and regions. For NO_x, mean marginal benefits of abatement are \$42,000 to \$50,000, depending whether weighted by pollution or population. Mean offset prices are \$1,100 to \$4,300. Thus, the ratio of marginal benefits of abatement to offset prices is 12 to 37. For VOCs, we obtain a ratio of 9 to 29.

To better interpret these ratios, consider an incumbent firm deciding whether to permanently decrease NO_x emissions and generate offsets to sell. On average, the firm would receive \$1,100 to \$4,300 per ton for decreasing pollution. However, these same emissions reductions would create \$42,000 to \$50,000 per ton in health benefits to society. In this sense, regulation gives less incentive to clean up pollution than is optimal, so is too lenient.

Panels B through E of Table 3 show similar patterns in all four Census Regions. For NO_x and VOCs, both weighting schemes, and all four regions, the ratio of the marginal benefits of abatement to offset prices far exceeds one. For NO_x in the Northeast, for example, the marginal benefits of abatement are \$44,000, but mean offset prices are \$600. Ratios are modestly lower in the West, ranging from 4.6 to 8.2. Ratios are the lowest in the South, ranging from 2.3 to 20.4.

Figure 1 plots mean offset prices and the marginal benefits of abatement for all markets (Panel A) and each Census Region (Panels B through E), by year. The marginal benefits of abatement vary year-by-year due to changes in population and differences in baseline levels of all pollutants. Table 3 essentially shows the mean value of these lines in the period 2010-2019, while these graphs show the underlying year-by-year averages, for all years.

Figure 1 reveals the large gaps between the marginal benefits of abatement and offset prices in most regions, pollutants, and years. That gap reflects the finding that the marginal benefits of abatement dramatically exceed mean offset prices. The only exception is for VOCs in the South, where the marginal benefits of abatement and offset prices are closer. The yearly values in Figure 1 are near decadal means from Table 3.

Appendix Table 7 shows the ratio of the marginal benefits of abatement to offset prices for each of our largest markets, separately for NO_x and VOCs. These markets are heterogeneous—they include longstanding industrial cities like Cleveland and Pittsburgh; faster-growing, high-education cities, like Los Angeles and Washington, DC; and more rural areas like the Central Valley of California and the Upper Green River Basin in Wyoming.

Given this heterogeneity, it is striking that many markets have high ratios of the marginal benefits of abatement to offset prices. Across markets in Appendix Table 7, the median ratio is 40. In about three-fourths of the markets, this ratio exceeds 10. The only markets with a ratio below 4 are a few in California, markets in Houston, and one market in Wyoming. Even for these markets with lower ratios, only one of the forty markets listed in Appendix Table 7 has a ratio below one—VOCs in Houston.

What drives these differences? Figure 2 suggests that differences across markets are more driven by variation in the marginal benefits of abatement than by offset prices. This is because the marginal benefits of abatement (hollow red diamonds in the graph) vary widely between markets, from \$1,000/ton for VOCs in Wyoming to \$100,000/ton for NO_x in Los Angeles. By contrast, offset prices (the solid blue circles in the graph) vary less in dollar terms, though more in percentages, from \$100 in many markets to \$10,000 for NO_x in Los Angeles. Figure 2 also shows that for Houston VOCs, high offset prices rather than low marginal abatement benefits make the marginal benefits of abatement less than offset prices.

Appendix Figure 3 graphs year-by-year trends in the marginal benefits of abatement and the distribution of offset prices in the six largest markets where we observe transaction level offset prices. Panel A presents these graphs, pooling markets. Subsequent panels break out these trends by market. Blue bars show 10th to 90th percentile range of offset prices within a market×pollutant×year, thick black horizontal lines within each blue bar shows mean offset prices in each market×pollutant×year, and red dashed lines show marginal benefits of abatement. Panel A shows that for most years, the 90th percentile offset price is below the marginal benefit of abatement. Starting in 2014, the upper end of the VOC price distribution exceeds the average marginal benefit of abatement. This mostly comes from the Houston VOCs market, as shown in Panel E; prices in Houston were below \$1,000 until 2010, then skyrocketed to over \$10,000 per ton.

A few forces explain why there is price variation within a market×year. First, these markets could have search frictions. Appendix B.5 discusses offset price dispersion in the context of search frictions. Price dispersion may also emerge from heterogeneity in marginal abatement costs; as more abatement opportunities are exhausted within the marketplace, it becomes increasingly costly to abate. Similarly, intra-annual variation in supply and demand can generate equilibrium price volatility throughout the year.

Houston VOC prices are over six times the price of VOC offsets elsewhere. Houston offset prices for NO_x are also high. This may seem surprising since Texas traditionally has weaker political support for environmental regulation than in other states. Several reasons explain this apparent anomaly. First, growing demand for petrochemical, energy, and related industries to enter the Houston market substantially increased offset prices after 2010. Second, because the Clean Air Act is federal, states have limited discretion over precise standards regulating each plant. If states or localities do not regulate up to the federal standard, they face strict sanctions and threats of federal takeover of state regulatory implementation.

Appendix E.2 investigates sensitivity to alternative ways of summarizing offset prices. These alternative estimates generally change the ratio of offset prices to marginal abatement benefits in intuitive ways. Despite varying magnitudes, most qualitative patterns persist. Nearly all ratios far exceed one; the main exception is the Houston VOC market. Appendix E.2 also explores sensitivity to alternative estimates of the marginal benefits of pollution abatement. Most conclusions are qualitatively unchanged.

We use bounding to ask what VSL implies that regulation is efficient, i.e., that the ratio of marginal benefits to offset prices equals one. For NO_x, the implied VSL is \$0.5 million. For VOCs, it is \$1.1 million. These VSL bounds are considerably lower than the EPA's \$8.8 million VSL.

5 Conclusion

US air pollution offset markets are a key part of the Clean Air Act but have received little attention from academics. We analyze offsets and describe how they can help assess the efficiency of air pollution regulation using decentralized transactions data from many markets. This approach has appealing features—it uses revealed preference, reflects pecuniary and non-pecuniary abatement costs, obtains estimates that vary by pollutant, location, and time, and is straightforward to implement.

We find that the marginal benefit of pollution abatement far exceeds mean offset prices, as indicated by a wide range of air quality and valuation models. Using the intuition that prices in environmental markets reveal marginal abatement costs, this leads to our main policy conclusion that policy is more lenient than is efficient in most markets. Regulation in the Houston market for VOCs, however, may be moderately more stringent than efficiency would require. Outside Houston, unless marginal abatement costs rise or marginal benefits fall substantially (neither of which seems likely in plausible future US policy), Clean Air Act regulations are far from efficient. This general conclusion is in line with benefit-cost analyses. While these analyses generally rely on engineering estimates, they often conclude that incremental Clean Air Act regulations have a benefit/cost ratio above 10 (Keiser and Shapiro 2019).

Our conclusions about the stringency of environmental policy are not made in a vacuum. Reforms reducing compliance costs of the Clean Air Act, or larger estimates of the marginal benefits of abatement, would strengthen our conclusions. Alternatively, if marginal abatement costs continue increasing at their historical rate, marginal abatement costs could begin exceeding the benefits to society, and regulation would become more stringent than is efficient. At the same time, as firms face increasing compliance costs, the incentive for finding creative solutions to pollution abatement increases. Innovations in abatement technology would change the efficient level of environmental stringency.

We believe this paper offers several questions for future work. How can analysis of offset markets for other environmental goods or outside the US shed light on the efficiency of regulation? What other revealed preference strategies can estimate the marginal costs of pollution abatement? Such strategies could help compare abatement costs under different market designs and in areas without offset markets. Research has made extraordinary progress in measuring the marginal benefits of pollution abatement, but has made less progress in understanding the marginal costs of pollution abatement, though both parameters are essential to designing optimal policy.

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6 Figures and Tables

Table 1: Prevalence of Offset Markets

	Number of markets (1)	Population (mn)		GDP (trn)		Manufacturing employment (mn)	
		People (2)	% (3)	$ (4)	% (5)	Workers (6)	% (7)
Panel A. National							
Any pollutant	491	182.1	59	11.09	66	6.44	56
Ozone	282	173.2	56	10.66	63	6.09	53
Particulate matter	83	121.2	39	7.59	45	3.97	34
Panel B. National—analysis period							
Any pollutant	226	158.1	51	9.75	58	5.38	47
Ozone	118	145.0	47	9.09	54	4.83	42
Particulate matter	63	114.3	37	7.12	42	3.74	32
Panel C. Full sample (16 states plus Washington, DC) as proportion of all national markets							
Any pollutant	42	94.5	60	6.15	63	3.00	56
Ozone	37	94.5	65	6.15	68	3.00	62
Particulate matter	5	30.3	27	1.84	26	1.05	28

Notes: This table describes all US air pollution offset markets. Percentages in Panel C describe the sample as a share of all national offset markets. A market is a distinct nonattainment area × pollutant in states with offset markets, designated for nonattainment in any part of years 1992-2019 (Panel A) or 2010-2019 (Panel B). Ozone nonattainment areas have separate markets for nitrogen oxides and volatile organic compounds. Nitrogen dioxide markets are included in ozone. "Any pollutant" includes carbon monoxide, lead, and sulfur dioxide, in addition to ozone. Population, GDP, and employment represent the year 2010 and include any county which has a market for at least one pollutant. Population data are from the Population Census, county GDP data are from Bureau of Economic Analysis Regional Economic Accounts, and manufacturing employment data are from the Bureau of Labor Statistics Quarterly Census of Employment and Wages. "Trn" stands for trillion and "mn" for million. GDP is deflated to 2017 dollars using the GDP deflator.

Table 2: Trends in Offset Prices

	Offset prices		
	(1)	(2)	(3)
Panel A. All pollutants			
Year	0.05^{***}	0.08	0.06^{***}
	(0.02)	(0.06)	(0.02)
N	208	208	208
Panel B. Nitrogen oxides (NO_x)			
Year	0.05^{**}	0.08^{***}	0.06^{***}
	(0.02)	(0.02)	(0.02)
N	98	98	98
Panel C. Volatile organic compounds (VOCs)			
Year	0.05	0.08	0.05
	(0.03)	(0.09)	(0.03)
N	110	110	110
Weight		Tons	Population

Notes: Each unit of observation is a market × pollutant × year. Dependent variables in logs. For observations at the nonattainment area × pollutant × year level, offset prices are either mean weighted by tons traded or by county population, as indicated by the last row. All estimates include market × pollutant fixed effects. Standard errors are clustered within each market × pollutant. Asterisks denote p-value * < 0.10, ** < 0.05, *** < 0.01.

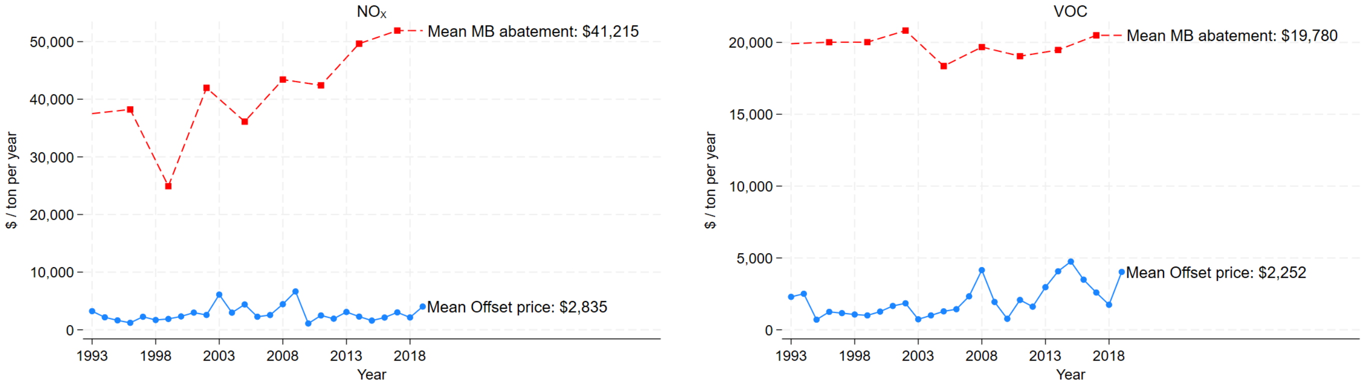
Table 3: Ratio of Marginal Benefits of Abatement to Mean Offset Prices, 2010-2019

	NO_x		VOCs	
	(1)	(2)	(3)	(4)
Panel A. Full sample (16 states plus Washington, DC				
1. Marginal benefits of abatement / Offset price	37.31	11.63	29.04	8.96
2. p-val: MBabatement / Offset price = 1	[0.00]	[0.00]	[0.00]	[0.00]
3. Mean marginal benefits of abatement	$42,035	$50,434	$24,807	$20,593
4. Mean offset prices	$1,127	$4,335	$854	$2,298
Panel B. Northeast				
1. Marginal benefits of abatement / Offset price	77.29	68.66	46.63	51.77
2. p-val: MBabatement / Offset price = 1	[0.00]	[0.00]	[0.00]	[0.00]
3. Mean marginal benefits of abatement	$43,784	$42,896	$28,980	$31,953
4. Mean offset prices	$566	$625	$621	$617
Panel C. South				
1. Marginal benefits of abatement / Offset price	20.35	5.87	11.66	2.29
2. p-val: MBabatement / Offset price = 1	[0.00]	[0.01]	[0.02]	[0.23]
3. Mean marginal benefits of abatement	$37,225	$28,684	$19,919	$13,431
4. Mean offset prices	$1,829	$4,886	$1,709	$5,856
Panel D. West				
1. Marginal benefits of abatement / Offset price	8.19	8.14	4.64	6.62
2. p-val: MBabatement / Offset price = 1	[0.00]	[0.00]	[0.00]	[0.00]
3. Mean marginal benefits of abatement	$35,256	$70,081	$7,433	$15,596
4. Mean offset prices	$4,304	$8,610	$1,601	$2,356
Panel E. Midwest				
1. Marginal benefits of abatement / Offset price	84.43	89.14	45.98	49.00
2. p-val: MBabatement / Offset price = 1	[0.04]	[0.02]	[0.02]	[0.01]
3. Mean marginal benefits of abatement	$44,122	$48,114	$19,841	$22,302
4. Mean offset prices	$523	$540	$432	$455
Weight:				
Tons	X		X	
Population		X		X

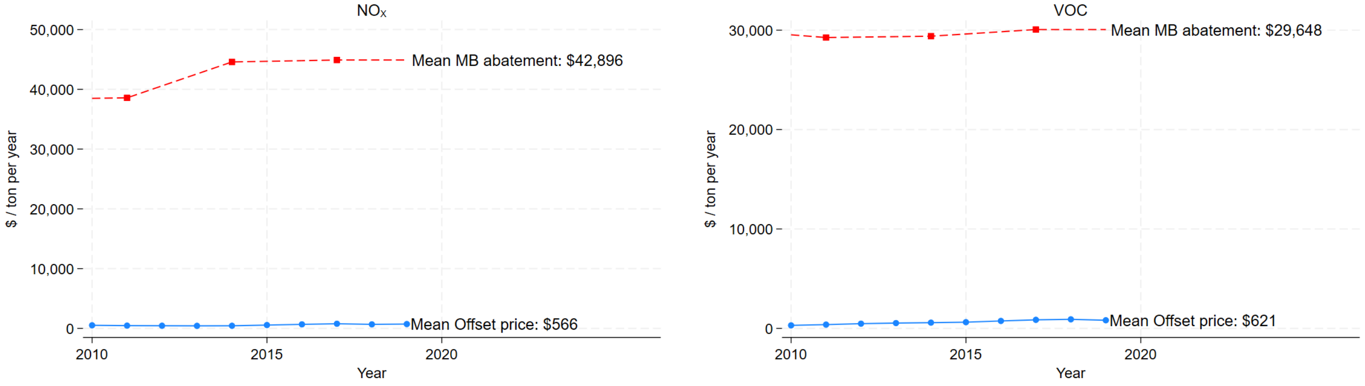
Notes: Offset prices and marginal benefits of abatement (MBabatement) are in $ per ton of emissions. Row 1 in each panel shows the ratio of marginal benefits of abating one ton of emissions to mean offset prices per ton of emissions. Row 2 shows the p-value for testing the null hypothesis that the ratio in Row 1 equals one. Rows 3 and 4 show the mean marginal benefits of abatement and mean offset prices, respectively. Data represent years 2010-2019. Offset prices are the mean price of pollution offsets per ton for the indicated census region, pollutant, and time period, weighted by transaction amount in tons or by population in offset markets, and annualized using the price ratio between permanent and temporary offset prices. Data on marginal benefits are available for years 2008, 2011, 2014, 2017, and linearly interpolated between years. All currency are in 2017$, deflated using the GDP deflator. Abatement marginal benefits for each region are weighted across counties within a market according to county population in 2010 Census, and weighted across markets by transaction amount in tons or by population in offset markets.

Figure 1: Pollution Offset Prices Versus Marginal Benefits of Abatement, by Year

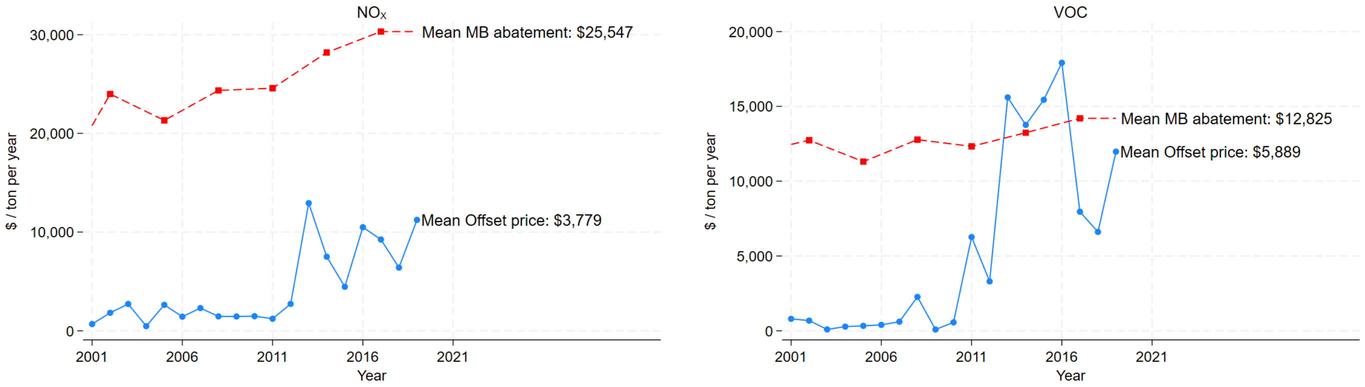
(A) Full sample (16 states plus Washington, DC)



(B) Northeast



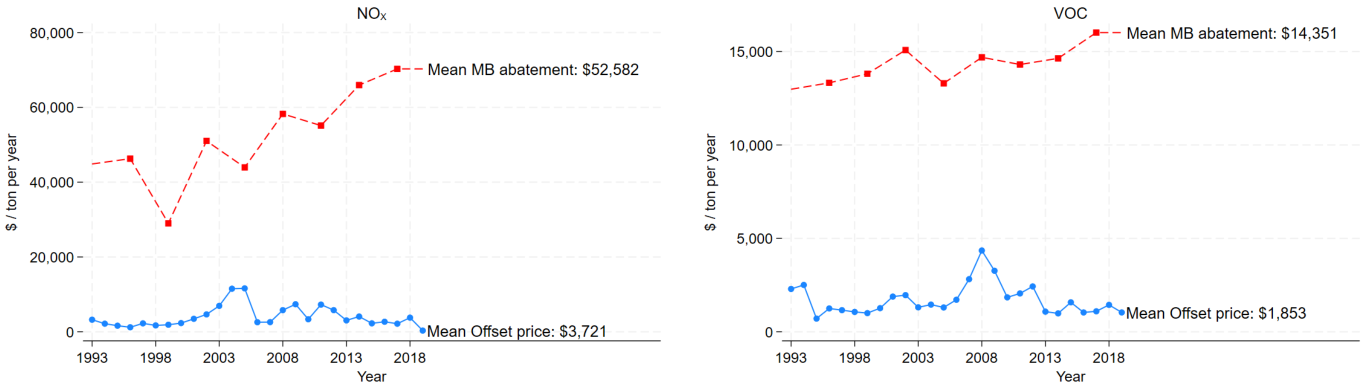
(C) South



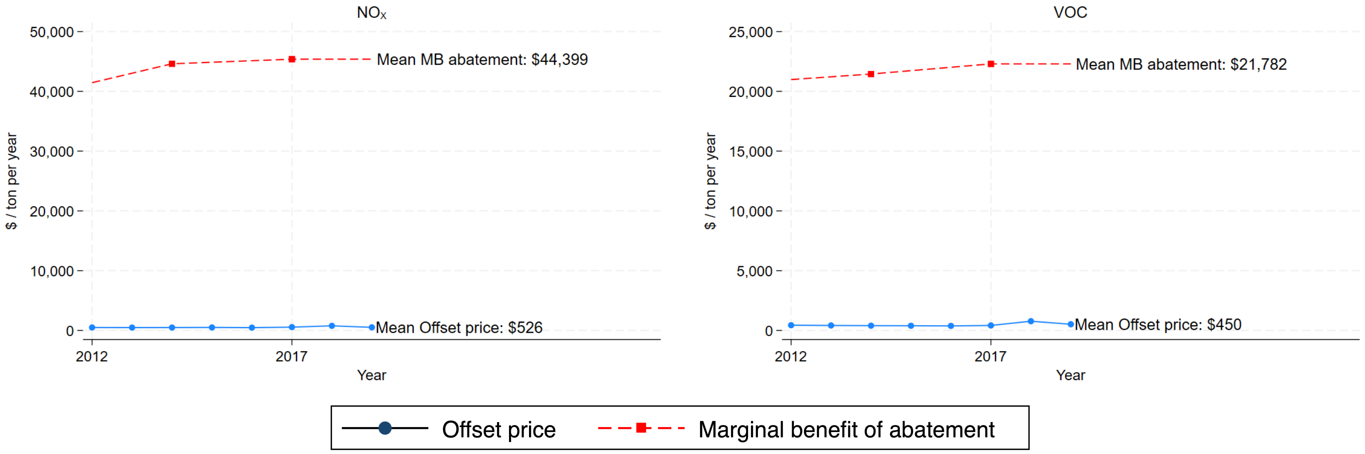
(Continued next page)

Figure 1: Pollution Offset Prices Versus Marginal Benefits of Abatement, by Year (Continued)

(D) West

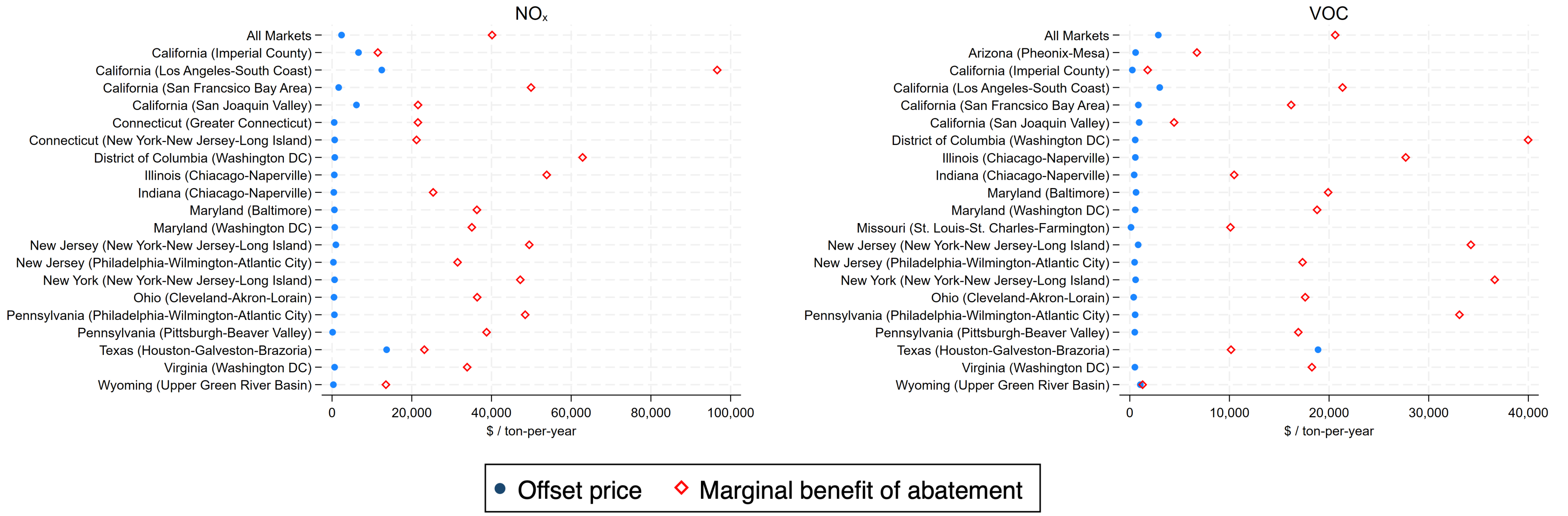


(E) Midwest



Notes: These graphs show pollution offset prices and the marginal benefits of pollution abatement by year, with separate graphs for each pollutant and census region. Blue solid line shows mean offset price in each market × pollutant × year; red dashed line shows marginal benefits of abatement. Offset prices are the mean price of pollution offsets per ton for the indicated nonattainment area, pollutant, and time period, weighted by transaction amount in short tons, and annualized using the observed price ratio between permanent and temporary offsets. Marginal benefits of abatement are the marginal external cost avoided per short ton abated for the indicated nonattainment area and pollutant for years 2008, 2011, 2014, and 2017, and linearly interpolated between years. Marginal benefits of abatement are weighted across counties within an offset market according to county population in 2010 Census. All currency are in 2017$, deflated by Federal Reserve's US GDP deflator.

Figure 2: Offset Prices and Marginal Benefits of Abatement, Large Individual Markets



Notes: This figure compares offset prices and the marginal benefits of pollution abatement in individual market × pollutants, for a set of large markets with data. Data represents years 2010-2019. The vertical axis lists the state that the data represent, then in parentheses, the market's name. Offset prices are the mean price of pollution offsets per ton for the indicated census region, pollutant, and time period, weighted by transaction amount in tons or by population in offset markets, and annualized using the price ratio between permanent and temporary offset prices. Marginal benefits of abatement are the marginal external cost avoided per ton abated for the indicated market and pollutant. Data on marginal benefits are available for years 2008, 2011, 2014, 2017, and linearly interpolated between years. All currency are in 2017$, deflated using the GDP deflator. Abatement marginal benefits for each market are weighted across counties within a market according to county population in 2010 Census. The Philadelphia-Wilmington-Atlantic City area includes Delaware.

Online Appendix:
Is Air Pollution Regulation Too Lenient?

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A Methodology for Counting References

To count the number of economics journal articles that investigate the cost and benefits of air pollution, we use the advanced search function on Google Scholar. We find articles that contains the exact phrase "air pollution," limit to articles published in *American Economic Review* (excluding Papers and Proceedings issues), *Econometrica*, *Journal of Political Economy*, *Quarterly Journal of Economics*, *Review of Economic Studies*, and limit to articles published in years 2000-2020. We then tag whether each article investigates the marginal cost of air pollution, the marginal benefit of air pollution, or both. An article is counted as estimating marginal costs if the article provides estimates of the economic cost to reduce a given unit of emission or ambient air pollution. Articles that estimate total economic costs of regulation (e.g., Greenstone 2002; Walker 2013) are not counted as estimating marginal costs. Similarly, an article is counted as estimating marginal benefits if the article estimates the benefits of reducing a given unit of emissions or ambient air pollution. Articles that estimate total effects of a regulation or large change (e.g., Currie et al. 2015) are not counted as estimating marginal benefits.

B Additional Institutional Background

This Appendix provides additional background on the Clean Air Act and offset markets.

B.1 Clean Air Act

Roughly every five years, the EPA convenes a group of scientists, who may propose to update air quality standards based on the best available evidence on the lowest pollution level that damages human health. Formally, the determination of these standards ignores costs. The Clean Air Act says the standards should be what is "requisite to protect the public health." Additionally, a unanimous 2001 Supreme Court decision (*Whitman v. American Trucking Associations, Inc.*) concluded that it was unconstitutional for the EPA to consider costs in setting these standards.

While formally the EPA may not consider costs, political factors including costs may have some bearing on revising air quality standards. Each presidential administration can delay implementation of new standards, choose exact standards among several that the scientific committee proposes, affect composition or deliberation of the scientific committee, and in other ways affect the choice of standards. Additionally, although the EPA does not directly consider costs in designing standards, it does publish detailed reports comparing costs and benefits of each reform (e.g., USEPA 2012), which are widely discussed in academic and public spheres.

This process suggests that regulators do not purposefully choose standards to equate marginal costs and benefits. At the same time, differences between costs and benefits of air quality regulation are controversial, politically important, and may affect the design of future regulation.

B.2 Offset Markets

Offsets apply only to plants and other "stationary" sources, which are important though not the only source of air pollution emissions. According to the EPA's estimates for 2019 from the National Emissions Inventory, stationary sources account for about 60 percent of anthropogenic VOC emissions and 40 percent of NO_x emissions; the main other sources are transportation, miscellaneous emissions like agriculture and forestry, and (non-anthropogenic) wildfires.

In addition to sources of offsets mentioned in the main text, incumbents can generate offsets by rewriting air quality permits to permanently decrease permitted production. This involves decreasing both a plant's production and pollution levels. While this is not a textbook example of end-of-pipe abatement, it does involve optimizing economic choices that trade off profits and pollution, and it is a source of abatement in cap-and-trade markets, pollution taxes, and other market-based environmental instruments.

Offsets are one of several emissions trading programs the EPA created in the 1970s. Another is "netting" (begun in 1974), which lets a plant offset a new emission source within a plant with decreases in emissions from other processes, discharge points, or smokestacks within the same plant without requiring New Source Review. "Bubbles," introduced in 1979, are similar to netting but allow trades between any different parts of a single plant, not merely between new and existing parts. "Banking" is similar but allows incumbent firms to save emissions reductions for future use by the same firm or for trading to another incumbent firm (Hahn and Hester 1987).

Hahn and Hester (1989) summarize early discussion of offset markets and their relationship to the EPA's other emissions trading programs. Before 1990, many offset trades were within firm, and a large share of inter-firm offset transactions occurred in the South Coast district around Los Angeles. They highlight the lack of market centralization and transaction costs as important contributors to low inter-firm transaction volume in the South Coast district and elsewhere in the 1980s. They summarize the cost savings from offset trading at the time as, "Probably large, but not easily measured" (p. 138). Fromm and Hansjurgens (1996) provide a case study of South Coast, which expanded offset trading but created the Regional Clean Air Incentives Market (RECLAIM) as a centralized cap-and-trade market for trading allowances for nitrogen oxides (NO_x) emissions. They compare institutional features of the RECLAIM cap-and-trade market to the South Coast offset market, and their comparisons echo differences described further in Appendix B.6. In the case of the South Coast, a centralized offset market may have contributed to a decentralized cap-and-trade market with lower frictions. We are not aware of similar comparisons. Specifically, we are not aware of direct or indirect links between offset markets and other prominent US cap-and-trade markets like the Acid Rain Program, NO_x Budget Trading Program, and Regional Greenhouse Gas Initiative.

The 1990 Clean Air Act Amendments made two important changes that had implications for offset markets. One directed the EPA to set air quality standards for several types of nonattainment (called marginal, moderate, serious, severe, and extreme), and to impose stricter regulations on the higher types of nonattainment. These types of nonattainment affect trading ratios, requiring that entrants in these more stringently defined nonattainment areas purchase 1.1-1.5 offsets for every ton of emissions. Offset trading before 1990 was limited due in part to strict rules (Foster and Hahn 1995). Before 1990, but less so afterwards, regulators rejected some proposals to generate offsets due to inadequate documentation or other reasons, or changed rules governing offsets in ways affecting their value (General Accounting Office 1982). The 1990 Clean Air Act Amendments liberalized these markets, and rules encouraged states and air districts to create "offset banks," so that a firm which generates an offset could sell it in subsequent years to other firms. The 1990 rules also encouraged states to organize formal certification programs which would make offsets simpler to use, and allowed shutdowns to generate a complete set of offsets (DuPuis 2000).

Offset markets have a few potential transaction costs. In 1990, one industry consultant estimated that intermediation costs, including locating a seller, conducting engineering studies, and obtaining regulatory approval, account for 10-30 percent of a trade costs. Another source quoted typical intermediation fees of 4 to 25 percent, depending on the transaction's complexity (Dwyer 1992). Since that time, many regulators have tried to lower these costs by providing centralized information clearinghouses for offset purchases and relevant contact information of existing firms holding offsets. Today, a firm seeking to buy an offset can call potential sellers who are listed on a publicly-available and regularly-updated website that most markets operate.

Market power may be another wedge or friction in these markets. If markets have a small number of market participants, firms may buy or sell offsets at prices that differ from their marginal abatement cost. For example, an incumbent may try to deter entry of a new competitor in the same industry and market. Available evidence is ambiguous on the importance of market power. In a typical snapshot where we have data from Houston and Los Angeles, for June 2014, both regions show large numbers of firms who could generate offsets. This ranges from a minimum of 274 firms in Houston-NO_x markets to a maximum of 828 firms in South Coast, CA. The number of firms with certified offsets available for sale ranges from 15 in Houston-NO_x to 218 in South Coast-VOCs. In the presence of markups, incumbents would charge offset prices above their marginal abatement costs. This would strengthen our paper's main finding—it would imply that the ratio of the marginal abatement costs to the marginal benefits of abatement is even smaller than we estimate, and so would suggest that regulation is even more lenient than is efficient.

B.3 Example Offset

Appendix Figure 5 shows an example offset. The firm Scan-Pac manufactures high-friction products used in steel mills, food processing, and other industries. Scan-Pac has a plant in the Houston nonattainment area, and that plant emits VOCs from coating fabrics. In May 2013, that plant installed a thermal oxidizer, an abatement technology which decomposes VOCs into harmless compounds. The state certified that Scan-Pac decreased VOC emissions by 21.8 tons per year, then issued the offset pictured in Appendix Figure 5.[11] In December 2013, Scan-Pac sold this offset to an oil and gas processing and transportation firm, Enterprise Products, for $3.6 million (=$165,000 per ton).[12] Enterprise used the offsets to build a $1.1 billion Houston-area facility that produces propylene, a common petrochemical, in the Houston area.

B.4 Temporary Versus Permanent Offsets

Some markets allow firms to sell temporary or "short term" offsets that last a single year.[13] In such markets, a permanent offset for a given pollutant might sell one week, and a one-year offset for the same pollutant may sell in the same market the next week. These permanent and temporary offsets are identical except for duration.

In most of the paper, we divide permanent offset prices by 9.3 to obtain an estimate of the one-year value of offsets. This reflects our calculation that on average in our transaction-level data,

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[11] All tons in the paper refer to short tons rather than metric tons, since short tons are the standard unit of denomination for US offset markets and for estimates of the marginal benefits of pollution abatement.

[12] Participants in the Houston market explained that while dates in the offset registry are typically close to the activity date, firms and regulators can have delays between when an offset is generated and when it is listed in the registry, or between when firms contract on the offset transaction and the date when the regulator officially certifies that contract, which can extend up to 18 months. Hence, although the registry lists the Scan-Pac abatement investment and offset sale as separated by several months, the decisions and actions may have been concurrent.

[13] These "temporary" offset programs provide firms with some year to year flexibility in complying with permitting rules. In California these are called "short term emissions reduction credits" (STERC), and in Texas they are called "discrete emissions reduction credits" (DERC). To maximize comparability among offsets, our main estimates in the rest of the paper only analyze permanent offsets, though sensitivity analyses add back in the several hundred temporary offset transactions. That sensitivity analysis does not discount prices of the temporary offsets.

permanent offsets sell at a price which is 9.3 times higher than one-year temporary offsets, for the same market, pollutant, and year. Henceforth all our references to "offset prices" or "annualized offset prices" refer to the one-year equivalent value of offset transactions. Although temporary and permanent offset are objectively comparable apart from duration, as a bounding exercise, we report sensitivity analyses which assume this ratio of permanent to temporary offset prices is 5.0, 7.0, or 12.0.[14]

What are the underlying economics which make permanent offsets sell at a price which is nearly ten times higher than temporary offsets? Firms should value the right to emit pollution in many years rather than just one year. Also, firms may discount future emissions rights according to their cost of capital or other prevailing discount rate. Firms may have expectations about future offset prices. Finally, offsets are a risky asset. If the area where the firm is located exits nonattainment, then the firm no longer needs to hold or purchase offsets, and any offsets the firm holds lose their value. If one interpreted the ratio of permanent to temporary offsets as reflecting firms' discount rates, it would imply a discount rate of 8 to 10 percent, though the discount rate interpretation is not needed to apply the ratio of permanent to temporary offset prices. While 8 to 10 percent is on the high side of firm discount rates for many economic settings, it partly reflects the high volatility and risk of offset prices, including the possibility that if an area exits nonattainment, offset prices fall to zero.

B.5 Offset Price Dispersion and Search Frictions

A few pieces of evidence suggest that search frictions are an important feature of offset markets. Price dispersion provides one indication of search costs or frictions in these markets. After residualizing prices by district×pollutant and quantity, the 90-10 log price difference in offset prices is 2.02. For comparison, in one well-known study of prescription medications, the 90-10 log difference is 1.64 (Sorensen 2000). Research on markets with search costs more often report the coefficient of variation (standard deviation divided by mean). This is large in our setting since offset prices (raw or residualized) are approximately lognormally distributed. The average offset market×year has a coefficient of variation of 1.04. For comparison, other studies of specific markets report a coefficient of variation for prices of 0.19 to 0.25 (retail wine), 0.20 to 0.24 (waste hauling), and 0.22 (prescription medication) (Sorensen 2000; Jaeger and Storchmann 2011; Salz 2022). The average market×year in our data has a coefficient of variation of log prices of 0.10.

The prevalence of brokers is another indicator of search frictions. Texas data provide information on brokered transactions, suggesting that almost 40 percent of transactions occur through the use of an intermediary. For reference, 13 percent of contracts in Salz (2022)'s dataset of waste hauling involve brokers.

Market participants also described anecdotes alluding to the importance of search costs. For example, some participants described contacting firms which they believe have an abatement opportunity, and then they will contract with those firms to generate an offset. In a number of conversations, there was not a single firm or broker that described contacting every firm with an abatement opportunity as a strategy to purchase offsets.

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[14] If we include temporary offsets lasting more than a year, the ratio of matched permanent and temporary offset prices is 9.1. Restricting to each pollutant implies ratios of 10.8 for NO_x and 7.1 for VOCs. Looking separately at each time period gives ratios of permanent to temporary offset prices of 9.0 for the 1990s, 6.6 for the 2000s, and 10.7 for the 2010s.

B.6 Offset Versus Cap and Trade Market Design

Offset markets differ from cap-and-trade markets in several ways (Fort and Faur 1997; Ellerman et al. 2003). Cap-and-trade markets regulate actual emissions; offset markets instead regulate emission limits as written into a source's air quality permit. Cap-and-trade markets require regulated sources to submit allowances to regulators at the end of each year covering the year's emissions; offsets are instead a one-time purchase, and the right to emit is guaranteed in perpetuity. Creating an offset to sell typically requires installation of abatement technology and certification of reductions by a regulator. Cap-and-trade markets allow some types of abatement that many offset markets do not, including temporary process changes, management or productivity improvements, input substitution, and others. Most cap-and-trade policies have a centralized market, whereas offset markets are decentralized and involve bilateral exchanges, sometimes via broker. Cap-and-trade markets typically replace other pollution standards (i.e., command and control requirements), while offset markets still require all sources to comply with prevailing command-and-control regulations. Offset markets are fragmented, with hundreds of separate markets, whereas the US has only a few cap-and-trade markets, which are typically large and each cover many sources and states.

C Additional Data Details

We deflate all prices to 2017 dollars using the Federal Reserve's US GDP Deflator, though show one sensitivity analysis using the regional Consumer Price Deflator (Federal Reserve Bank of St. Louis 2020a; US Bureau of Labor Statistics 2023).[15] In describing average features of markets, we weight across transactions according to the number of tons transacted. We focus on data for the years 2010-2019, though we also discuss data from the 1990s and 2000s.

We retrieve nonattainment areas from the Environmental Protection Agency's Green Book (US Environmental Protection Agency 2019b). We also manually collect state air districts in California and Texas along with a broader set of offset ratios provided in the data supplement (Shapiro and Walker 2025).

C.1 Offset Markets

We use two types of offset transaction data—market-average data for 14 states plus Washington, DC, obtained from the firm Emission Advisors (Emission Advisors Inc, 2020); and transaction-level data from California and Texas (California Air Resources Board 2019, 2020; Texas Commission on Environmental Quality 2019a,b), obtained from state regulators. In all these data, the main analysis sample excludes temporary offsets and transactions between subsidiaries of the same firm or that in other respects are not at arm's length.

The market-average data describe transactions in which Emission Advisors staff directly participated, transactions where Emission Advisors staff learned of prices due to interactions with market participants, and in a limited number of cases, prices where Emission Advisors staff knew sellers were ready to transact at a given price in a market × year but no trades occurred in that market × year. In part to maintain some confidentiality of individual transactions, many of these data are rounded to the nearest hundred or five hundred.

In the market-level data, in some cases the data separate a single offset market into multiple observations when the market spans more than one state. For example, the data contain three

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[15] The main results use the GDP deflator since we study assets valued for production, which does not exactly fit either the producer or consumer price index.

separate data points per year for the New York-New Jersey-Connecticut offset market, one for each of the three states, even though the three states together represent a single integrated market. Similarly, the data separate New York from Pennsylvania offset transactions in the Ozone Transport Region offset market. Two of the states covered in these data, Delaware and Wisconsin, do not have directly reported transactions, but these states are part of a multi-state offset market for which we have transaction prices in other parts of the market For Wisconsin, we have transaction prices from Illinois for the Chicago-Naperville, IL-IN-WI market; for Delaware, we have data transaction prices from Pennsylvania for the Philadelphia-Wilmington-Atlantic City PA-NJ-MD-DE market.

Most particulate matter offset markets regulate particulate matter smaller than 10 micrometers (PM_{10}), but most health damages and damage estimates involve the smallest component of that pollution, $PM_{2.5}$. To accurately compare offset prices to the marginal benefits of abatement, we therefore convert PM_{10} offset prices to what the corresponding $PM_{2.5}$ offset prices would be, using the best available estimates as to compliance cost differences between PM_{10} and $PM_{2.5}$.

Our results for particulates increase PM_{10} offset prices by a third in order to compare them with $PM_{2.5}$ marginal benefits of abatement. We focus on this one-third comparison because common abatement technologies and fuel switching achieve broadly similar percentage reductions of PM_{10} and $PM_{2.5}$ (ECR Incorporated 1998; van Harmelen et al. 2001). Hence, determining the abatement cost for PM_{10} versus $PM_{2.5}$ can be simplified to obtaining data on baseline $PM_{2.5}$ emissions as a share of baseline PM_{10} emissions.

Evidence indicates that industrial $PM_{2.5}$ emissions are around a third less than industrial PM_{10} emissions. The EPA's National Emissions Inventory indicates that the ratio of $PM_{2.5}$ to PM_{10} emissions for industrial sources is 0.69. Across California offset markets, this ratio is 0.50 (South Coast), 0.68 (San Joaquin Valley), and 0.82 (Bay Area). Across some of the dirtiest industries, this ratio varies from 0.42 (nonmetallic mineral manufacturing, including cement) to 0.90 (utilities including electricity generation). In Europe and China, the ratio of $PM_{2.5}$ to PM_{10} is about 0.61 (Klimont et al. 2002; Zhou et al. 2016, p. 10).[16] Research in environmental engineering calculates that the global ratio of anthropogenic $PM_{2.5}$ to PM_{10} emissions is 0.72 (Huang et al. 2014, p. 13836).

C.2 Market Coverage and Offset Sources

This subsection discusses other estimates of the value, size, and coverage of offset markets, and some data on sources of offsets. By law, pollution transacted in offset markets must exactly equal the pollution emitted by large entrants or plants undergoing retrofits. In this sense, offset markets cover 100 percent of the relevant benchmark (large entrants in regulated markets). Thus, the quantity of pollution transacted in offset markets is fully determined by and exactly equals the pollution of larger firms entering regulated markets.

A second statistic assesses how the emissions in offset transactions compare to total emissions. This ratio should be far below one since offsets reflect large entrants while total emissions in the market reflect all incumbents and entrants. Across markets, the mean ratio between annual offset quantity transacted in our data and total emissions in the National Emissions Inventory for the corresponding markets, weighted by market transaction quantity, is 7 percent. This statistic

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[16] Some regulators analyze PM_{10} and $PM_{2.5}$ abatement interchangeably. In an interview, a California regulator said that they use PM_{10} offset markets to comply with $PM_{2.5}$ nonattainment since engineering estimates of PM_{10} abatement are more widely available. Some EU analyses assume that PM_{10} and $PM_{2.5}$ abatement are interchangeable (Smeets et al. 2007, p. 3-4). A report for UK regulators assumes that $PM_{2.5}$ has an identical marginal abatement cost curve to PM_{10}, except that $PM_{2.5}$ levels are half of PM_{10} levels (AEA 2001).

compares the flow of new pollution (entry, reflected in offsets) versus the stock of pollution from entrants an incumbents (reflected in NEI). Across markets, maximum ratio of 19 percent is in the San Joaquin air district.

A third statistic calculates the total value of transactions in offset markets. For this market size calculation, we take the weighted mean of these offset transactions, weighting by the traded quantity. Multiplying these mean offset prices by the total emissions in each market gives a mean offset market value of $86 million for an air-district×pollutant. The total value summed across all markets corresponds to $2.1 billion. As a point of comparison, the market size of the NO_x Budget Program, a prominent cap-and-trade market for NO_x in 19 Eastern States, was about $1 billion per year (Deschenes et al. 2017). Hence, the offset markets in our data have similar market size as at least one other important environmental market.

Finally, we discuss the limited available data on the the share of firms participating in offset markets. Our offset transaction data report firm or establishment identifiers in Texas.[17] Three air regions in Texas are in nonattainment for ozone—Beaumont, Houston, and Dallas. We observe 39 unique participants in the Beaumont market for VOC or NO_x offsets, 43 unique participants in the Dallas market for VOC or NO_x offsets, and 250 unique participants in the Houston market for VOC or NO_x offsets. We lack data on the total number of major source facilities in these air regions, but we can use the Texas emissions inventory from 2018 to explore the number of facilities in these regions that emit either VOC or NO_x. This overstates the total number of major source facilities but serves as a useful lower bound on market participation. These data identify 104 facilities that emit either VOC or NO_x in Beaumont, corresponding to 40 percent (39/104) participating in the offset market. The numbers in Dallas and Houston are 15 percent (43/288) and 55 percent (250/457), respectively.

The Houston offset data identify which offsets originate from plant shutdown, and so let us analyze their importance. In the 2010s, plant shutdowns represented 11 percent of offset tons transacted. This share is slightly higher for NO_x, at 14 percent, and somewhat lower for VOCs, at 9 percent. While Houston only represents one market, and other regions lack data on offset sources needed to obtain these statistics. These statistics do suggest that plant shutdowns provide a modest source of offsets.

C.3 Marginal Benefits of Abatement

We calculate county-level marginal benefits of pollution abatement from the AP3 model (Holland et al. 2020a).[18] Most applications of AP3 calculate the social cost of a one-ton increase in pollution emissions. Because the marginal effects of pollution in the AP3 model turn out to be fairly linear for small changes in emissions, the effects of a one-ton increase or decrease in emissions in AP3 are practically identical.

AP3 begins with emissions of all criteria pollutants from all sources, measured from the National Emissions Inventory. AP3 then inputs these emission rates into the Climatological Regional Dispersion Model (CRDM), an air pollution transport model, to calculate ambient concentrations of each pollutant in each county. AP3 then applies concentration-response functions for each outcome it considers. AP3 calculates mortality in each of 19 different age groups used in the US census (0 years old, 1-4 years old, 5-9 years old, ..., 80-84 years old, 85+ years old). AP3 uses separate adult and infant concentration-response functions. AP3 then monetizes the change in mortality using an

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[17] We can link these to state regulators' identifiers (Texas Commission on Environmental Quality 2019a; US Environmental Protection Agency 2019a) by facility names.

[18] The marginal benefits of pollution abatement are comparable to the marginal damages of pollution emissions.

estimate of the value of a statistical life (VSL).

The atmospheric chemistry underlying these models is sometimes described as a "source-receptor" relationship or "reduced complexity" air quality model, since it seeks to approximate chemistry models with much greater complexity, but using representative values for each county or other geographic region (Kolstad and Williams 1989).

To calculate the marginal benefits of abatement using AP3, we start from the raw data files and programs that constitute AP3 (Muller 2020). To calculate the marginal benefits of abating a pollutant in a given county, we decrease emissions of that pollutant by one ton in that county and calculate the change in monetized damages.

Two clarifications on estimating marginal damages may be useful. One involves the potential gap between damages and marginal willingness to pay. Estimates of the marginal damages of air pollution may understate true marginal willingness-to-pay, since people may value clean air for reasons not captured in the damage function approach (e.g., pure amenity value). In practice, property value (hedonic) models have been economists' primary approach to estimating marginal willingness to pay for clean air. Comparing hedonic estimates with those from integrated assessment models' damage functions does not suggest that the damage function approach substantially understates marginal willingness-to-pay; if anything, the hedonic estimates are smaller than the damage function estimates used in AP3 (Smith and Huang 1995; Chay and Greenstone 2005; Bajari et al. 2012; Holland et al. 2020b). While there is uncertainty in each estimate from the literature, this suggests that AP3 does not dramatically understate the marginal benefits of pollution abatement relative to prevailing direct estimates of marginal willingness to pay for air quality.

The other clarification involves interactions between pollutants. We calculate the marginal benefits of abating one ton of each pollutant, evaluated at baseline emission levels of other pollutants. The damages of one pollutant can depend on the levels of others. The obvious example is that ground-level ozone formation depends on emission levels of both NO_x and VOCs, though ozone accounts for a small share of the damages we measure, and particulates count for the vast majority of the damages. Evaluating damages from baseline levels fits the definition of marginal changes, is the natural comparison in our setting, and is typically used in research. It also reflects technology—many leading abatement technologies used for the pollutants we study, such as selective catalytic reduction or thermal oxidizers, primarily affect emissions of the pollutants they target, while having limited effects on emissions of other pollutants.

A related issue is the question of how to quantify the benefits of policies that target one pollutant but affect others ("co-pollutants") (Aldy et al. 2020). The air quality models we use account for ways in which each emitted pollutant affects ambient concentrations of other pollutants (e.g., how NO_x emissions affect ambient $\mathrm{PM}_{2.5}$). At the same time, we believe the issue of co-pollutants is less important in our setting than in other settings, in part for the same reason that the abatement technologies used in offset markets primarily target one pollutant at a time. Much discussion of co-pollutants occurs with greenhouse gas emissions or toxic pollutants, neither of which we study; those other pollutants are cases where the abatement technologies used for one pollutant have large effects on emissions of others (e.g., the scrubbers used to comply with mercury regulations substantially decrease emissions of particulate matter).

C.3.1 Mortality Concentration-Response Function

The $\mathrm{PM}_{2.5}$ concentration-adult mortality relationship accounts for a large majority of air pollution damages. Because we report several alternative versions of this relationship and address a discrepancy in how AP3 measures it, we discuss it in detail.

Epidemiological studies typically report the relative risk of a health incident (e.g., death) for a given change in pollution exposure. This is commonly implemented as a Cox proportional hazard regression, i.e., a log-linear model of the relative risk. This assumes the relationship between the mortality rate for the treated population r, the mortality rate in the baseline, r_0, depends on the change in exposure $\Delta E = E_1 - E_0$, and the concentration-response parameter, β:

$$\frac{r_1}{r_0} = \exp(\beta \times \Delta E) \tag{1}$$

The change in the number of deaths relates to changes in the mortality rate by

$$r_1 - r_0 = r_0 \times \Bigg[\exp(\beta \times \Delta E) - 1\Bigg] \tag{2}$$

The change in incident rate relates to changes in mortality or morbidity cases by

$$\Delta \text{Deaths} = \text{Population} \times (r_1 - r_0) \tag{3}$$

Substituting (2) into (3) gives the following response function:

$$\Delta \text{Deaths} = \text{Population} \times r_0 \times \Bigg[\exp(\beta \times \Delta E) - 1\Bigg] \tag{4}$$

Each epidemiological study reports the relative risk $\frac{r_1}{r_0}$ and the change in concentration ΔE ; we substitute these into equation (1) to recover the coefficient β. Given β, we can then use equation (4) and data on the baseline incidence rate r_0 and population to compute the additional deaths due to a change in pollution.

We report results from six different published estimates of the $PM_{2.5}$ concentration-adult mortality response function. AP3's baseline uses the estimate of $\frac{r_1}{r_0} = 1.06$ per $\Delta E = 10\mu g/m^3$ of $PM_{2.5}$ exposure, from Krewski et al. (2009, p. 126, Commentary Table 4). For sensitivity analyses, we report estimates based on the 5th percentile of Krewski et al. (parameter estimate 1.04) and the 95th percentile (1.08). A separate sensitivity analysis uses an epidemiological estimate of $\frac{r_1}{r_0} = 1.14$ per $\Delta E = 10\mu g/m^3$, from Lepeule et al. (2012, p. 968, Table 2). We also report a sensitivity analysis using the spatial regression discontinuity instrumental variable regression of mortality on PM_{10} from Ebenstein et al. (2017, p. 10388, Table 3), which estimates a ratio of $\frac{r_1}{r_0} = 1.08$ per $\Delta E = 10\mu g/m^3$ of PM_{10} exposure in China. To translate PM_{10} to $PM_{2.5}$, we use estimates from Zhou et al. (2016), which suggests a ratio of 0.61 unit of $PM_{2.5}$ per unit of PM_{10} in China. The final sensitivity analysis uses a mortality estimate for the population aged over 65, from an instrumental variable regression of mortality on $PM_{2.5}$ from Sanders et al. (2020, p. 164, Table 3), who estimate a change of 0.006 in over-65 log mortality per $\Delta E = 1\mu g/m^3$ of $PM_{2.5}$ exposure. The Sanders et al. study uses nonattainment as an instrumental variable for pollution.

To calculate infant mortality, we use an infant mortality hazard ratio of $\frac{r_1}{r_0} = 1.07$ per $\Delta E = 10\mu g/m^3$ of $PM_{2.5}$ from Woodruff et al. (2006, p. 788), Table 3. In the 5th and 95th percentile sensitivity analyses, we pair the 5th and 95th percentile adult mortality concentration response (described above) with the 5th percentile (0.93) and 95th percentile (1.24) infant mortality concentration response. We report fewer sensitivity analyses for infant mortality since it is estimated to be a much smaller share than adult mortality of total damages.

None of these elasticity estimates is perfect. The epidemiological estimates have high-quality pollution measurement and control for other determinants of cardiorespiratory health, but represent essentially an observational comparison with potential for omitted variable bias. One quasi-experimental estimate uses a more credible research design to deal with spatially correlated unobservables, but is set in China, where the pollution-mortality elasticity might differ substantially from the US, and is measured in terms of PM_{10}, so requires translation to $PM_{2.5}$. Another quasi-experimental estimate focuses on the US, but is limited to the population aged over 65.

The main AP3 model computes only monetized damage from $PM_{2.5}$ mortality. In an additional sensitivity analysis, we compute damages from other channels not included in AP3 but that are included in the precursor of AP3, APEEP (Muller and Mendelsohn 2009). The additional sources of pollution damages include crop yields, timber yields, forest-system ecology, chronic bronchitis, acute mortality from ozone, respiratory illness hospital admissions from ozone, asthma emergency visits from ozone, chronic asthma morbidity from ozone, chronic obstructive pulmonary disease hospital admissions from NO_x and ischemic heart diseases hospital admissions from NO_x. Although this sensitivity analysis incorporates many additional channels of damages, it only slightly increases AP3's estimate of the marginal benefits of abatement.

C.3.2 Addressing One Discrepancy

The original AP3 programs compute damages as follows. First, it computes the baseline number of deaths D_0 using the concentration response function β, baseline population, and baseline mortality rate r_0 at ambient level E_0:

$$D_0 = \text{Population} \times r_0 \times \left[1 - \frac{1}{\exp(\beta E_0)}\right] \tag{5}$$

AP3 monetizes D_0 by summing over all counties and multiplying by willingness to pay (WTP) to get baseline damage $D_0 \times WTP$.

The original programs then compute the new number of deaths with the ambient level E_1 obtained from the air transport model after increasing emissions by one ton in a specified county:

$$D_1 = \text{Population} \times r_0 \times \left[1 - \frac{1}{\exp(\beta E_1)}\right] \tag{6}$$

The new damage is $D_1 \times WTP$.

Equations (5) and (6) imply that in the original version of AP3, the change in deaths is calculated as

$$\begin{aligned}
\Delta\text{Deaths} &= D_1 - D_0 \\
&= \text{Population} \times r_0 \times \left[\frac{1}{\exp(\beta E_0)} - \frac{1}{\exp(\beta E_1)}\right] \\
&= \text{Population} \times r_0 \times \left[\frac{\exp(\beta E_1)}{\exp(\beta E_0)\exp(\beta E_1)} - \frac{1}{\exp(\beta E_1)}\right] \\
&= \text{Population} \times r_0 \times \left[\frac{1}{\exp(\beta E_1)} \times \exp(\beta \underbrace{(E_1 - E_0)}_{\Delta E} - 1)\right] \qquad (7)
\end{aligned}$$

Comparing equations (7) and (4) highlights the discrepancy. The original version of AP3 multiplies damages by the term $\frac{1}{\exp(\beta E_1)}$. In our California and Texas sample, this would make it understate damages by about 7.5 percent. We correct this discrepancy and modify AP3 to apply equation (4) everywhere, rather than equation (7), to calculate pollution damages.

C.3.3 Value of Statistical Life

Our baseline estimates use the USEPA (2023)'s preferred VSL of \$8.8 million (in 2017 dollars). This estimate primarily reflects hedonic models of the labor market which assess how a worker's wage increases as the worker's occupational fatality risk increases. An alternative is a VSL of \$3.7 million, which reflects a similar study covering all countries in the Organization for Economic Cooperation and Development (OECD 2012). The OECD includes many countries with lower GDP per capita than the US, such as Mexico and Turkey, so it is perhaps unsurprising than a VSL estimate for the OECD is lower than a VSL estimate for the US

One potential criticism of standard VSL estimates is that they monetize all mortality equally regardless of the age of death. The EPA's VSL estimate is the same for all individuals, but the VSL for a prime-aged worker may differ from the VSL for a 100-year old person. If air pollution causes premature mortality primarily for older populations, monetizing mortality equally or differently across ages can affect benefit estimates. We therefore conduct a sensitivity analysis where we adjust the monetary value of mortality according to expected life years remaining.

We implement this in a similar way as described in Appendix H.1 of Carleton et al. (2022), which in turn is based on Murphy and Topel (2006). First, we take the VSL and divide by the expected life-years remaining of a median-age US person to obtain the value of life year. Then, for each death in each age group estimated from the AP3 model, we calculate age-adjusted VSL by multiplying the value of life-years by the expected life years remaining for a person in that age group.

C.3.4 Other Inputs to Estimate Marginal Benefits of Abatement

AP3's estimates use data on the baseline population and mortality rates in each county. We use population data from the US Census and the Center for Disease Control (CDC) with mortality data from the National Bureau of Economic Research, CDC, and the National Center for Health Statistics (US Bureau of Labor Statistics 2020a; US Census Bureau 2017, 2019, 2020a,b,c; Centers for Disease Control and Prevention 2020b,a; National Bureau of Economic Research 2020b,a; Arias 2014). AP3 distinguishes between marginal benefits of abatement from non-point and point sources, and between point sources with different stack heights. Stack heights matter because the altitude at which a pollutant is emitted influences the pollutant's ambient level and spatial distribution. Our analysis of offset markets focuses on point sources in California and Texas. The source-level emission data from National Emissions Inventory (NEI) shows that less than 0.01% of emissions come from stack heights over 250 meters. We apply AP3 assuming stack heights are lower than 250 meters.

C.3.5 Alternative Models for the Marginal Benefits of Abatement

We also show sensitivity analyses using the three main other integrated assessment models besides AP3 which estimate the marginal damages of emitting a ton of each pollutant in each US county. The models are the Intervention Model for Air Pollution (InMAP; Tessum et al. 2017), Estimating Air Pollution Social Impact Using Regression (EASIUR; Heo et al. 2016); and the Air Pollution Emission Experiments and Policy Analysis Model, 2 (AP2; Muller 2014), which is the precursor of AP3.[19] Atmospheric chemists have developed extraordinarily detailed and computationally-intensive chemical transport models that assess how one specific change in emissions, such as closing

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[19] The underlying raw data and programs of InMAP, EASIUR, and AP2 are made available by the Center for Air, Climate and Energy Solutions (Center for Air, Climate and Energy Solutions, 2020).

a specific power plant, affects air quality everywhere. The models we use (AP3, AP2, InMAP, EASIUR) simplify the richer chemical transport models models to instead assess how emissions from any source in a county affect air quality and damages everywhere. The journal articles cited above which described the simplified integrated assessment models, in addition to Gilmore et al. (2019), compare the integrated assessment models against the more detailed chemical transport models, and find strong though imperfect correspondence.

C.4 Implied Discount Rates

The main text divides permanent offset prices by 9.3 to obtain the annualized value. Here, as an alternative, we use the price ratio of permanent to temporary offsets to learn what discount rate firms implicitly use. To maximize comparability among offsets, our main estimates only use permanent offsets, though a sensitivity analyses in the Appendix adds back in temporary offsets. That sensitivity analysis does not discount prices of the temporary offsets.

We use the following standard annuity formula:

$$P_{permanent} = P_{temporary} \left[\frac{1-(1+r)^{-n}}{r/(1+r)} \right] \tag{8}$$

Here, $P_{permanent}$ is the price of a standard offset, $P_{temporary}$ is the price of a temporary offset, r is the discount rate firms implicitly use, and n is the duration that firms expect offsets to last. Regulatory analyses of air pollution abatement regularly assume an average region will be in nonattainment for 20 years. We therefore calculate discount rates assuming $n = 20$, though we report sensitivity to assuming $n = 10$ and $n = \infty$. We limit the analysis of discount rates to permanent offsets that are in the same market, pollutant, and year as a traded temporary offset. Practically, we calculate the ratio of permanent and temporary offset prices in these markets, then numerically solve nonlinear equation (8) for r.

Applying the standard annuity formula, assuming that “permanent” offsets last for 20 years, implies that firms use a discount rate of 10.2 percent. Weighting transactions by the number of tons transacted implies a discount rate of 10.6 percent. Including multi-year temporary permits, rather than only single-year temporary permits, implies a discount rate of 10.5 percent (unweighted) or 10.9 percent (weighted by transactions in tons. These statistics include all years’ transactions, and if we restrict the sample to transactions in the 2010s, we recover a discount rate of 7.9 percent (weighted) or 8.1 percent (unweighted).

D Additional Policy Discussion

D.1 Other Existing Environmental Regulations

This subsection describes some of the other principal regulations for NO_x and VOCs facing plants in our data. These regulations use two policy instruments—standards and cap-and-trade markets. The US does not primarily use pollution taxes for NO_x or VOCs.

Most plants face federal command-and-control type emission standards for NO_x and VOCs under the Clean Air Act. The standard which applies to a plant depends on its location and nonattainment status. The standards have various acronyms–a firm may have to install the Best Available Control Technology (BACT), Reasonably Available Control Technology (RACT), etc. Many plants face additional local, state, or federal technology or emissions standards. For example, Berman and Bui (2001) count 46 separate local air pollution regulations for manufacturing plants in the area around Los Angeles, a count which excludes state and federal regulations. Apart from detailed descriptions of federal regulation (e.g., Morss and Wooley (2022)), we are unaware of any systematic national enumeration of local and state air quality regulations.

A few cap-and-trade programs also regulate some plants in our data. The Regional Clean Air Incentives Market (RECLAIM) regulates NO_x emitters in the South Coast region around Los Angeles, though in specific cases ERCs can substitute for RECLAIM allowances. Houston has a Mass Cap-and-Trade market (MECT) for NO_x, and a Highly Reactive Volatile Organic Compound Emissions Cap and Trade Program (HECT), both of which target electricity generation units. In addition, a series of NO_x cap-and-trade markets has operated for electricity generating units and a handful of large industrial plants (e.g., oil refinereis) in the Eastern US, beginning with the NO_x Budget Trading Program (2003-2008), which transitioned to the Clean Air Interstate Rule (CAIR), 2009-2014), and then the Cross-State Air Pollution Rule (2015 and beyond).

E Additional Results

E.1 Relating Offset Prices to Other Environmental Aggregates

Throughout Section 3.3, an industry represents a 6-digit North American Industry Classification (NAICS) code. Additionally, we define polluting plants to include all plants in industries that account for at least 0.5 percent of national, stationary-source emissions for that pollutant, where emissions are measured from the EPA's National Emissions Inventory (NEI).

Pollution Abatement Costs and Expenditures

We report estimates of the following equation:

$$ln(P_c) = \beta ln\left(\frac{A_{ci}}{Y_{ci}}\right) + \mu_i + \epsilon_{ci} \tag{9}$$

Each observation in this regression represents a county c and industry i. Here A_{ci} represents either total dollars of spending on pollution abatement in a county×industry, measured from PACE; or short tons of pollution emissions, measured from the NEI. The variable Y represents output of polluting plants, measured from the 2005 ASM (corresponding with the 2005 PACE) or 2012 CM (corresponding with the 2011 NEI). The term P_c represents mean offset prices in county c for the corresponding Census year. We aggregate abatement expenditures or emissions A_{ci} to the county×industry level, in part to avoid zeros before taking logs. The regression includes fixed effects for each industry, μ_i, to control for differences across industry in abatement expenditures or emissions intensity. We weight each regression by the total value of shipments in a county×industry cell. We estimate different versions of equation (9), where Y represents value added or output; P is the price of offsets for different pollutants; and where A represents different versions of abatement expenditures or pollution emissions. The coefficient β in equation (9) represents the elasticity of offset prices with respect to abatement costs or emission rates. For example, we test how NO_x offset prices are related to survey measures of abatement costs for NO_x emitting firms. While these are cross-sectional regressions that are correlational in nature, they provide some insight on the association of abatement costs and emissions rates.

Appendix Table 1 presents 24 separate estimates of equation (9). Each entry shows one estimate of the elasticity β. Columns (1) and (2) show pollutant-specific regressions. Column (3) pools estimates across all pollutants. Parentheses show standard errors clustered by air district.

Pollution Emissions

Appendix Table 2 estimates a version of Equation (9), where A_{ci} represents the short tons of air pollution emissions from a county×industry, divided by output or value added. Each column and panel shows a separate regression. Panel A measures emission rates per dollar of shipments, and Panel B measures emissions per dollar of value added. Columns (1) and (2) show different pollutants and column (3) combines pollutants. For example, column (1) of Panel A shows an estimate of the relationship between the NO_x offset price in that air district×year and NO_x emissions per dollar of shipments in NO_x-emitting establishments.

Polluting Industrial Activity

We use the following equation to test how offset prices respond to polluting industrial activity:

$$lnP_{dt} = \sum_{l=0}^{2} \gamma_l lnY_{d,t-l} + \alpha_d + \eta_t + \epsilon_{dt} \tag{10}$$

Here P_{dt} represents the mean offset price in air district d and year t. The term $Y_{d,t-l}$ represents total output or value added of polluting industries in district d and year t, lagged by l years, and measured from the Census of Manufactures and the Annual Survey of Manufacturers. We include district fixed effects and year fixed effects, α_d and η_t. Regressions are weighted by the total value of shipments in each air district×year. Standard errors are clustered by air district. We aggregate output and value added taking an output-weighted mean. The lags capture some dynamics of price responses. We focus on the cumulative effect, measured as $\sum_{l=0}^{2} \gamma_l$.

Appendix Table 3 presents estimates of equation (10). Panel A measures price responses to total output, and Panel B measures price responses to total value added. Each entry shows one estimate of the elasticity γ_t. Columns (1) and (2) show pollutant-specific regressions. Column (3) pools estimates across all pollutants. Parentheses show standard errors clustered by air district.

Nonattainment Designations

The 1990 Clean Air Act Amendments introduced a new National Ambient Air Quality Standard for ozone including classifications for ozone nonattainment severity. Depending on ambient ozone levels, areas could be classified into five different nonattainment classifications: Extreme, Severe, Serious, Moderate, and Marginal. Increasing nonattainment stringency can affect offset markets for ozone precursors, NO_x and VOC, for two reasons. First, large facilities must purchase offsets. Under the more stringent nonattainment classifications, the EPA uses a stricter criteria that define more facilities as large. Second, as the nonattainment severity increases, facilities become required to purchase proportionally *more* offsets than they emit depending on a severity-specific trading ratio. These trading ratios range from 1-to-1 for marginal nonattainment to 1.5-to-1 for extreme nonattainment. All large facilities must install the most stringent (Lowest Achievable Emissions Rate) abatement technology, regardless of the nonattainment classification.

We use the following regression to relate offset prices to nonattainment stringency:

$$lnP_{dpt} = \sum_{g} \psi_g 1[d \in g] + \epsilon_{dpt} \tag{11}$$

Each observation is a district d, pollutant p, and year t. The dependent variable is the mean log offset price. Each independent variable is an indicator for the severity g of the ozone nonattainment designation for an air district.

Appendix Table 4 presents results from four separate regressions, one per column. The excluded (reference) category for nonattainment severity is “marginal”. Regressions are weighted by average tons of offsets transacted for a district×pollutant.[20] Parentheses show standard errors clustered by district×pollutant.

E.2 Sensitivity of Results

Panel A of Appendix Figure 4 investigates sensitivity to alternative ways of summarizing offset prices. The main estimates assume that permanent offsets sell at a price of about nine times the price of temporary offsets; Appendix Figure 4 shows alternative values assuming the ratio of permanent to temporary prices is 7, 5, 12, or 15.5. The values of 12 and 15.5 here correspond to discount rates of 6% or 2.9% from Giglio et al. (2021), calculated using equation (8) from Appendix C.4. The rate of 6% represents the mean return to real-estate, while 2.9% represents very long-run (100+ years) rates. Additional rows show alternative estimates for the markets with transaction-level offset prices. Appendix Figure 4 next shows a value of offset prices which is adjusted by the required offset ratio between offset generation and use, discussed in Appendix B.2. The next two rows show values for the tenth percentile of offset prices in each market, and the ninetieth percentile of offset prices. We then consider the ninetieth percentile of transaction sizes in tons, which may be relevant if transaction costs are fixed rather than variable and thus the larger transactions would less reflect transaction cost. The last few rows include data from 1993-2009, analyze temporary offsets, use a regional consumer price deflator, and show results for a different pollutant with fewer offsets (particulate matter, listed in the NO_x graph for simplicity).

Appendix Figure 4, Panel B, shows sensitivity to alternative estimates of the marginal benefits of pollution abatement. We consider alternative estimates of the value of a statistical life (VSL); alternative estimates of the mortality concentration-response function for particulate matter; we add in damages from capital depreciation, crop yields, and other channels not included in the main AP3 model; we use the original version of the AP3 model, without correcting the epidemiology discrepancy; and we consider three alternative integrated assessment models. The AP2 model does estimate differential damages from NO_x, though the main improvement in AP3 involves redesigning the atmospheric chemistry through which NO_x transforms into particulate matter in ways that align better with leading atmospheric chemistry models.

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[20] We weight by the average quantity of tons transacted since these models are estimated outside of the Federal Research Data Center, and we do not have information on the total value of shipments at the district level.

Appendix Table 1: Relationship Between Offset Prices and Abatement Expenditures

	(1) NO_x Offset Price	(2) VOC Offset Price	(3) Combined Offset Price
$\frac{\text{Operating Costs}}{\text{Output}}$	1.791*	1.015***	1.424***
	(0.753)	(0.314)	(0.337)
Adj. R-squared	0.538	0.499	0.767
$\frac{\text{Operating Costs}}{\text{Value Added}}$	3.475***	1.222**	1.851***
	(0.821)	(0.445)	(0.409)
Adj. R-squared	0.740	0.470	0.784
$\frac{\text{Total Costs}}{\text{Output}}$	1.298*	0.611***	0.890***
	(0.531)	(0.167)	(0.199)
Adj. R-squared	0.558	0.521	0.766
$\frac{\text{Total Costs}}{\text{Value Added}}$	2.189***	0.720***	1.109***
	(0.529)	(0.180)	(0.214)
Adj. R-squared	0.731	0.527	0.787
$\frac{\text{Capital Stock}}{\text{Output}}$	1.303*	0.502**	0.789***
	(0.575)	(0.202)	(0.210)
Adj. R-squared	0.505	0.426	0.731
$\frac{\text{Capital Stock}}{\text{Value Added}}$	2.223**	0.541*	0.927***
	(0.685)	(0.256)	(0.255)
Adj. R-squared	0.648	0.405	0.737
$\frac{\text{Operating+Capital Stock}}{\text{Output}}$	1.303*	0.606***	0.888***
	(0.540)	(0.172)	(0.201)
Adj. R-squared	0.552	0.513	0.763
$\frac{\text{Operating+Capital Stock}}{\text{Value Added}}$	2.213***	0.712***	1.105***
	(0.550)	(0.191)	(0.217)
Adj. R-squared	0.725	0.517	0.783
N	129	339	603

Note: This table presents regression results from 24 separate regressions, 3 per row. An observation is a county×NAICS-6 industry, where the independent variable corresponds to a different measure of abatement expenditures per dollar of output or value added, as indicated in the row heading. The dependent variable in all regressions is the price of emissions reduction credits or offset prices. All dependent and independent variables are in logs. Observations are limited to industries that account for at least 0.5 percent of national, stationary-source emissions for the pollutant specified in each Column (NO_x, VOC). All regressions are weighted by the total value of shipments and control for NAICS-6 industry fixed effects. Standard errors clustered at the district-level are in parentheses. Abatement expenditures and capital stock come from the 2005 Pollution Abatement Costs and Expenditure Survey, and output and value added come from the 2005 Annual Survey of Manufacturers.

Appendix Table 2: Relationship Between Offset Prices and Plant-level Emissions Intensity

	(1) NO_x Offset Price	(2) VOC Offset Price	(3) Combined Offset Price
	Panel A: Emissions Per Unit of Output		
$\frac{\text{Emissions}}{\text{Output}}$	-0.169*	-0.143	-0.137***
	(0.083)	(0.093)	(0.045)
Adj. R-squared	0.26	0.24	0.471
N	1599	2266	4497
	Panel B: Emissions Per Unit of Value Added		
$\frac{\text{Emissions}}{\text{Value Added}}$	-0.149*	-0.139	-0.130***
	(0.085)	(0.085)	(0.043)
Adj. R-squared	0.255	0.24	0.47
N	1599	2266	4497

Note: This table presents regression results from 6 separate regressions, 3 per panel. An observation is a county×NAICS-6 industry, where the independent variable is calculated as the output-weighted average of emissions per dollar of shipments (Panel A) or emissions per dollar of value added (Panel B). The dependent variable in all regressions is the price of emissions reduction credits or offset prices. All dependent and independent variables are in logs. Observations are limited to industries that account for at least 0.5 percent of national, stationary-source emissions for the pollutant specified in the column heading. All regressions control for NAICS-6 industry fixed effects and are weighted by the total value of shipments; column (3) also includes pollutant fixed effects. Standard errors clustered at the district-level are in parentheses. Emissions data come from the 2011 National Emissions Inventory, and output and value added come from the 2012 Census of Manufacturers.

Appendix Table 3: Relationship Between Offset Prices and Value Added

	(1) NO_x Offset Price	(2) VOC Offset Price	(3) Combined Offset Price
	Panel A: Value Added		
ln(Value Added)	0.376***	0.106	0.263**
	(0.027)	(0.465)	(0.108)
ln(Value Added)$_{t-1}$	0.585***	0.183	0.295
	(0.119)	(0.670)	(0.494)
ln(Value Added)$_{t-2}$	0.386***	1.105**	0.849**
	(0.125)	(0.512)	(0.346)
Cumulative Effect	1.347***	1.394	1.407*
	(0.215)	(1.099)	(0.713)
p-value	0.000	0.221	0.064
Adj. R-squared	0.794	0.596	0.712
	Panel B: Output		
ln(Output)	0.236	-0.227	-0.081
	(0.238)	(0.193)	(0.176)
ln(Output)$_{t-1}$	0.410**	-0.108	0.029
	(0.155)	(0.214)	(0.123)
ln(Output)$_{t-2}$	-0.038	0.212	0.175
	(0.244)	(0.334)	(0.234)
Cumulative Effect	0.608*	-0.123	0.123
	(0.304)	(0.420)	(0.350)
p-value	0.067	0.772	0.729
Adj. R-squared	0.536	0.415	0.488
N	100	200	300

Note: This table presents regression results from 6 separate regressions, 1 per column in each panel. An observation is a district×year, where the dependent variable is the mean log offset price for a given pollutant, as indicated in the column headings. The independent variable in Panel A is the log value added of industrial output, and the independent variable in Panel B is the log total value of shipments. Observations are limited to industries that account for at least 0.5 percent of national, stationary-source emissions for the pollutant specified in the column heading. All regressions are weighted by the total value of shipments and control for district and year fixed effects. Standard errors clustered at the district-level are in parentheses. Observation numbers have been rounded to the nearest hundredth for disclosure avoidance. Source: Census and Annual Survey of Manufacturers.

Appendix Table 4: Relationship Between Offset Prices and Stringency of Nonattainment Designation

	(1) Offset Price	(2) Offset Price	(3) Offset Price	(4) Offset Price
1[Extreme Nonattainment]	1.725^{***}	1.657^{***}	1.657^{***}	1.654^{***}
	(0.469)	(0.515)	(0.518)	(0.474)
1[Severe Nonattainment]	1.375^{***}	1.364^{***}	1.363^{***}	1.363^{***}
	(0.456)	(0.486)	(0.483)	(0.459)
1[Serious Nonattainment]	0.732^{*}	0.783^{*}	0.780^{**}	0.769^{**}
	(0.375)	(0.394)	(0.375)	(0.362)
1[Moderate Nonattainment]	0.159	0.318	0.317	0.293
	(0.293)	(0.306)	(0.294)	(0.268)
Constant	8.175^{***}	8.125^{***}	8.126^{***}	8.135^{***}
	(0.329)	(0.343)	(0.329)	(0.309)
N	480	480	480	480
adj. R^2	0.220	0.237	0.236	0.244

Standard errors in parentheses

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Note: This table presents regression results from 4 separate regressions, 1 per column. An observation is a district×pollutant×year, where the dependent variable is the mean log offset price. Each independent variable is a dummy equal to 1 reflecting the severity of the ozone designation for an air district. The excluded category is "Marginal". Regressions are weighted by average tons transacted for a district×pollutant. Standard errors clustered at the district×pollutant level are in parentheses.

Appendix Table 5: Ratio of Marginal Benefits of Abatement to Maximum Offset Prices, 2010-2019

	NO_x		VOCs	
	(1)	(2)	(3)	(4)
Panel A. California and Texas				
1. Marginal benefits of abatement / Offset price	23.59	5.23	17.30	4.51
2. p-val: MBabatement / Offset price = 1	[0.00]	[0.00]	[0.00]	[0.00]
3. Marginal benefits of abatement	$42,098	$50,737	$24,810	$20,565
4. Max offset prices	$1,784	$9,699	$1,434	$4,557
Panel B. California				
1. Marginal benefits of abatement / Offset price	5.79	3.70	2.26	3.05
2. p-val: MBabatement / Offset price = 1	[0.00]	[0.00]	[0.02]	[0.00]
3. Marginal benefits of abatement	$39,138	$70,962	$8,772	$16,549
4. Max offset prices	$6,765	$19,184	$3,875	$5,431
Panel C. Texas				
1. Marginal benefits of abatement / Offset price	1.84	1.20	0.81	0.47
2. p-val: MBabatement / Offset price = 1	[0.63]	[0.86]	[0.91]	[0.66]
3. Marginal benefits of abatement	$23,468	$23,380	$8,268	$8,903
4. Max offset prices	$12,736	$19,462	$10,248	$18,821
Weight:				
Tons	X		X	
Population		X		X

Notes: This table has same structure as Table 3, except this table only shows the two states where we have transaction-level price data needed to calculate maximum offset prices, California and Texas. Offset prices and marginal benefits of abatement (MBabatement) are in $ per ton of emissions. Row 1 in each panel shows the ratio of marginal benefits of abating one ton of emissions to the maximum offset price per ton of emissions. Row 2 shows the p-value for testing the null hypothesis that the ratio in Row 1 equals one. Rows 3 and 4 show the mean marginal benefits of abatement and maximum offset price, respectively. Data represent years 2010-2019. Offset prices are the maximum price of pollution offsets per ton for the indicated region, pollutant, and time period. When combining maximum amounts across markets, we weight by transaction amount in tons or by population in offset markets. Data on marginal benefits are available for years 2008, 2011, 2014, 2017, and linearly interpolated between years. All currency are in 2017$, deflated using the GDP deflator. Abatement marginal benefits for each region are weighted across counties within a market according to county population in 2010 Census, and weighted across markets by transaction amount in tons or by population in offset markets.

Appendix Table 6: Ratio of Marginal Benefits of Abatement to Median Offset Prices, 2010-2019

	NO_x		VOCs	
	(1)	(2)	(3)	(4)
Panel A. California and Texas				
1. Marginal benefits of abatement / Offset price	40.97	13.58	29.63	9.45
2. p-val: MBabatement / Offset price = 1	[0.00]	[0.00]	[0.00]	[0.00]
3. Marginal benefits of abatement	$42,098	$50,737	$24,810	$20,565
4. Median offset prices	$1,028	$3,735	$837	$2,176
Panel B. California				
1. Marginal benefits of abatement / Offset price	8.41	9.61	4.03	6.33
2. p-val: MBabatement / Offset price = 1	[0.00]	[0.00]	[0.00]	[0.00]
3. Marginal benefits of abatement	$39,138	$70,962	$8,772	$16,549
4. Median offset prices	$4,652	$7,387	$2,175	$2,614
Panel C. Texas				
1. Marginal benefits of abatement / Offset price	5.28	3.60	1.93	1.09
2. p-val: MBabatement / Offset price = 1	[0.17]	[0.20]	[0.63]	[0.93]
3. Marginal benefits of abatement	$23,468	$23,380	$8,268	$8,903
4. Median offset prices	$4,442	$6,496	$4,295	$8,177
Weight:				
Tons	X		X	
Population		X		X

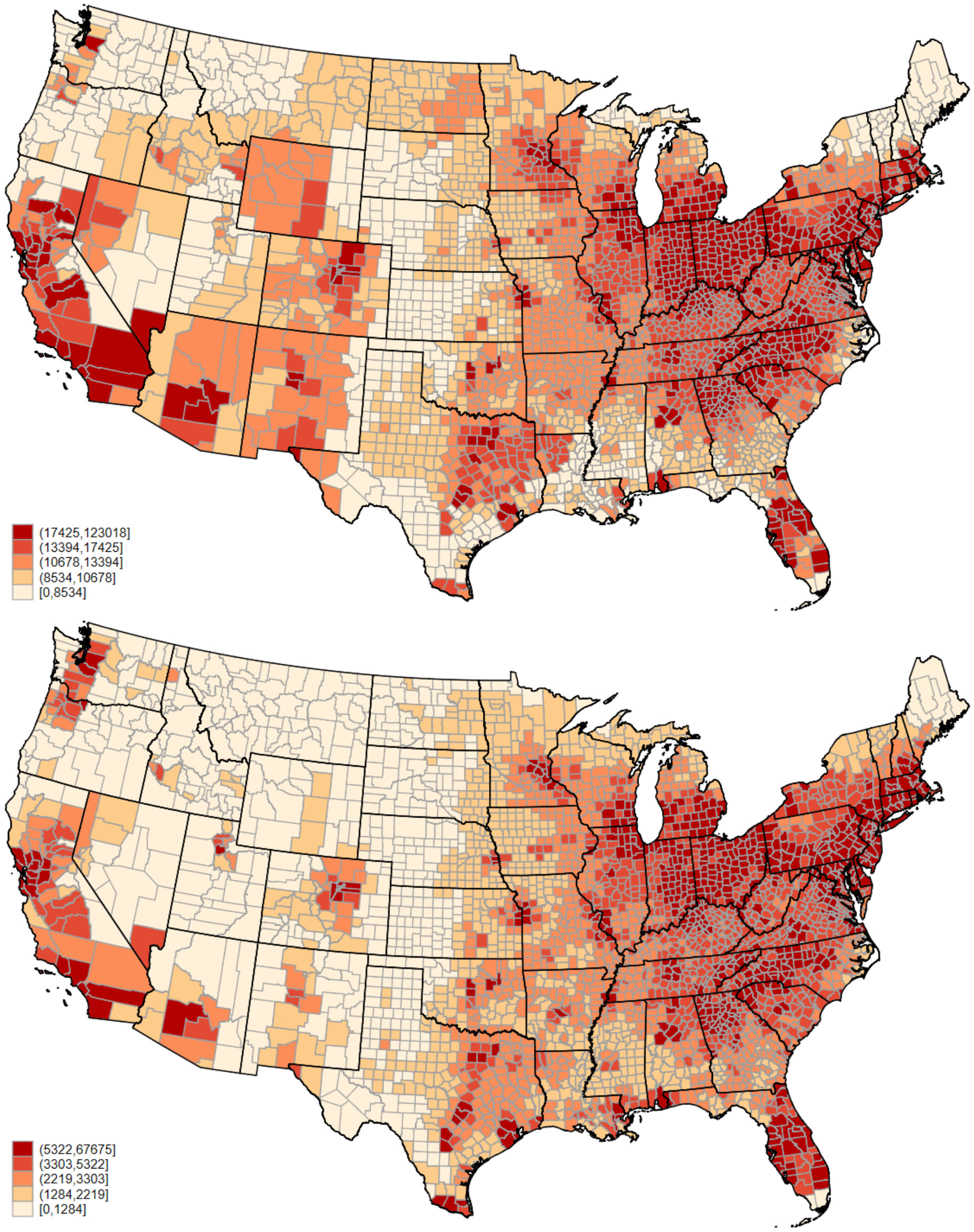
Notes: Table has same structure as Table 3, except this table only shows the two states where we have transaction-level price data needed to calculate median offset prices, California and Texas. Offset prices and marginal benefits of abatement (MBabatement) are in $ per ton of emissions. Row 1 in each panel shows the ratio of marginal benefits of abating one ton of emissions to the median offset price per ton of emissions. Row 2 shows the p-value for testing the null hypothesis that the ratio in Row 1 equals one. Rows 3 and 4 show the mean marginal benefits of abatement and median offset price, respectively. Data represent years 2010-2019. Offset prices are the median price of pollution offsets per ton for the indicated region, pollutant, and time period. When combining median amounts across markets, we weight by transaction amount in tons or by population in offset markets. Data on marginal benefits are available for years 2008, 2011, 2014, 2017, and linearly interpolated between years. All currency are in 2017$, deflated using the GDP deflator. Abatement marginal benefits for each region are weighted across counties within a market according to county population in 2010 Census, and weighted across markets by transaction amount in tons or by population in offset markets.

Appendix Table 7: Ratio of Marginal Benefits of Abatement to Offset Prices, by Market

	NO_x (1)	VOCs (2)
Arizona (Phoenix-Mesa)	—	11.60
California (Imperial County)	1.73	7.02
California (Los Angeles-South Coast)	7.75	7.11
California (San Francisco Bay Area)	30.12	18.80
California (San Joaquin Valley)	3.52	4.73
Connecticut (Greater Connecticut)	39.88	—
Connecticut (NY-NJ-Long Island)	32.36	—
District of Columbia (DC-MD-VA)	92.36	73.42
Illinois (Chicago-Naperville, IL-IN-WI)	95.40	49.70
Indiana (Chicago-Naperville, IL-IN-WI)	57.39	23.70
Maryland (Baltimore)	61.78	31.82
Maryland (Washington, DC-MD-VA)	51.54	34.53
Missouri (St. Louis-St. Charles-Farmington, MO-IL)	—	82.59
New Jersey (NY-NJ-CT-Long Island)	51.57	40.66
New Jersey (Philadelphia-Wilmington-Atlantic City PA-NJ-MD-DE)	91.91	35.96
New York (NY-NJ-CT-Long Island)	74.93	62.97
Ohio (Cleveland-Akron-Lorain)	74.45	45.31
Pennsylvania (Philadelphia-Wilmington-Atlantic City PA-NJ-MD-DE)	82.07	61.47
Pennsylvania (Pittsburgh-Beaver Valley)	273.71	33.78
Texas (Houston-Galveston-Brazoria)	1.69	0.54
Virginia (Washington DC-MD-VA)	52.95	35.69
Wyoming (Upper Green River Basin)	40.00	1.21

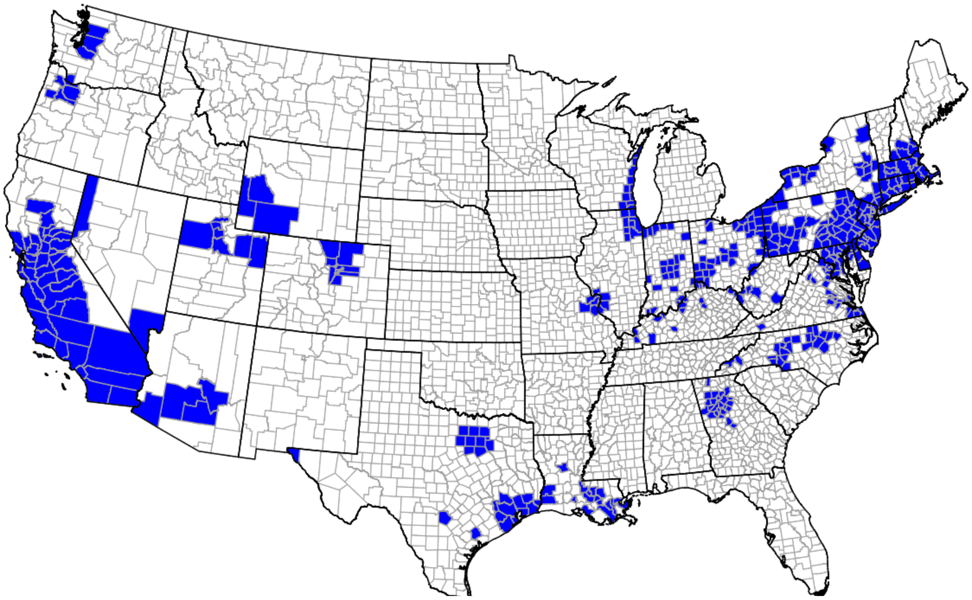
Notes: The first column lists the state and, in parentheses, the specific market. The numbers represent the ratio of marginal benefits of abatement to mean offset prices in each state and market, averaged over years 2010-2019. Offset prices are the mean price of pollution offsets per ton for the indicated nonattainment area, pollutant, and time period, weighted by transaction amount in tons, and annualized using the price ratio between permanent and temporary offset prices. Marginal benefits of abatement are the marginal external cost avoided per ton abated for the indicated nonattainment area and pollutant. Data on marginal benefits are for years 2008, 2011, 2014, 2017, and linearly interpolated between years. All currency are in 2017$, deflated using the GDP deflator. Abatement marginal benefits for individual markets are weighted across counties within a market according to county population in 2010 Census.

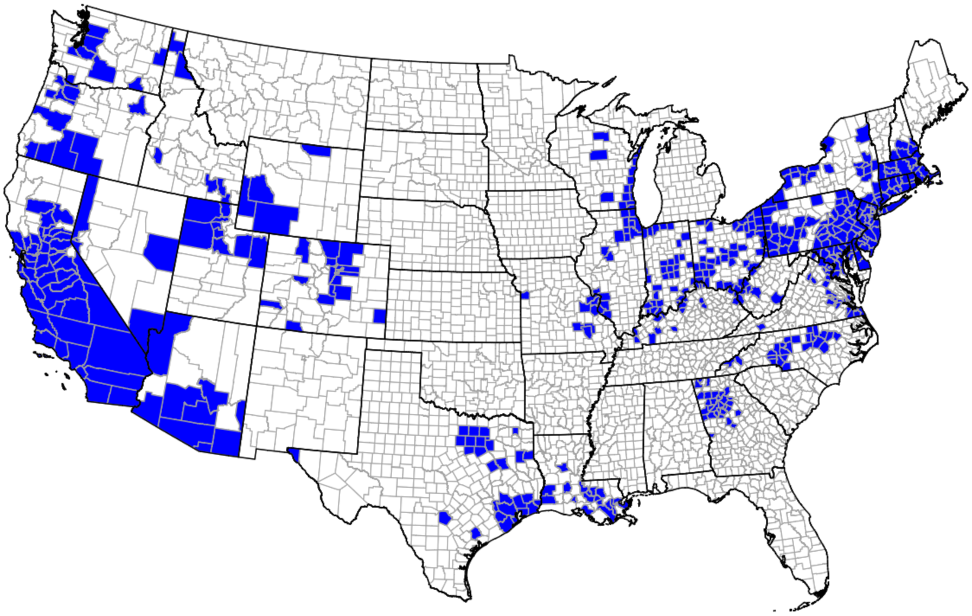
Appendix Figure 1: Marginal Benefits of Pollution Abatement, by Pollutant and County



Notes: Data shows the mean marginal benefits over the years 2011, 2014 and 2017. Marginal benefits of abatement are the marginal external cost avoided per ton abated for the indicated nonattainment area and pollutant, as estimated by the AP3 model. Dollars are deflated to real 2017 values using the GDP deflator.

Appendix Figure 2: Maps of Areas with Offset Markets

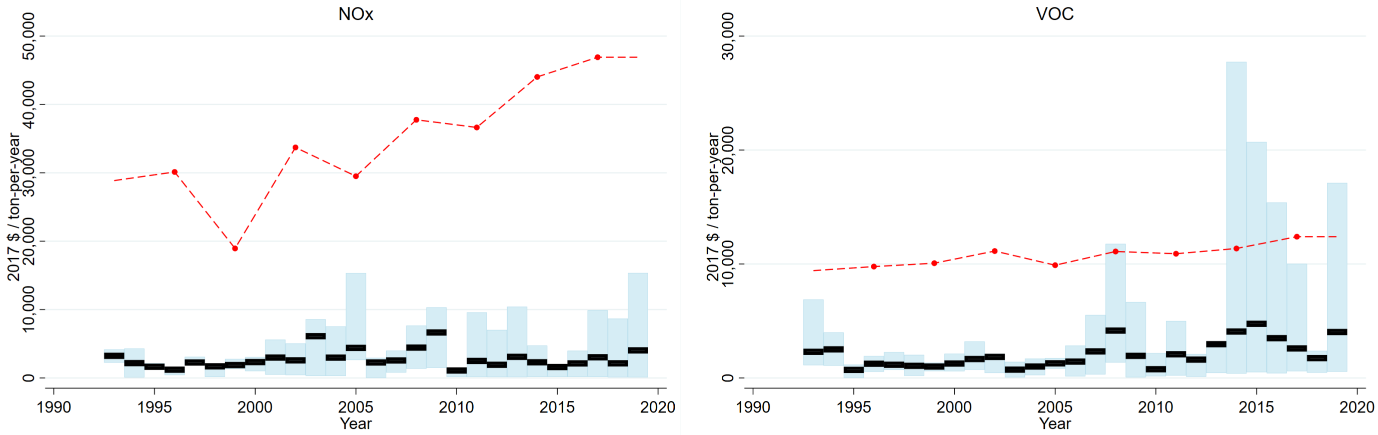




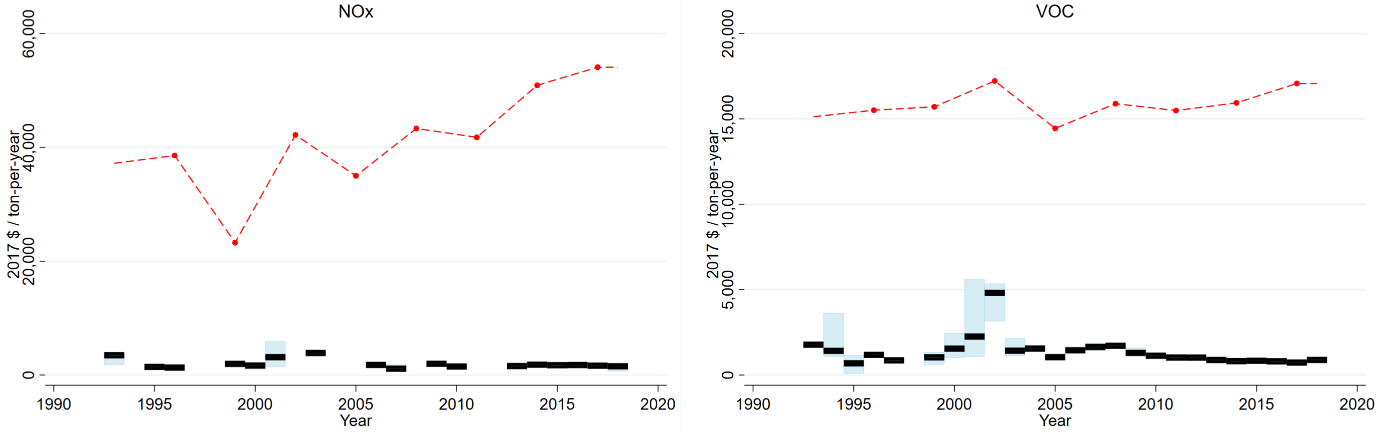
Notes: Shaded blue areas are in nonattainment in any years 2010-2019, and in states with offset markets. "Other pollutants" includes CO, PM, and SOx. States with markets are identified by using a list from Emission Advisors (https://www.emissionadvisors.com/emissions-markets/; Accessed 4/16/2020) and verifying internet market listings. Ozone nonattainment typically requires two separate markets (one for NO_x, one for VOCs. We consider PM_{10} and $PM_{2.5}$ to be a single market for particulate matter.

Appendix Figure 3: Pollution Offset Prices Versus Marginal Benefits of Abatement, by Year

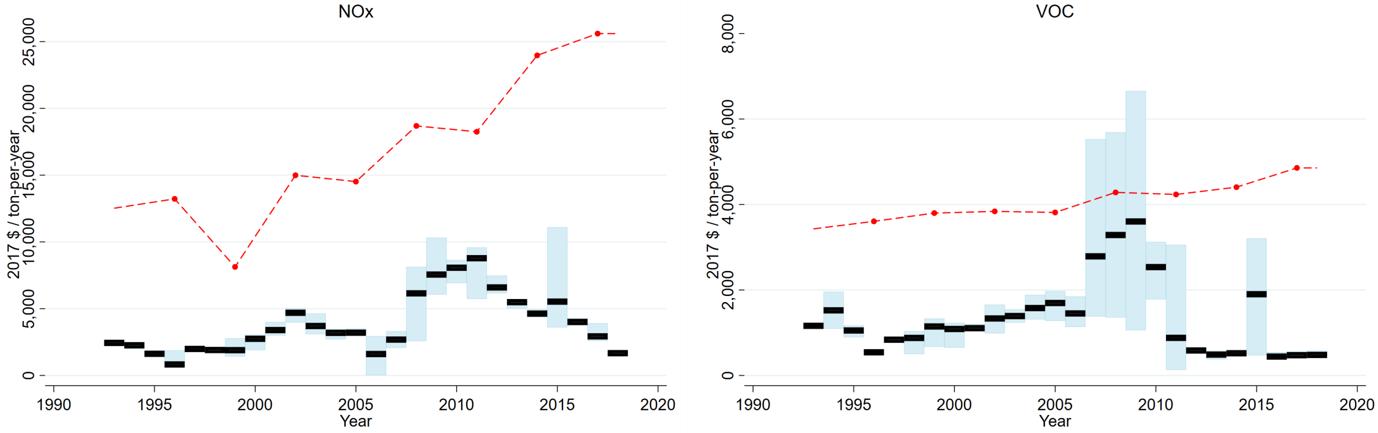
(A) All Markets Pooled



(B) San Francisco Bay Area, California



(C) San Joaquin Valley, California



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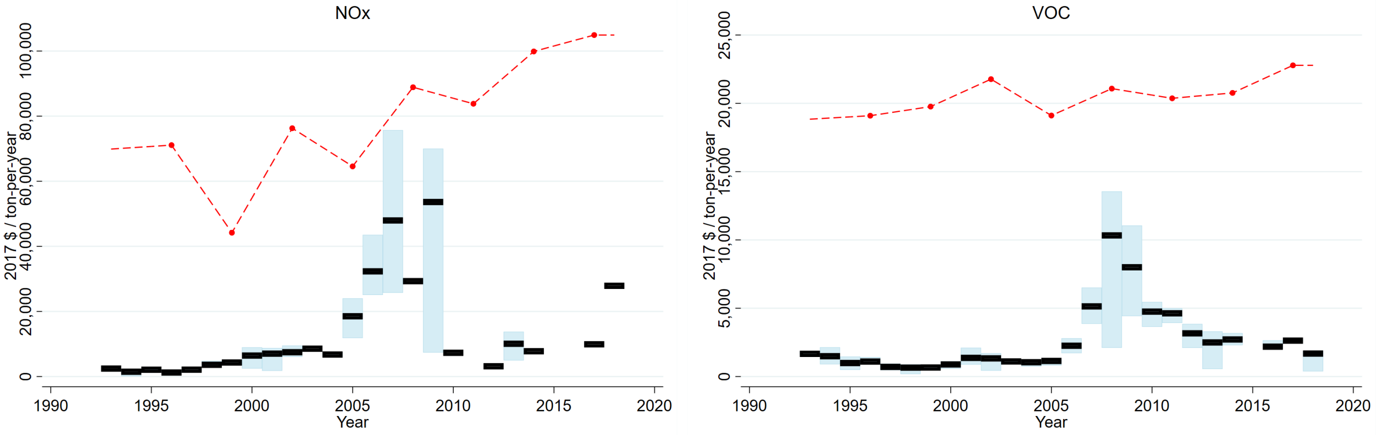
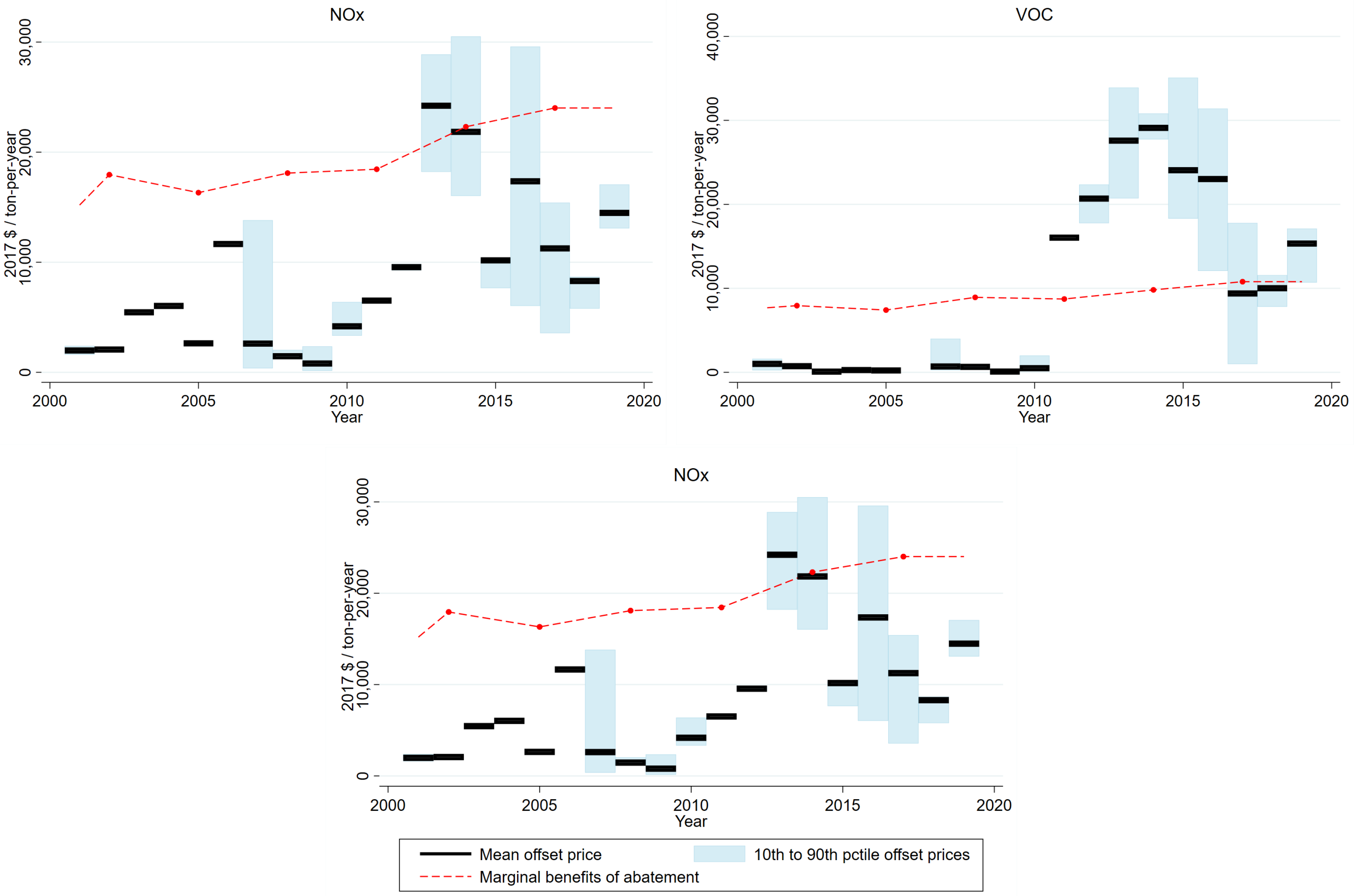
Appendix Figure 3: Pollution Offset Prices Versus Marginal Benefits of Abatement, by Year (Continued)

(D) South Coast, California



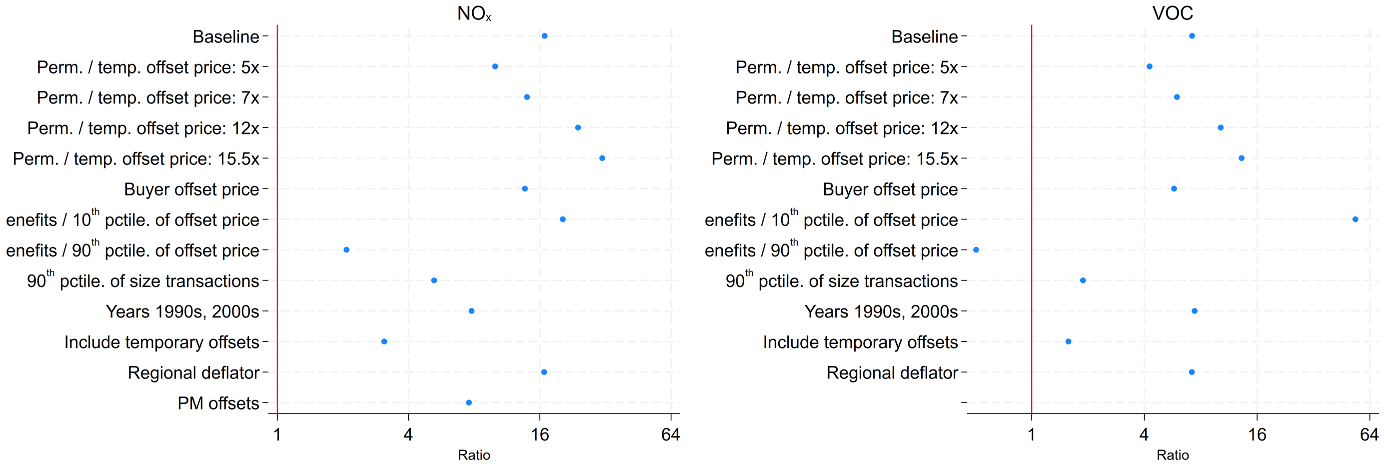
(E) Houston-Galveston-Brazoria, Texas



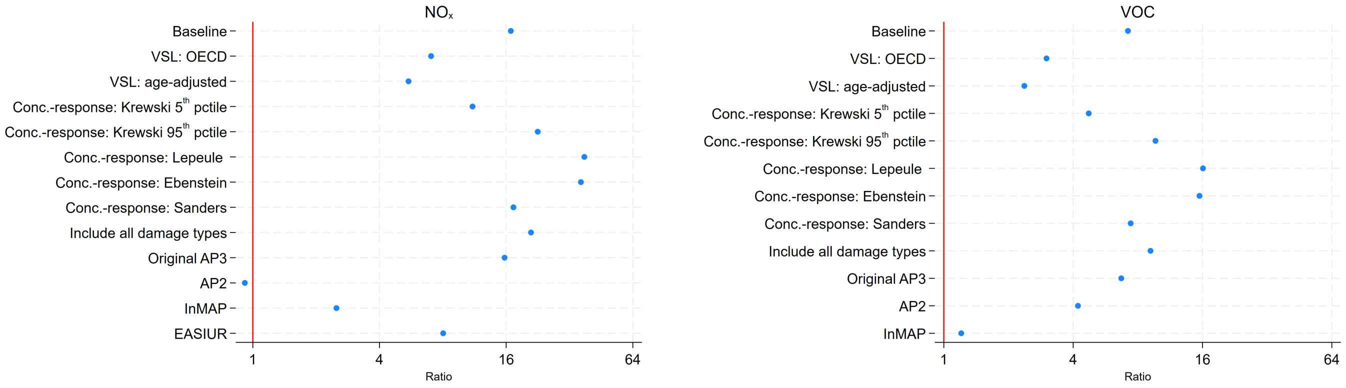
Notes: This figure graphs pollution offset prices and the marginal benefits of pollution abatement by year, with a separate graph for each pollutant and market. Blue bars show 10th to 90th percentile range of offset prices within a market × pollutant × year, thick black horizontal line within each blue bar shows mean offset price in each market × pollutant × year, and red dashed line shows marginal benefits of abatement. Offset prices are the mean price of pollution offsets per ton for the indicated nonattainment area, pollutant, and time period, weighted by transaction amount in short tons, and annualized using a 10% discount rate over a 20-year horizon. Marginal benefits of abatement are the marginal external cost avoided per short ton abated for the indicated nonattainment area and pollutant, as estimated by the AP3 model (Holland et al. forthcoming) for years 1990, 1996, 1999, 2002, 2005, 2008, 2011, 2014, and 2017, and linearly interpolated between years. Marginal benefits of abatement are weighted across counties within an offset market according to county

Appendix Figure 4: Ratio of Marginal Benefits of Pollution Abatement to Mean Offset Prices: Sensitivity Analyses

Panel A. Alternative estimates using different parameterizations of offset prices

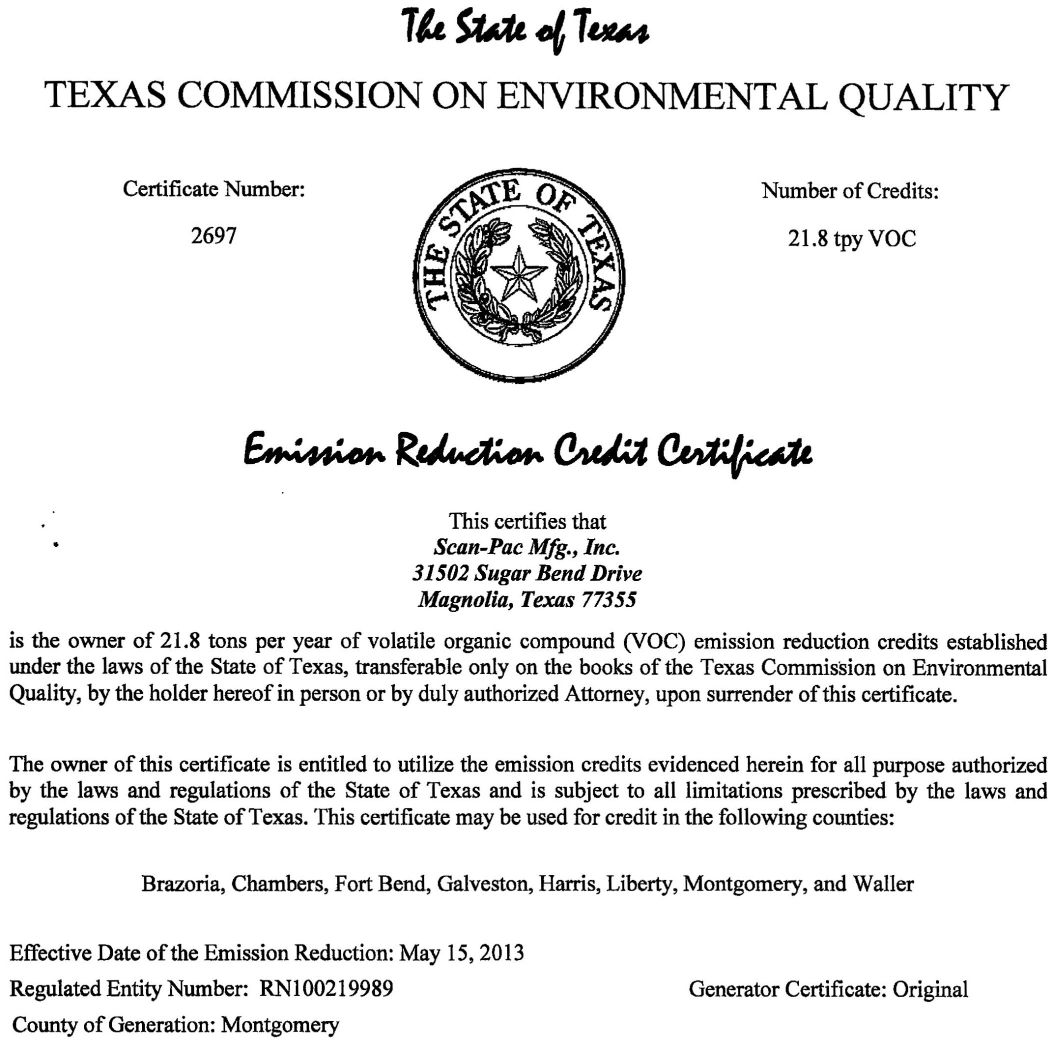


Panel B. Alternative estimates of the marginal benefits of abatement



Notes: These figures present alternative ways of calculating the ratio marginal benefits of abatement to mean offset prices. Panel A presents alternate ways of calculating offset prices, while using the baseline estimates of marginal benefits of abatement. Panel B presents alternative ways of calculating marginal benefits of abatement, while using the baseline calculation of offset prices. Data represent years 2010-2019, except where otherwise noted. Ratio is calculated as mean offset prices divided by mean marginal benefits of abatement, except where otherwise noted. Offset prices are the mean price of pollution offsets per short ton for the indicated nonattainment area, pollutant, and time period, weighted by transaction amount in short tons, and annualized using the observed price ratio between permanent and temporary offsets, unless otherwise noted. Marginal benefits of abatement are the marginal external cost avoided per short ton abated for the indicated nonattainment area and pollutant. All currency are in 2017$, deflated using the GDP deflator. Marginal benefits of pollution abatement are weighted across counties within an offset market according to county population in 2010 Census. Horizontal axis uses logarithmic scale to make dispersion in values near one more easily visible.

Appendix Figure 5: Example of a Pollution Offset



The State of Texas

TEXAS COMMISSION ON ENVIRONMENTAL QUALITY

Certificate Number:	Number of Credits:
2697	21.8 tpy VOC

Emission Reduction Credit Certificate

This certifies that
Scan-Pac Mfg., Inc.
31502 Sugar Bend Drive
Magnolia, Texas 77355

is the owner of 21.8 tons per year of volatile organic compound (VOC) emission reduction credits established under the laws of the State of Texas, transferable only on the books of the Texas Commission on Environmental Quality, by the holder hereof in person or by duly authorized Attorney, upon surrender of this certificate.

The owner of this certificate is entitled to utilize the emission credits evidenced herein for all purpose authorized by the laws and regulations of the State of Texas and is subject to all limitations prescribed by the laws and regulations of the State of Texas. This certificate may be used for credit in the following counties:

Brazoria, Chambers, Fort Bend, Galveston, Harris, Liberty, Montgomery, and Waller

Effective Date of the Emission Reduction: May 15, 2013
Regulated Entity Number: RN100219989
Generator Certificate: Original
County of Generation: Montgomery