Is Air Pollution Regulation Too Stringent?*

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Abstract

This paper describes a novel approach to estimating 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 costs exceeding their marginal benefits. The approach utilizes an important yet underexplored 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. We describe conditions under which offset transaction prices can be interpreted as measures of the marginal cost of pollution abatement, and 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. Marginal abatement costs are increasing rapidly in real terms. Notably, our revealed preference estimates of marginal abatement costs differ enormously from typical engineering estimates. Some evidence suggests that using price rather than existing quantity regulation in these markets may increase social welfare.

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A classic idea in economics is that firms may provide too much of an externality such as pollution because they do not account for its full social costs. Policy designed to address this market failure can maximize social welfare by regulating emissions until the marginal cost of complying with the 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 complying with the policy and the benefits to society of reducing the externality. For externalities including crime, innovation, smoking, and others, it can be difficult to estimate the total costs and benefits to society of a given 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 would require.

These issues are especially important for air pollution. Some research estimates that over five percent of premature U.S. mortality comes from air pollution, and a third to a half of measured benefits of all recent federal regulations came from reducing a single type of air pollution, particulate matter (Fann et al. 2012; Dominici et al. 2014). Cleaning up air pollution may also be costly—U.S. air quality for some regulated pollutants has improved by more than 90 percent since 1970. The marginal cost of pollution abatement typically increases with the quantity of abatement, so these enormous decreases in ambient pollution levels naturally lead to the question of when the marginal costs of increasing regulation begin to exceed its marginal benefits.

Public debates have also questioned the optimal stringency of air pollution regulation. Two law professors, for example, recently summarized, "[The Environmental Protection Agency's] ozone standard is insufficiently stringent, not overly expensive" (Livermore and Revesz 2015). In contrast, an air pollution official in The Trump Administration explained, "Some people like to believe we should have the most stringent programs in the books that we possibly can . . . but I think that's totally wrong" (King 2018).

In part to help reconcile these disparate views, this paper develops a novel approach to estimating the marginal cost of pollution abatement separately by pollutant, county, and year. We utilize an important yet underexplored provision of the Clean Air Act that forbids increases in pollution emissions from large industrial sources in counties with poor air quality ("nonattainment areas"). Polluting plants that wish to enter nonattainment areas must offset their emissions by paying an incumbent polluter in the same or neighboring counties to reduce their emissions. New plants can spend millions of dollars on purchasing such pollution "offsets" from incumbents. Market participants describe expenditures on these offsets as one of or the largest environmental expenditures for new or expanding polluting plants in offset market areas. We use newly available offset transaction records from 16 U.S. states plus Washington, DC, obtained from public records and directly from industry participants. Our data cover over 100 markets, including the seven largest metro areas of the country. Our data collectively represent about 60 percent of economic activity from U.S. offset trading areas.

Clean Air Act regulations have created several hundred separate markets for pollution offsets across the U.S., which differ by pollutant and metro area.[1] For example, there are separate offset markets for particulate matter in the San Francisco Bay Area, nitrogen oxides in the Bay Area, and nitrogen oxides in Houston. These offset markets differ in many ways from cap-and-trade markets. Beyond our setting, offset markets are common in Australia, Brazil, Canada, the EU, and elsewhere, for wetlands, fish, and other environmental goods (Stavins 2003).

These offset markets provide information on the marginal cost of air pollution regulation for different locations, pollutants, and years. On the margin, an entrant should invest in pollution abatement until the marginal cost of additional abatement equals the market price of pollution offsets. For example, a new plant that will emit 100 tons of pollution per year must purchase 100 tons of offsets from incumbents. Alternatively, this plant could spend more on pollution control equipment that lets it emit only 80 tons of pollution per year, and thereby only need to buy 80 tons of offsets. More generally, if the marginal cost of pollution abatement for a firm is cheaper than the market price of offsets, firms should abate more. Similarly, incumbent sources should invest in pollution abatement to generate offsets until the marginal cost of additional abatement for the firm equals the market price of offsets.

We formally show that even in the presence of real transaction costs, efficient environmental policy should equate the price of pollution offsets to the marginal benefits of pollution abatement to society; the marginal benefits of abatement include health and other benefits from emissions reductions. The price of pollution offsets provides a revealed preference measure of policy stringency that captures the abatement and transaction costs that the regulation requires. Our results also provide a simple empirical test. In markets where offset prices exceed the marginal social benefits of emissions reductions, regulation is more stringent than efficiency would require. In markets where the marginal social benefits of emissions reductions exceed offset prices, regulation is more lenient than efficiency would require. We also describe a weaker set of assumptions under which offset prices provide an upper bound on the marginal abatement costs of incumbents.

We find that regulation for most pollutants and markets where we have data is much less stringent than efficiency would require, though recent regulations in Houston appear to be an exception. Nationally, we estimate that the marginal benefits of abatement for nitrogen oxides (NO_x) and volatile organic compounds (VOCs) on average are about 10 times mean offset prices. We find similarly large ratios in each region of the country, in most individual markets, for other pollutants with more limited data availability (particulate matter and sulfur oxides), and in numerous sensitivity analyses. In the Houston market, however, the marginal benefits of abating VOCs are only about half of mean offset prices.

While marginal benefits of abatement are far above offset prices overall, offset prices are increasing quickly over time, by more than 6 percent annually in real terms on average over the last 25

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[1] As subsequent sections discuss in more detail, the Clean Air Act sets air quality standards for six common "criteria pollutants": particulate matter, ozone, sulfur oxides, nitrogen dioxide, carbon monoxide, and lead. Areas in which ambient air quality of a given pollutant exceeds the regulatory standard are designated as "nonattainment" for the pollutant in question. Each pollutant within a nonattainment area has a separate offset market.

years. This implies that offset prices double in real terms every 13 years. Hence, if current patterns continue, offset prices would begin approaching the marginal benefits of pollution abatement in the medium-term future.

Because these data provide new revealed preference estimates of the marginal cost of pollution abatement, we compare them against the leading alternative method of estimating marginal abatement costs, engineering estimates. Using the exact engineering software and data that the Environmental Protection Agency and state regulators use to evaluate major changes in air pollution policy, we find that engineering estimates of marginal abatement costs differ systematically from air pollution offset prices. In many markets, offset prices and engineering estimates differ by a factor of ten or more for the same firms, pollutants, and years. In several cases, the offset prices and engineering estimates of marginal abatement costs differ enough to have non-overlapping support (e.g., the most expensive engineering estimate is less than the cheapest revealed preference offset price). We carefully discuss reasons for these differences, but broadly conclude they strongly underscore concerns about the accuracy of engineering estimates for measuring the economic costs that firms incur to comply with environmental policy.

While the paper focuses primarily on using offset markets to assess whether the quantity of pollution emitted is efficient, we also briefly discuss whether offset markets are an optimal policy instrument. Some evidence suggests that the marginal abatement cost curves for the markets and pollutants we study have steeper slopes than the marginal abatement benefit curves. Building on the insight of Weitzman (1974), this would imply that price policies for air pollution, such as a tax, may produce higher expected social welfare than the existing quantity policies. Practically, this would imply that replacing offset markets with pollution emission taxes may increase expected social welfare.

Our analysis uses data from 16 states plus Washington, DC. Together, the markets we study cover about 60 percent of the population, GDP, or manufacturing employment located in US offset markets. It is typically difficult to obtain data on contract terms for decentralized bilateral markets in any setting. We use publicly available data from two states which require public disclosure of contract terms, and we purchased additional data on fourteen other states from a leading firm that specializes in advising offset transactions. Most of these data have never been publicly analyzed or discussed in government or academic analyses.

This research builds on several literatures. First, we provide a novel approach to measuring the marginal costs of air pollution abatement for different pollutants, locations, and years. This approach has advantages over existing methods, like engineering estimates or empirically estimated cost functions—it uses revealed preference, reflects both pecuniary and non-pecuniary abatement costs, obtains estimates that vary by pollutant, location, and time, and is transparent and simple to implement.[2] This focus is especially useful given that economic research has focused more on

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[2] Researchers have used cost function estimates primarily to analyze sulfur dioxide abatement from coal-fired power plants (e.g., Gollop and Roberts 1985; Carlson et al. 2000; Muller and Mendelsohn 2009). Other researchers have attempted to estimate some components of total but not marginal costs of regulation (Greenstone 2002; Walker 2013). Other studies

measuring the marginal benefits than the marginal costs of air pollution policy.[3] Showing trends in offset prices also provides a novel way to measure how regulatory stringency is evolving; other studies have estimated trends in the shadow price of pollution, though through the lens of models requiring strong assumptions (van Soest et al. 2006; Shapiro and Walker 2018).

This paper also provides the first comprehensive empirical analysis of U.S. air pollution offset markets. These markets are a central part of the Clean Air Act but have not been a focus of empirical research. Among market-based environmental policies, economists once described 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; Abbott and Brady 1990; Swift 2001; NRC 2006; Fraas et al. 2017; Leonard 2018; Stavins 2003). A narrow focus on offset markets is also relevant to policy since several governments are investigating reforms of offset markets, including the federal government plus state and local governments in Arizona, California, and Louisiana.

Lastly, we contribute to a literature showing how engineering estimates of abatement costs can differ substantially from market-based revealed preference estimates (e.g., Carlson et al. 2000; Keohane 2007; Fowlie et al. 2018). The importance of this literature stems from a textbook concern that regulators typically use accounting or engineering estimates to measure abatement costs of existing or proposed policies, and this might miss important economic costs or fail to account for changes in firm behaviors like innovation. In a standard analysis, engineers calculate how end-of-pipe abatement technologies like catalytic converters or scrubbers affect pollution emissions. Accountants then calculate the technologies' capital, operating, and maintenance costs. Analysts then identify the technologies with the lowest predicted cost per ton of pollution abated. We add to this literature by comparing our estimates of marginal abatement costs by pollutant, location, and year to engineering estimates using the same software that the Environmental Protection Agency (EPA) and local regulators use.

Before proceeding, a few clarifications may be useful. One natural question is whether offset prices represent the marginal cost of abating pollution, as opposed to some other measure of costs. We discuss a simple model in which offset prices equal marginal abatement costs. Intuitively, firms should abate pollution when the firm's marginal abatement cost differs from offset prices, since otherwise the firms are missing a profitable arbitrage opportunity and leaving money on the table. Under weaker assumptions, offset prices would represent an upper bound on marginal abatement

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observe the market price of permits in cap-and-trade markets, though the U.S. has only a handful of cap-and-trade markets for air pollution (Fowlie et al. 2012; Deschenes et al. 2017). While the cap-and-trade markets cover many states, they do not separately identify marginal abatement costs in each location (only across the entire market), which makes it hard to tailor to the existing reality of different regulatory stringency across cities and counties; and they cover a limited set of pollutants and years. Estimating marginal abatement costs for greenhouse gas emissions is somewhat distinct because it can boil down to estimating demand systems for fossil fuels (Kolstad and Toman 2005).

[3] In five top general-interest economics journals, a review that we and a research assistant completed found 13 papers on the marginal benefits of air pollution regulation and only 3 on the marginal costs of air pollution regulation, all on focused settings such as sulfur dioxide emissions from coal-fired power plants or vehicle environmental inspections in developing countries (see Appendix A for details).

costs of incumbents. Because marginal abatement costs by definition represent the lowest cost of abating a pollutant in a region, most forces which could make offset prices differ from marginal abatement costs, such as market power or transaction costs, would make marginal abatement costs weakly lower than offset prices for sellers, which are incumbents.

A related question is how the existence of other environmental regulations affects our interpretation. While other environmental policies do create costs for firms, they do not change the marginal decision for a plant—increasing expenditure on abatement decreases required expenditure on offsets, and an optimizing plant should equate these marginal costs. Moreover, abatement in offset markets is additional and beyond the abatement required by other environmental regulations, and given the typical assumption that marginal abatement costs increase with the quantity of abatement, abatement costs for other regulations may thus be weakly below abatement costs in offset markets. Thus, such frictions would tend to strengthen our finding that the marginal benefits of pollution abatement exceed the marginal costs of abatement.

In extrapolating our estimates to other settings or policies, it is important to weigh external validity carefully. We study efficiency within the context of the Clean Air Act's National Ambient Air Quality Standards (NAAQS). The offset markets that are created and used in regions not in compliance with NAAQS are widespread, important, and understudied, but some care is warranted in generalizing. Offset markets can involve higher transaction costs than other market-based policies like pollution taxes or cap-and-trade markets, which would suggest that policies using other market-based instruments may have even lower abatement costs than offset markets. The abatement investments allowable in offset markets may also differ from investments allowed in other market designs. In addition, while the polluted "nonattainment" regions where offset markets operate represent a majority of U.S. economic activity, they may have different marginal abatement costs than less-regulated "attainment" regions. As we highlight in the conclusion, developing methods to calculate and compare abatement costs under different market designs, and in regions without offset markets, would be valuable for future work.

Finally, since offsets are traded by a limited set of firms, and some offset markets or transactions are small, one may wonder whether much is to be learned from studying these markets. For example, some studies of the total or average cost of environmental regulation analyze every firm in an industry, the majority of manufacturing plants in the country, or all pollution emissions over large time periods. While we only analyze entrants and incumbents trading offsets, these are the marginal emissions decisions in a location. Although not every incumbent source trades offsets, because every incumbent has the opportunity to do so, these marginal costs represent the marginal costs for the entire population of plants and not merely for those plants which choose to trade offsets.[4] In total we analyze numerous transactions, across 9 to 25 years per market,

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[4] Similarly, plants in cap-and-trade markets may hold allowances without buying or selling them. The decision of some plants not to trade allowances in a cap-and-trade market does not change the standard interpretation that cap-and-trade markets reveal marginal abatement costs for the population of plants. Analogously, many incumbent plants choose not to trade in offset markets even when all plants are eligible to do so.

involving four pollutants, and covering over 100 offset markets. These markets include the seven largest U.S. metro areas (New York, Los Angeles, Chicago, Dallas, Philadelphia, Houston, and Washington, DC) plus many others (Baltimore, Cleveland, Phoenix, Pittsburgh, San Francisco, St. Louis, etc.). We consider four separate air quality and valuation models, two quasi-experimental and four epidemiological estimates of the main health elasticity determining benefits (the $PM_{2.5}$ mortality-concentration response function), three different estimates of the value of a statistical life, and numerous subsets of the data by year, transaction size, and other characteristics. While any one market, year, or specification may not be fully representative, and while there is important heterogeneity across markets which we discuss in detail, together these estimates provide a broad and robust picture of emissions decisions for the country's largest offset markets.

The rest of the paper proceeds as follows. Section 1 describes the pollution offset markets. Section 2 explains the data. Section 3 provides a simple model of offset prices to guide our interpretation. Section 4 presents the main results and sensitivity analyses, Section 5 discusses the additional questions on trends in offset prices, comparison to engineering estimates, and price versus quantity instruments. Section 6 concludes.

1 Design of Pollution Offset Markets

This section summarizes the main design features of U.S. air pollution offset markets, drawing on existing descriptions (Dudek and Palmisano 1988; Fraas et al. 2017; Leonard 2018).[5] Appendix B provides additional detail, including the history of these markets, and differences between offset and cap-and-trade market designs.

Each year the EPA designates counties with air quality violating federal standards for a pollutant as a "nonattainment area" for that pollutant. Large polluting plants that are opening or undertaking significant modifications in these areas are subject to New Source Review, a policy which requires that firms meet certain environmental requirements.[6] New Source Review also requires every large firm to offset any projected pollution emissions by paying other sources in the same area to decrease their emissions of the same pollutant.[7]

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[5] While we refer to these transactions as pollution offsets, formally they are called "Emission Reduction Credits." For simplicity, we refer to sources that are new or undergoing significant modifications as entrants. While some pollution sources are not factories, e.g., large oil and gas extraction operations, for simplicity in some cases we refer to pollution sources generically as "plants."

[6] Offsets apply only to plants and other "stationary" sources, which are an 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.

[7] 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 regulations. "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). Appendix B highlights differences between

In practice, an incumbent may choose to decrease its emissions, then receive an "offset" certificate from regulators which specifies the tons per year, pollutant, and nonattainment area. Installing more stringent abatement technology than is required, closing down a plant or part of it, and decreasing total production can all generate offsets since they all decrease pollution emissions.

The incumbent can then sell the offset to an entrant, or it can sell parts of the offset to different entrants. Although the state or air quality management district typically maintains a registry of offsets and records transactions, offset markets are decentralized and bilateral, so buyers and sellers directly write bilateral offset contracts (i.e., there is no central market operator like the Chicago Climate Exchange). Some transactions involve brokers who help expedite and manage the process.

Polluting plants generally require an air quality permit to operate, and offsets are documented in the purchaser's air quality permit. The rules governing offset transactions differ by state and, in some cases, by air quality management district within states. Not all nonattainment areas have offset markets. State or air district regulators must set them up and determine associated regulations.

The EPA requires an offset to satisfy four requirements: it must be surplus, federally enforceable, quantifiable, and permanent. 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 thus may specify the plant's 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." Permanent means the "reduction is unending or indefinite," which often requires installing or removing capital equipment that is documented in photographs and record keeping (Rucker 2018). Some offset markets, particularly for greenhouse gas emissions, suffer from concerns that the offsets are not additional or not legitimate. States and the EPA tightly enforce the requirements on the offset markets we study, and such concerns have not been prominent for these markets.[8]

The supply of offsets reflects the availability of abatement opportunities. A region like Los Angeles has been in nonattainment for decades and has already exploited inexpensive abatement options from older sources. Hence, the supply of offsets in Los Angeles represents the remaining, relatively expensive potential abatement technologies from incumbents, meaning that we should expect high offset prices in Los Angeles. A county that recently entered nonattainment should have relatively more inexpensive abatement options for incumbents, and so we should expect lower offset prices, all else equal. The demand for offsets reflects the demand for entry or expansion of

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the design of offset markets and cap-and-trade markets.

[8] Although this practice is uncommon, incumbents can generate offsets by rewriting their air quality permits to permanently decrease their permitted production level. 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 tradeoff profits and pollution, and it is a source of abatement in cap-and-trade markets, pollution taxes, and other market-based environmental instruments. The theory we describe accommodates this type of abatement and shows how it still allows offsets to provide information on marginal abatement costs.

polluting firms and associated pollution abatement costs.

Appendix Figure 1 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 1.[9] 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). Enterprise used the offsets to build a \$1.1 billion Houston-area facility that produces propylene, a common petrochemical, in the Houston area.

These 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.

Some areas require an exchange rate or "offset ratio" between generated and sold offsets. In a county with an offset ratio of 1.1 to 1, an entrant which emits 10 tons of NO_x per year would need to buy 11 tons of offsets. States have some discretion to choose the relevant offset ratios. We have lists of these offset ratios for some markets, and report sensitivity analyses accounting for them.

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 does not strongly support the idea that market power is a dominant force here. We have firm identifiers in two markets—Houston and South Coast (around Los Angeles), CA. In a typical snapshot where we have data from both markets, 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. However, entrants would still equate their own marginal abatement costs to offset prices. 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.

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

2 Data

This section describes key data; Appendix C provides additional details. We deflate all prices to 2017 dollars using the Federal Reserve's U.S. GDP Deflator. 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.

2.1 Offset Markets

To measure prices and quantities of pollution offset transactions, we obtain data from a few sources. For 14 states plus Washington, DC, we use records describing NO_x and VOC offset transactions that we obtained from a leading emissions offset brokerage and advisor, Emission Advisors.[10] These records list the average price in each market×year. They also describe the market size in one of four bins (0-350 tons total traded over the years 2010 to 2019; 351-600 tons, 601-1,150 tons, >1,150 tons). In addition, we use transaction-level records from the California Air Resources Board over the period 1993-2018, and the Texas Commission on Environmental Quality over the period 2001-2019. The California data list price, quantity, and the air quality management district responsible for managing the offset. The Texas data also include the names of the selling and buying firms and a unique identifier code tracking the lifecycle of each offset. The analysis sample excludes intra-firm and temporary offset transactions (Appendix C.1 provides additional details).

Table 1 describes all US air pollution offset markets and the set of markets in our data. Panel A shows that the U.S. has several hundred offset markets that together cover about 180 million people or $11 trillion in GDP; this represents about 60 percent of the U.S. population, GDP, or manufacturing employment. The market sizes are skewed, and a large share of markets represent low-population areas with few transactions. Panel B shows that our data cover about 60 percent of the population, GDP, or manufacturing employment of all US air pollution offset markets.

Most reviews of market-based instruments mention a handful of U.S. environmental markets, such as the Acid Rain Program (Stavins 2003). This analysis of offset markets represents a far larger number of distinct environmental markets than has been previously analyzed. This is useful because the social costs of many pollutants regulated under the Clean Air Act are highly localized, and existing regulations differ by location, time, and pollutant. Efficiency requires equating marginal benefits and marginal costs of abatement by location, and by analyzing many markets simultaneously, we are able to have a more comprehensive picture as to the efficiency of existing stationary source regulations for different locations, pollutants, and time periods.

Figure 1 maps the locations of these markets. These maps show counties that are in states with policies that set up offset markets and that have had been part of a nonattainment area at any

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[10] The 14 states are Arizona, Connecticut, Delaware, Illinois, Indiana, Maryland, Missouri, New Jersey, New York, Ohio, Pennsylvania, Virginia, Wisconsin, and Wyoming, plus Washington, DC. As discussed in Appendix C.1, we do not have offset transactions directly from Delaware and Wisconsin, but we do have transactions from other states in offset markets that are shared with these states.

time over the period 1993 to 2019. Panel A of Figure 1 describes markets for NO_x and VOCs, corresponding to nonattainment for ground-level ozone. More markets have existed for these pollutants than for any others. They cover most of California, the Northeast from Maryland to Southern New Hampshire, and large urban areas in the industrial Midwest, South, Pacific Northwest, and Southwest. Panel B shows areas with markets for other pollutants; the most common is for particulate matter, but some of these markets also cover carbon monoxide, lead, and sulfur oxides; the coverage is similar as for ozone.

Permanent Versus Temporary Values

Most offsets represent the permanent right to emit a ton of pollution. Most estimates of the marginal benefits of abating local "criteria" pollution represent the marginal benefits of decreasing emissions of one ton of pollution in a single year. To compare permanent offset prices and temporary pollution abatement benefits in the same units, we infer what price offset transactions would have been if the offsets only lasted for one year.

Some markets allow firms to sell temporary or "short term" offsets that last a single year.[11] 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 similar but have different 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, 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.[12]

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

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[11] 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.

[12] 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.

value. If one interpreted the ratio of permanent to temporary offsets as reflecting firms' discount rates, it would imply a discount rate of about 10.6 percent, though the discount rate interpretation is not needed to apply the ratio of permanent to temporary offset prices.[13] While 10.6 percent is a high discount rate 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.

2.2 Marginal Benefits of Pollution Abatement

We use estimates of the marginal benefits of pollution abatement from a leading "integrated assessment" model, AP3, though also report sensitivity analyses using three other such models.[14] AP3 and its predecessor models are widely used in influential economics and policy research (Muller and Mendelsohn 2009; National Research Council 2010; Gowrisankaran et al. 2016; Fowlie et al. 2018). Using AP3, we calculate the benefit of a one-ton decrease in pollution emissions, separately for each county and pollutant.

The AP3 model includes four main components. First, it uses an inventory of air pollution emissions from each US source. Second, it uses an air quality model translating emissions from each source county into ambient air quality in all counties. Third, it uses published elasticities linking air quality to outcomes like mortality. Fourth, it uses estimates of the value of these outcomes (e.g., the value of a statistical life, or VSL). We use the raw AP3 code generously provided by Nick Muller, though address one issue involving the functional form of mortality damages (see Appendix C.2.2); this correction increases the marginal benefits of abatement by about 7.5 percent.

Appendix Figure 2 maps the marginal benefits of pollution abatement from AP3, which vary by pollutant and county. The marginal benefits of abatement are positively correlated with population density. For example, abating one ton of NO_x in Queen's County, New York, creates benefits of \$80,000 (2017 dollars), while abating one ton of the same pollutant in Aroostook County, Maine, creates benefits of only \$1,500.

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 Organization for Economic Cooperation and Development (OECD 2012), and also an age-adjusted VSL (Murphy and Topel, 2006; Carleton et al., 2019). Our baseline estimate of the $PM_{2.5}$ concentration-adult mortality response function, which accounts for most estimated damages

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[13] We calculate this from the following standard annuity formula:

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

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. To calculate the implied discount rate, we follow regulatory analyses of air pollution abatement in assuming a typical region will be in nonattainment for 20 years ($n = 20$).

[14] The marginal benefits of pollution abatement are comparable to the marginal damages of pollution emissions. Technically the former represent a marginal decrease in pollution emissions and the latter represents a marginal increase.

from air pollution, is from Krewski et al. (2009). We also report five alternative estimates of this parameter—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 instrumental variable for air quality (Sanders et al. 2020). We also assess sensitivity to using three other air quality and valuation models—InMAP, EASIUR, and AP2. 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 such much greater complexity, but using representative values for each county or other geographic region (Kolstad and Williams 1989).

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 (Smith and Huang 1995; Chay and Greenstone 2005; Bajari et al. 2012; Holland et al. 2020). 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 $PM_{2.5}$). 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).

2.3 Engineering Estimates of Marginal Abatement Costs

We obtain engineering (i.e., accounting) estimates of marginal abatement costs using software called the Control Strategy Tool (CoST; Appendix C.3 provides additional details). CoST is the standard tool that federal and local regulators use to estimate the cost of air quality regulations.

CoST uses several inputs. It uses the EPA's National Emissions Inventory, which lists the emissions of each polluting plant in the U.S., separately by pollutant and year. Additionally, it incorporates lists of the abatement technologies currently used in each plant, which it takes from a variety of EPA reports and databases, regional planning organizations, and state environmental agencies. It also uses data on the abatement technologies available for each plant, and their associated capital and operating cost.

Given these inputs, CoST applies simple optimization software to find different sets of technologies that a specific scenario would require. For example, CoST can estimate the least-cost way to decrease NO_x emissions from the San Francisco Bay Area by 100 tons. For any such scenario, CoST outputs the specific plants' control technologies and costs that it recommends. We are not aware of previous use of CoST in academic economics research.

3 Simple Model of Pollution Abatement

This section describes a simple framework which helps guide our interpretation of offset prices. It resembles classic approaches in economics (Baumol and Oates 1988; Stavins 1995; Montero 1997; Muller and Mendelsohn 2009), except that we explicitly account for non-pecuniary transaction costs.

Source i emits X_i tons of pollution. Let $X = X_1, \ldots, X_N$ denote the vector of emissions.[15] We consider three types of costs: control costs; transaction costs; and pollution damages.

A source must pay control costs $C_i(X_i)$, which include all non-transaction costs that source i incurs in order to emit pollution level X_i. These may include lost profits from producing less output (e.g., curtailment), producing a different product, or capital and operating expenditures on pollution abatement technology.

To achieve emissions X, agents must pay transaction costs $T(X_i)$. These may include search and matching costs; bargaining and decision costs; monitoring and enforcement costs; and uncer-

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[15] Many command-and-control policies regulate emissions rates, i.e., emissions per unit of output, which can create an implicit output subsidy. Offset markets govern physical emissions in tons (not emission rates), so we describe firms choosing pollution levels rather than emission rates.

tainty costs including delays. We assume that firms are aware of and make choices in response to transaction costs, and thus that offset prices and quantities fully reflect transaction costs. Both $C_i(\cdot)$ and $T(\cdot)$ exclude transfers that do not represent real resource costs, such as markups.

The market design influences the transaction cost function $T(\cdot)$. We treat the market design as fixed, so the planner does not choose the shape of the transaction cost function $T(\cdot)$. In other words, conditional on choosing a particular set of offset requirements, the planner treats the function $T(\cdot)$ as fixed (though the actual value of $T(\cdot)$ depends on the quantities of emissions X_i chosen). One could think of this as choosing the level of abatement required in offset markets, hence, it is a second-best problem.

We refer to the sum of control and transaction costs as "abatement costs." In offset markets, firms must pay both control and transaction costs in order to emit a given level of pollution. Much of the environmental economics literature equates control costs with abatement costs and abstracts from transaction costs. Equating control and abatement costs is not the most appropriate for offset markets, where transaction costs may be more important than for other market designs.

Emissions produce the pollution damages $D(X)$, which represent the external or social costs of pollution. The damage function $D(\cdot)$ may be a nonlinear function of emissions X. Damages include the monetized value of changes in mortality, morbidity, visibility, firm productivity, and other externalities induced by emissions level X_i. We assume control and transaction costs decrease with emissions but pollution damages increase with emissions ($\partial C_i(X_i)/\partial X_i < 0$, $\partial T_i(X_i)/\partial X_i < 0$, and $\partial D(X)/\partial X_i > 0$).

3.1 The Planner's Problem

The planner chooses emissions from each source to minimize the sum of control costs, transaction costs, and pollution damages:

$$min_X \sum_i C_i(X_i) + T(X_i) + D(X) \tag{2}$$

The planner faces a trade-off—allowing a plant to increase its emissions increases pollution damages but decreases control and transaction costs. Differentiating the planner's problem gives

$$-\frac{\partial C_i(X_i)}{\partial X_i} - \frac{\partial T(X_i)}{\partial X_i} = \frac{\partial D(X)}{\partial X_i} \quad \forall\, i \tag{3}$$

The first term in equation (3), the marginal control cost, describes how a marginal increase in emissions affects control costs. The second term, the marginal transaction cost, describes how a marginal increase in emissions affect transaction costs. The right-hand side of equation (3), the marginal benefits of abatement, describes how a marginal increase in emissions affects the damages from pollution. Equation (3) shows that the planner chooses emissions from each source so the marginal benefits of abatement equal the marginal cost of emissions plus the marginal transaction cost from additional emissions.

In the textbook efficiency rule, the planner equates marginal abatement costs to marginal pollution damages. This rule also holds in equation (3), except that we interpret marginal abatement costs to reflect both transaction and control costs. The idea is that transaction costs are not a nuisance term which an analyst should seek to exclude or ignore when comparing the marginal costs and benefits of a policy. Instead, transaction costs are a component of the true economist cost that a firm incurs when complying with a policy, and thus they are part of the marginal abatement cost.

While we primarily interpret equation (3) conditional on policy design (so the $T(\cdot)$ function is fixed, though the level of transaction costs still depends on emissions X_i), it is interesting to note how the choice of this design affects efficient abatement. When transaction costs like broker fees rise, holding marginal benefits of abatement constant, it is efficient for firms to abate less. Many existing environmental policies have high transaction costs, like command and control regulations that set prescriptive and inflexible rules for each firm, and can require litigation and uncertainty. Equation (3) shows that policies with high transaction costs have a downside for the environment because they decrease the efficient amount of abatement.

3.2 Decentralization

We assume firm i chooses its emissions to maximize profits:

$$max_{X_i} P_y Y(X_i) - E_i(X_i) - PX_i - T_i(X_i) \tag{4}$$

The firm sells output $Y(X_i)$ at price P_y. The firm must also purchase pollution offsets at the market price P to cover its emissions, pay the operating, maintenance, and other engineering control costs $E_i(X_i)$, and pay transaction costs for its offsets $T_i(\cdot)$.

Differentiating equation (4) with respect to emissions X_i for an operating firm, and defining a firm's marginal control costs as $-\frac{\partial C_i(X_i)}{\partial X_i} = P_y \frac{\partial Y(X_i)}{\partial X_i} - \frac{\partial E_i(X_i)}{\partial X_i}$, gives the condition for production efficiency:

$$-\frac{\partial C_i(X_i)}{\partial X_i} - \frac{\partial T_i(X_i)}{\partial X_i} = P \tag{5}$$

This says that for a firm's efficient choice of emissions, the firm should invest in abatement until the sum of marginal control costs and marginal transaction costs equals the market price of offsets. Notably, abatement here includes various types, such as end-of-pipe abatement technology or decreasing total output.

Combining the planner's efficiency condition from equation (3) with the firm's production efficiency condition from equation (5) shows a simple condition for efficient offset prices:

$$P = \frac{\partial D(X)}{\partial X_i} \tag{6}$$

Equation (6) indicates that the efficient market price of offsets should equal the marginal social damage from pollution emissions. This condition is similar to what one would obtain in a standard frictionless cap-and-trade market, but is also true here in the presence of transaction costs.

This suggests a simple test for the efficiency of offset prices. If the price of pollution offsets exceeds the marginal social damage from pollution, the offsets are more expensive than is efficient. In this case, social welfare would increase if regulation was less stringent, and equilibrium offset prices were lower. Alternatively, Equation (5) shows the two additional classes of policy reforms that could then increase welfare—decreasing marginal control costs $\partial C_i(\cdot)/\partial X_i$ or decreasing transaction costs $\partial T_i(\cdot)/\partial X_i$.

One consideration is that changing the stringency of regulation in one location may encourage polluting firms to emit more pollution in other locations. The additional emissions in other locations are not relevant from the perspective of the local (county or municipal) social planner imposing the regulation, but are relevant for a national social planner. The welfare consequences of this kind of relocation depend on where firms relocate and how efficient the stringency of regulation is in other locations. For example, if increasing offset prices in Los Angeles leads to emissions increases in Reno, but pollution regulation in Reno is efficient, then the emissions in Reno do not affect social welfare since their marginal costs and benefits are equal. Since we do not observe potential entrants, our setting makes it difficult to observe where firms might relocate to (or to know the efficiency of regulation in areas where firms might relocate), but we leave the interesting question of spatial spillovers to future work.

Another consideration is the presence of other environmental regulations. Polluting plants must comply with other federal environmental policies, in addition to local policies, which can increase their compliance costs. Offset requirements are in addition to these other policies. While these other costs do increase the total cost of environmental policy, they do not change a plant's assessment of its demand for offsets—the production efficiency condition (5) still shows that a plant should invest in abatement until the marginal cost of abatement equals prevailing offset prices.

4 Results

4.1 Offset Prices Versus Marginal Benefits of Abatement

Table 2 compares the marginal benefits of pollution abatement to offset prices, using our full data from 16 states plus Washington, DC, over the years 2010-2019. Columns (1) and (2) describe transactions for NO_x, and columns (3) and (4) for VOCs. Columns (1) and (3) show a mean which is weighted by the tons of pollution it represents; columns (2) and (4) show a mean which is weighted by the population it represents. Panel A pools all markets, while Panels B through E describe the four regions of the US, as defined by the US Census Bureau. Within each 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 offset prices represent the mean marginal costs of abatement, row 1 would be interpreted as the ratio of marginal benefits to marginal costs of pollution abatement.

Table 2 shows that national mean marginal benefits of abatement are well above offset prices. This provides our main finding that air pollution regulation in these markets is less stringent than is efficient. This conclusion is statistically precise at greater than 99 percent confidence for all pollutants and regions. On average for NO_x, mean marginal benefits of abatement are \$40,000 to \$51,000, depending whether the average is weighted by tons of pollution or population. Mean offset prices, however, are \$2,200 to \$4,000. Thus, the ratio of mean marginal benefits of abatement to mean offset prices is 13 to 18. Of course, this is far above a ratio of one. Similarly, for VOCs, we obtain a ratio of 8 to 10.

To interpret these ratios economically, consider an incumbent firm deciding whether to decrease its NO_x pollution emissions and thus generate offsets for sale. On average, the firm would receive between \$2,200 to \$4,000 per ton for cleaning up pollution. At the same time, by decreasing emissions, the firm would be creating \$40,000 to \$51,000 per ton in health and welfare benefits to society. In this sense, regulation is giving less incentive to clean up pollution than is optimal, and thus is too lenient.

Table 2, Panels B through E, show similar patterns in all four regions of the country. For both pollutants NO_x and VOCs, both weighting schemes, and all four regions, the ratio of the marginal benefits of abatement to offset prices is well above one. This would suggest that the regulations we study are too lenient on average in all these regions. The ratios are largest in the Northeast and Midwest, where the marginal benefits of abatement are more than fifty times mean offset prices. For NO_x in the Northeast, for example, the marginal benefits of abatement are approximately \$44,000, but mean offset prices are only about \$500. The ratios are modestly lower in the West, at 7.1 to 9.2. The ratios are the lowest in the South, at 1.4 to 6.6.

Figure 2 plots offset prices and the marginal benefits of abatement for all markets (Panel A) and for each census region (Panels B through E), separately by year. The marginal benefits of abatement vary year-by-year due to changes in population density and differences in baseline levels of all pollutants. For example, the marginal damages of emitting NO_x depend on the baseline ambient levels of NO_x, VOCs, and other pollutants in each market. Table 2 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.

A glance at the lines in Figure 2 shows the enormous vertical distance between the marginal benefits of abatement and offset prices in most regions and pollutants. That gap reflects the finding that the marginal benefits of abatement are much higher than mean offset prices. Once again, the only exception is for the VOC market in the South, where the marginal benefits of abatement and offset prices have been closer in the last decade. The year-by-year values in Figure 2 are similar to the mean values over the entire last decade from Table 2.

Table 3 shows more detailed geographical variation in the ratio of the marginal benefits of abatement to offset prices. For each of the largest markets in our data, this table shows that ratio 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 less urban areas like the Central Valley of California and the Upper Green River Basin in Wyoming. Some are in areas with strong environmental regulation, like Connecticut and New Jersey; others are in areas with weaker environmental regulation, like Texas and Wyoming.

Given this heterogeneity across markets, it is striking that the ratio of marginal benefits of abatement to offset prices is high in so many markets. Across all markets in Table 3, 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 large markets in California, the markets in Houston, and one market in Wyoming. Even for these markets with lower ratios, only one of the forty markets listed in Table 3 has a ratio below one—the market for VOCs in Houston.

What drives these differences? Figure 3 suggests that a larger proportion of variation across individual markets is driven by variation in the marginal benefits of abatement, rather than by offset prices. This can be seen because the marginal benefits of abatement (the hollow red diamonds in the graph) vary widely between markets, from \$1,000 per ton for VOCs in Wyoming to \$100,000 per ton for NO_x in Los Angeles. By contrast, offset prices (the solid blue circles in the graph) vary less in dollar terms (though a more comparable amount in percentage terms), from \$100 in many markets to \$10,000 for NO_x in Los Angeles. Figure 3 also shows that in the Houston VOC market, it is a relatively high level of offset prices rather than a low level of marginal benefits of abatement which makes the marginal benefits of abatement be less than offset prices.

Because the Houston market is anomalous, Appendix Figure 3 graphs the year-by-year patterns in the marginal benefits of abatement and mean offset prices for this market. These graphs show that VOC offset prices were fairly low until 2010, in the range of \$1,000. Beginning in 2011, offset prices skyrocketed, to well over \$10,000.

Why have Houston offset prices been so high over the last decade? The value of a one-ton VOC offset in Houston over the last decade is more than six times the price of a one-ton VOC offset in other markets. Houston offset prices for NO_x are also high. Market participants have suggested that offset prices in Houston are high due to substantial recent demand for petrochemical, energy, and related industries to enter the Houston market, due in part to cheap natural gas prices spurred by fracking, but limited opportunities for inexpensive abatement by incumbents.

Figure 4, Panel A, investigates sensitivity to many alternative ways of summarizing offset prices. The main results show mean marginal benefits of abatement divided by mean offset prices; we also consider the mean of (benefits / offset prices). The main estimates assume that permanent offsets sell at a price of about nine times the price of temporary offsets; Figure 4 shows alternative values assuming the ratio of permanent to temporary prices is 7, 5, or 12.

The additional rows in Figure 4, Panel A, show alternative estimates for the markets where we have transaction-level offset prices. Figure 4 next shows a value of offset prices which is adjusted by the required offset ratio between offset generation and use, discussed earlier in Section 1. 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, include temporary offsets, and show results for a different pollutant with fewer offset transactions (particulate matter or sulfur oxides).

These alternative estimates generally change the ratio of offset prices to marginal abatement benefits in intuitive ways. Despite this varying magnitude, most qualitative patterns persist. Nearly all ratios are well above one; the main exception is the Houston VOC market, which means that the ninetieth percentile of offset prices for VOCs exceeds the marginal benefits of abatement.

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 $PM_{2.5}$ mortality concentration-response function; 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 higher 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. Again, most of the conclusions with these different approaches are qualitatively unchanged.

We have also investigated a bounding exercise that asks what VSL would imply 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, and for VOCs, it is \$1.1 million. These VSL bounds are considerably lower than the EPA's \$8.8 million estimate.

4.2 Trends in Offset Prices Versus Marginal Benefits of Abatement

The results thus far suggest that most air pollution regulations we study are less stringent than is efficient. We now ask how the costs of regulation have changed over time.

Table 4 uses versions of the following statistical model to estimate the time trends in these graphs:

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

Here O represents the ton-weighted mean log offset price for market m, pollutant p, and year y. This variable is regressed on a linear year trend y_y and market×pollutant fixed effects μ_{mp}. The variable ϵ_{mpy} represents the error term. The main coefficient of interest, β, is the mean change in log offset prices each year, conditional on the fixed effects.

Columns (1)-(3) of Table 4 present estimates of the parameter β from this model. Panel A pools across pollutants and markets. These results suggest that offset prices are increasing by 6 to 8 percent per year in real terms. 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). Panels B and C show each pollutant separately. The two pollutants have similar trends. Table 4 includes all years with data; limiting the sample to years 2010-2019 delivers smaller annual growth rates, which may be in part due to the price volatility stemming from the Great Recession or the advent of hydraulic fracturing.

Table 4 shows rapid price increases that exceed inflation by 6 to 8 percent per year. At this rate of increase, real offset prices in these markets are doubling every decade. For comparison, the long-term rate of return on stocks and housing is around 7 percent per year, while the rate of return on bonds and treasury bills is lower, at 1 to 3 percent per year (Jorda et al. 2019).

Determining how the marginal cost/benefit ratio is changing also requires information on trends in the marginal benefits of abatement. Columns (4) to (6) of Table 4 show this trend. The marginal benefits of abatement are increasing by 2 percent per year, which is statistically larger than zero, but is smaller than the positive trend in offset prices. Accordingly, columns (7) through (9) show that log offset prices are growing by 4 to 8 percent per year faster than the log of the marginal benefits of abatement.

Why are offset prices increasing? One natural explanation is that the limit on pollution emissions in these markets is fixed, while economic growth implies that the demand for pollution offsets is increasing. Growing demand for an asset with fixed supply will increase its price.

Motivated by this potential explanation, Appendix Figure 4 compares the pattern of offset prices against the length of time a region has been in nonattainment. Each circle in the graph shows the mean log offset price for areas that have been in nonattainment for the number of years indicated in the x-axis. Appendix Figure 4 shows that offset prices are higher in areas that have been in nonattainment for more years. Being in nonattainment for one additional year is associated with a 7 percent increase in real offset prices per ton.

4.3 Engineering Estimates Versus Revealed Preference

How do offset prices compare to prevailing estimates of marginal costs from the EPA's own model and data? This comparison may be useful for a few reasons. Engineering estimates provide a standard and widely used method for estimating marginal abatement costs, so this comparison helps assess how revealed preference numbers from offset prices differ from accounting measures of engineering costs. Additionally, comparing against engineering estimates separately for each market and pollutant may provide some insight into where these estimates are more or less accurate.

Table 5 compares engineering estimates and offset prices. Panel A describes all states in our data, while panels B through E describe each census region. Within each panel, row 1 shows the ratio of engineering estimates to mean offset prices; row 2 shows the p-value for a hypothesis test that this ratio equals one; row 3 shows engineering estimates; and row 4 shows mean offset prices. The first two columns describe NO_x, while the last two columns describe VOCs. Columns (1) and (3) are weighted by tons, while columns (2) and (4) are weighted by population.

The engineering estimates in Table 5 are consistently far from actual offset prices, and the estimates statistically reject the hypothesis of equality. For NO_x in columns (1) and (2), engineering estimates are on average too low, and on average are a third of actual offset prices. This obscures regional variation. In the South and West regions, engineering estimates for NO_x are far below offset prices; in the Midwest and Northeast, engineering estimates for NO_x are above offset prices. For VOCs in columns (3) and (4), the opposite is true—engineering estimates are around six times larger than offset prices. That ratio ranges from 22 in the Northeast to 2 in the South.

The differences between engineering estimates of marginal abatement costs and mean offset prices are economically large. In the Northeast, for example, the EPA's engineering software predicts that it costs over \$10,000 per ton to abate VOCs, while offset prices are only about \$600 per ton. By contrast, in the West, the EPA's engineering software predicts that it costs \$1,000 per ton to abate NO_x, while offset prices are well over \$3,000 per ton.

Figure 5 graphically describes the distribution of individual offset prices, engineering estimates, and marginal benefits of abatement for four large markets where we have transaction-level data—the South Coast market around Los Angeles, California, the Houston-Galveston-Brazoria market in Texas, the San Joaquin Valley in California, and the San Francisco Bay Area. This helps nonparametrically describe the distributions underlying the averages in Table 5. In these graphs, the red dotted line describes engineering cost estimates, the blue solid line depicts the distribution of offset prices, and the black dashed line describes the marginal benefits of abatement.

Figure 5 shows large differences between offset prices and engineering estimates. For NO_x in Los Angeles, Figure 5, Panel A, shows that the engineering software predicts that abatement opportunities are available at under \$1,000 per ton, while offset pries range from approximately \$5,000 to \$50,000. This is not just a difference in means or first order stochastic dominance—it is actually non-overlapping support. Non-overlapping support also occurs for NO_x in Houston, where the engineering software predicts a distribution of prices under \$2,000, but actual offset prices exceed \$2,000 per ton. For VOCs, the engineering estimates are far above offset prices in the Los Angeles market, though closer in the Houston market.

Given large differences between revealed preference and engineering estimates, which is more accurate? While external validity may depend on the setting, for the markets we study, the offsets describe firms' actual costs. Take an example a market participant described to us—a Korean manufacturing firm was opening a plant in Houston that would emit substantial amounts of NO_x. For this firm's actual decisions, the engineering estimates of abatement costs from the EPA's software, which predict the availability of abatement opportunities among incumbent firms for a few hundred dollars per ton, are incorrect—the firm would have to spend over $10,000 per ton to purchase offsets, regardless of what the engineering model predicts.

Why do the engineering and revealed preference estimates differ so much? Discussing this question with regulators, including some who helped create the engineering software, suggests several possible explanations. First, the revealed preference estimates include economic costs that the engineering estimates are unlikely to include, such as search and matching frictions. Second, the two approaches measure different types of abatement. Offset markets require abatement to be surplus, federally enforceable, quantifiable, and permanent. Some engineering estimates may involve abatement technologies that do not satisfy these criteria. Third, industries may simply have a tendency to overstate compliance costs, particularly when communicating to regulators when there is the possibility that higher reported costs leads to weaker regulation.

Fourth, engineering estimates can have incomplete and inaccurate data. Abatement costs for industrial facilities can be site-specific and depend on available space for ductwork, technical specifications of existing technology, and other features. Federal regulators have not required firms or local regulators to share updated lists of abatement technologies used at specific plants, and thus the data the engineering software uses can be far out of date. Additionally, the engineering software only has data on a single abatement technology at each plant. This may help explain why the engineering model predicts the existence of inexpensive abatement opportunities for NO_x, even when offset prices are far higher. One regulator highlighted that much of the data on VOC abatement technology in the engineering cost model is over 30 years old.

We believe the pattern across pollutants suggests an important role at least for the fourth explanation. Offset transactions can involve tens of millions of dollars, and the engineering cost estimates would imply that many of these transactions are mistakes. In these tightly regulated markets, it is plausible that firms have already installed many of these control technologies, but firms and regulators did not update the emissions inventories used in the engineering software.

To provide additional evidence on the reasons for differences between CoST predictions and offset prices, we attempted to compare CoST's estimates of the cost of an individual abatement technology at a specific plant against an actual offset generated by the same plant. Identifying the individual abatement technology used for an offset transaction then linking to the same technologies in CoST is difficult due to data limitations and must be done by hand for each transaction. As a way of providing some insight, we investigated 20 VOC offset transactions by hand. While all 20 incumbent plants appear in the CoST data, CoST was unable to recommend any VOC abatement technology for 18 of the 20 plants, at any price, using any technology. CoST appears to lack any information on the abatement technologies these 18 offset transactions actually installed, including a vapor combustor unit, a vapor recovery pump, specific process or solvent changes, and a storage tank floating roof landing. Cursory searches for these technologies on the internet suggests that industry uses them widely and that regulators have written many documents discussing them; however, they are not in the menu of abatement opportunities available to firms in the CoST model.

For the two of 20 plants where CoST successfully recommended an abatement technology, CoST's estimated costs differed wildly from offset prices. In one case, a metal coating firm installed a regenerative thermal oxidizer, then sold the offsets at $1,000 per ton. For this firm, the abatement technology CoST recommends as the lowest-cost option is a permanent total enclosure, at $27,665 per ton. In other words, the least-cost technology CoST can identify is twenty eight times the cost of the technology a firm actually installed. In the second case, an industrial solvents firm redesigned part of its plant and routed emissions to a thermal oxidizer, then sold the offsets at $60,000 per ton. For this firm, the lowest-cost abatement technology CoST recommends is a combination of work practice standards, solvent substitution, and add-on controls, at negative $1,357 per ton (i.e., CoST predicts this abatement investment would more than pay for itself). In this second case, CoST's recommendation is off from actual offset costs by a factor of negative forty four.

4.4 Prices Versus Quantities

When the marginal abatement cost and benefit curves are known with certainty, price policies produce equivalent expected outcomes to quantity policies. When the marginal abatement benefit curve (equivalently, the marginal pollution damage curve) is uncertain, this equivalence persists. When the marginal abatement cost curve is uncertain, however, this equivalence fails. The relative expected welfare consequences of price versus quantity policies then depend on the relative slopes of the marginal abatement cost and benefit curves (Weitzman 1974).

What is known about the slope of the marginal abatement benefit curve? Economists and epidemiologists typically estimate nonlinear models to express damages in terms of relative risks, and ambient pollution levels may not vary linearly with pollution emissions (Krewski et al. 2009; Lepeule et al. 2012). Consensus is emerging within the fields, however, that the marginal abatement benefit function for many criteria air pollutants is modestly sloped or fairly flat at pollution levels near the Clean Air Act regulatory standards. Thus, the marginal benefits of abatement do not typically change dramatically due to modest changes in emission levels (Apte et al. 2015). While the marginal abatement benefit curve is nonlinear and does have larger slope for bigger changes in pollution, in Figure 5, the marginal abatement benefit curves are so flat that they appear as a completely horizontal line over this quantity of abatement. Figure 5 only shows eight markets, but the marginal abatement benefit curve is similarly flat for other markets.

Figure 5 also plots two descriptions of marginal abatement costs, one from engineering estimates and the other from offset prices. In every graph, these curves have steep slopes (note the log scale). The engineering data describe the marginal abatement cost curve, while the slopes in the offset lines may reflect search frictions or local shocks to offset demand. We interpret engineering cost estimates cautiously, given that they are not revealed preference numbers and subject to many concerns, including substantial differences from offset prices. Offset prices vary substantially, though in this setting we do not have scope to pin down to what extent this is due to a steep slope of the true marginal abatement cost curve versus search frictions or volatility in market fundamentals.

While we are cautious in this conclusion given the uncertainties involved in inferring the entire marginal abatement cost curve, the steeper slope of the marginal abatement cost curve relative to the marginal benefits curve in the available evidence would tend to suggest that price instruments produce higher expected welfare than quantity policies in these markets. In this interpretation, levying a tax equal to the marginal expected damages for new entrants (i.e., a price instrument) would lead to larger expected welfare gains than capping the market level of allowable emissions and letting firms trade offsets (i.e., a quantity instrument). Researchers have made similar arguments for taxes versus cap-and-trade markets to address global climate change (Pizer 2002).

Price policies in these markets could take different forms. Reforms could replace offset markets with emissions taxes. Another possible approach is to use hybrid policies. Regulators could guarantee provision of additional offsets at a certain predetermined high price. In some settings, prices are at the price ceiling or floor so often that hybrid instrument essentially becomes a tax (Borenstein et al. 2019). Many cap-and-trade markets have a price floor or ceiling, which in some cases is imposed after episodes of extreme price volatility. We are unaware of any such policy proposals for U.S. air pollution offset markets, though this paper provides economic reason to consider such ideas.

5 Conclusions

This paper describes a novel approach to estimating the marginal cost of air pollution regulation. This approach has several appealing features—it uses revealed preference, reflects both pecuniary and non-pecuniary abatement costs, obtains estimates that vary by pollutant, location, and time, and is transparent and simple to implement.

We exploit policies that require firms opening or substantially retrofitting a polluting plant in a region to offset their pollution emissions by paying incumbents in the same region to decrease their emissions of the same pollutant. These policies create several hundred decentralized, bilateral markets for pollution that existing research has largely not analyzed. Using data from 16 states plus Washington, DC, that together cover 60 percent of the economic activity in all US air pollution offset markets, we describe how offset prices can provide revealed preference measures of the marginal cost of relevant air pollution regulations. We then compare offset prices against leading estimates of the marginal benefits of emissions reductions. These conclusions are relevant to policy in general, and also specifically to reforms that the EPA, think tanks, and state and local governments are discussing for offset markets and associated regulations.

Our main finding is that policy is more lenient than is efficient in most markets, though regulation in one market, the Houston metro market for VOCs, may be moderately more stringent than efficiency would require. In practice, stringency can change in various ways. One possible approach to reforming policy would be for incumbents to face tighter pollution standards. Entrants in the markets we study already face an extremely strict pollution standard, while incumbents face weaker standards. Because cost-effectiveness requires equating marginal abatement costs across sources, tightening standards for entrants further relative to standards for incumbents is not likely to be efficient. Alternatively, charging a facility-specific pollution tax equal to the marginal damages from their annual emissions would increase expected social welfare.

Additionally, an important fraction of local pollution emissions come from mobile sources such as cars and trucks. Abatement opportunities for mobile sources may be cheaper than stationary sources in ways that could generate further improvements in air quality at lower costs. Appendix D describes additional policies that could reform offset markets in ways to decrease marginal abatement costs, such as allowing trades between markets. While these reforms would produce welfare gains, in the absence of other policy reforms, they would actually expand the gap between marginal abatement costs and benefits, so would not achieve efficient policy.

Our conclusions about the stringency of environmental policy are not made in a vacuum. If reforms reduced the compliance costs of the Clean Air Act, or if estimates of the marginal benefits of emissions reductions increased, these changes would strengthen our conclusions. Alternatively, if marginal abatement costs continue increasing at their rapid past rate, the costs of emissions reductions could begin to exceed 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. New innovations in pollution abatement technology would have also implications for the efficient level of environmental stringency for society.

We believe this paper offers several questions for future work. Many countries use offset markets for a variety of environmental goods. To what extent can the approach used here help identify the marginal costs of environmental policy in other settings? More generally, what are other revealed preference strategies that can be applied broadly to 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 had made extraordinary progress in measuring the marginal benefits of pollution abatement, but comparatively less progress in measuring the marginal costs of pollution abatement, even though both parameters are essential to designing optimal environmental policy.

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Table 1—Prevalence of Offset Markets

	Number of markets	Population (mn)		GDP (trn)		Manufacturing employment (mn)	
		People	%	$	%	Workers	%
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Panel A. National							
Any pollutant	553	182.1	59%	$11.09	66%	6.44	56%
Ozone	300	173.2	56%	$10.66	63%	6.09	53%
Particulate matter	104	121.2	39%	$7.59	45%	3.97	34%
Other	149	109.9	36%	$7.19	43%	3.59	31%
Panel B. Full sample (16 states plus Washington, DC) as proportion of all national markets							
Any pollutant	115	108.4	60%	$6.99	63%	3.41	53%
Ozone	63	108.4	63%	$6.99	66%	3.41	56%
Particulate matter	18	36.3	30%	$2.18	29%	1.21	31%
Other	34	42.2	38%	$2.57	36%	1.43	40%

Notes: This table describes all US air pollution offset markets. Percentages in Panel B 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. Ozone nonattainment areas have separate markets for nitrogen oxides and volatile organic compounds. Nitrogen dioxide markets are included in ozone. "Other" pollutants include carbon monoxide, lead, particulate matter, and sulfur dioxide. 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—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	17.99	12.99	7.88	9.82
2. p-val: MBabatement / Offset price = 1	[0.00]	[0.00]	[0.00]	[0.00]
3. Mean marginal benefits of abatement	$40,309	$51,172	$20,477	$20,389
4. Mean offset prices	$2,241	$3,941	$2,599	$2,077
Panel B. Northeast				
1. Marginal benefits of abatement / Offset price	87.21	77.74	51.79	57.70
2. p-val: MBabatement / Offset price = 1	[0.00]	[0.00]	[0.00]	[0.00]
3. Mean marginal benefits of abatement	$44,777	$44,015	$29,169	$32,274
4. Mean offset prices	$513	$566	$563	$559
Panel C. South				
1. Marginal benefits of abatement / Offset price	4.28	6.55	1.40	2.56
2. p-val: MBabatement / Offset price = 1	[0.00]	[0.00]	[0.00]	[0.00]
3. Mean marginal benefits of abatement	$29,481	$28,805	$13,315	$13,283
4. Mean offset prices	$6,887	$4,395	$9,536	$5,198
Panel D. West				
1. Marginal benefits of abatement / Offset price	9.22	9.09	7.72	7.10
2. p-val: MBabatement / Offset price = 1	[0.00]	[0.00]	[0.00]	[0.00]
3. Mean marginal benefits of abatement	$35,202	$70,827	$10,336	$15,196
4. Mean offset prices	$3,819	$7,788	$1,338	$2,141
Panel E. Midwest				
1. Marginal benefits of abatement / Offset price	95.69	101.25	50.08	53.43
2. p-val: MBabatement / Offset price = 1	[0.00]	[0.00]	[0.00]	[0.00]
3. Mean marginal benefits of abatement	$44,503	$48,581	$19,734	$22,215
4. Mean offset prices	$30	$30	$40	$40
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.

Table 3—Ratio of Marginal Benefits of Abatement to Offset Prices, by Market

	NO_x (1)	VOCs (2)
Arizona (Phoenix-Mesa)	—	12.68
California (Imperial County)	1.90	7.71
California (Los Angeles-South Coast)	8.67	7.78
California (San Francisco Bay Area)	7.25	3.42
California (San Joaquin Valley)	3.99	5.18
Connecticut (Greater Connecticut)	44.61	—
Connecticut (NY-NJ-Long Island)	36.53	—
District of Columbia (DC-MD-VA)	105.28	81.08
Illinois (Chicago-Naperville, IL-IN-WI)	104.94	54.13
Indiana (Chicago-Naperville, IL-IN-WI)	63.09	25.61
Maryland (Baltimore)	69.35	35.04
Maryland (Washington, DC-MD-VA)	58.75	38.10
Missouri (St. Louis-St. Charles-Farmington, MO-IL)	—	83.96
New Jersey (NY-NJ-CT-Long Island)	58.43	45.30
New Jersey (Philadelphia-Wilmington-Atlantic City PA-NJ-MD-DE)	103.11	39.49
New York (NY-NJ-CT-Long Island)	85.41	70.67
Ohio (Cleveland-Akron-Lorain)	95.93	50.47
Pennsylvania (Philadelphia-Wilmington-Atlantic City PA-NJ-MD-DE)	92.30	67.78
Pennsylvania (Pittsburgh-Beaver Valley)	304.26	36.71
Texas (Houston-Galveston-Brazoria)	1.88	0.60
Virginia (Washington DC-MD-VA)	59.71	39.64
Wyoming (Upper Green River Basin)	42.94	1.40

Notes: The first column lists the state and, in parentheses, the specific market. The numbers represent the ratio 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.

Table 4—Trends in Offset Prices and Marginal Benefits of Abatement

Dependent Variable	Offset prices			Marginal benefits of abatement			Offset prices - marginal benefits of abatement		
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Panel A. All pollutants									
Year	0.06***	0.08	0.06***	0.02***	0.02*	0.02***	0.04**	0.07	0.04**
	(0.02)	(0.06)	(0.02)	(0.00)	(0.01)	(0.01)	(0.02)	(0.06)	(0.02)
N = 238									
Panel B. Nitrogen oxides (NO_x)									
Year	0.06***	0.09***	0.06***	0.03***	0.04***	0.03***	0.03	0.04	0.03*
	(0.02)	(0.02)	(0.02)	(0.00)	(0.01)	(0.00)	(0.02)	(0.03)	(0.02)
N = 114									
Panel C. Volatile organic compounds (VOCs)									
Year	0.05*	0.08	0.05	0.01***	0.00*	0.01***	0.04	0.08	0.05
	(0.03)	(0.09)	(0.03)	(0.00)	(0.00)	(0.00)	(0.02)	(0.09)	(0.03)
N = 124									
Weight		Tons	Population		Tons	Population		Tons	Population

Note: Each unit of observation is a market × pollutant × year. All estimates are restricted to use only the sample of observations where both offset prices and the marginal benefits of abatement are observed. Dependent variables in logs. Marginal benefits of abatement are only observed in years 1990, 1996, 1999, 2002, 2005, 2008, 2011, 2014, and 2017. 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.

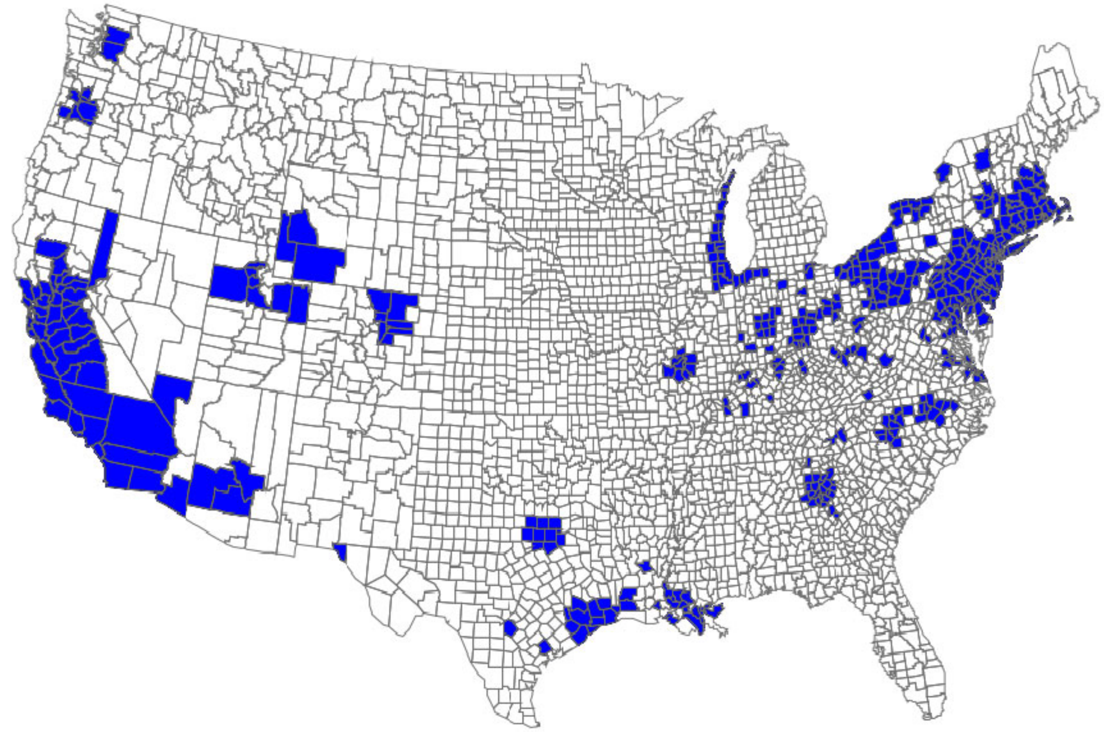
Table 5—Engineering Estimates of Marginal Abatement Costs Versus Offset Prices

	NO_X		VOCs	
	(1)	(2)	(3)	(4)
Panel A. Full sample (16 states plus Washington, DC)				
1. Engineering est. / offset price	0.31	0.30	4.59	6.76
2. p-val: engineering est. / offset price = 1	[0.00]	[0.00]	[0.00]	[0.00]
3. Mean engineering estimate	$798	$804	$9,401	$9,712
4. Mean offset prices	$2,586	$2,686	$2,050	$1,437
Panel B. Northeast				
1. Engineering est. / offset price	1.51	1.38	21.50	17.64
2. p-val: engineering est. / offset price = 1	[0.00]	[0.00]	[0.00]	[0.00]
3. Mean engineering estimate	$773	$830	$12,110	$10,407
4. Mean offset prices	$513	$603	$563	$590
Panel C. South				
1. Engineering est. / offset price	0.18	0.28	1.94	3.02
2. p-val: engineering est. / offset price = 1	[0.00]	[0.00]	[0.05]	[0.04]
3. Mean engineering estimate	$613	$659	$10,541	$8,449
4. Mean offset prices	$3,491	$2,395	$5,427	$2,795
Panel D. West				
1. Engineering est. / offset price	0.33	0.18	6.79	7.35
2. p-val: engineering est. / offset price = 1	[0.00]	[0.00]	[0.00]	[0.00]
3. Mean engineering estimate	$1,117	$935	$11,470	$12,701
4. Mean offset prices	$3,351	$5,303	$1,690	$1,728
Panel E. Midwest				
1. Engineering est. / offset price	1.25	1.26	6.78	6.68
2. p-val: engineering est. / offset price = 1	[0.00]	[0.00]	[0.00]	[0.00]
3. Mean engineering estimate	$580	$583	$2,672	$2,682
4. Mean offset prices	$465	$463	$394	$402
Weight:				
Tons	X		X	
Population		X		X

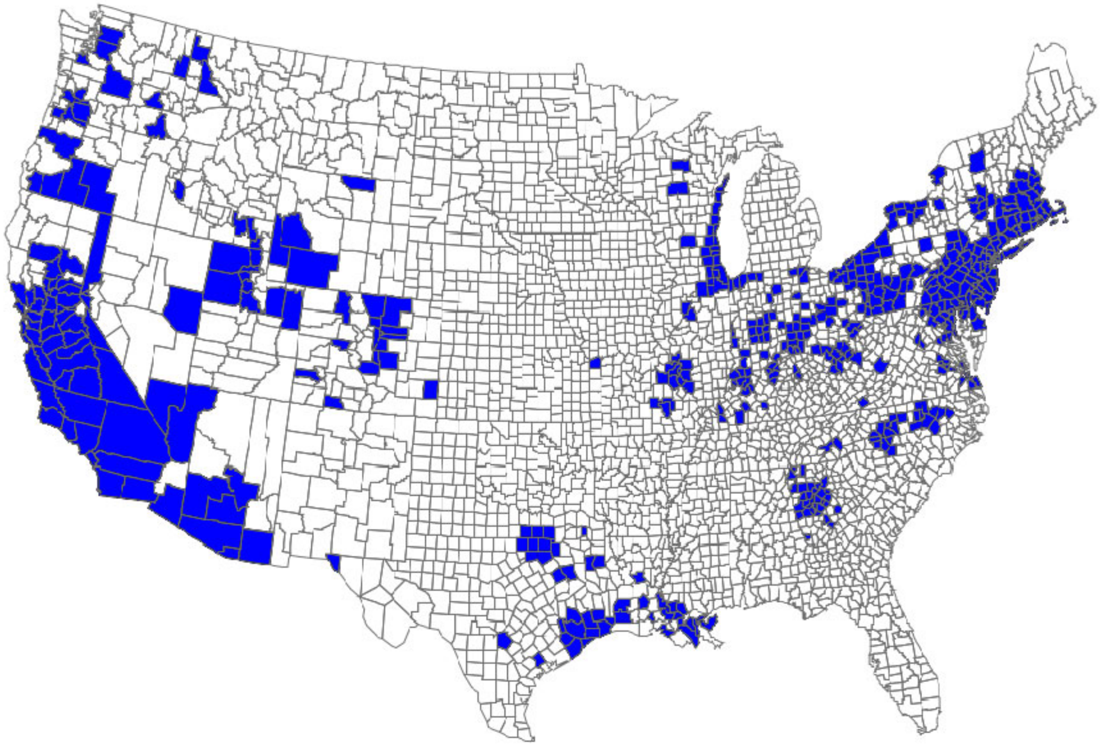
Notes: Row 1 in each panel shows the ratio of mean engineering estimate of abatement costs to the offset price in the specified census region. Row 2 in each panel shows the p-value for the test of the null hypothesis that this ratio equals one. Rows 3 and 4 show the engineering estimate of abatement cost and mean offset prices. Offset price data cover the years 2010-2019. Engineering estimates come from the EPA's Control Strategy Tool (CoST), which we apply using EPA's National Emissions Inventory for point sources for years 2011, 2014, and 2017. All currency are in 2017$, deflated using the GDP deflator.

Figure 1—Maps of Areas with Offset Markets

(A) Market areas for ozone (NO_x and VOC)



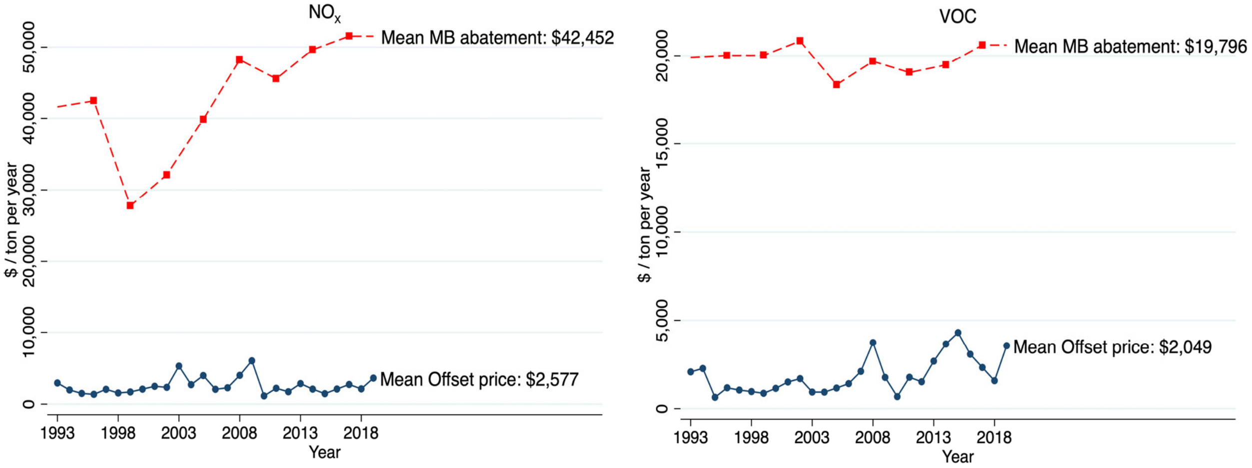
(B) Market areas for other pollutants



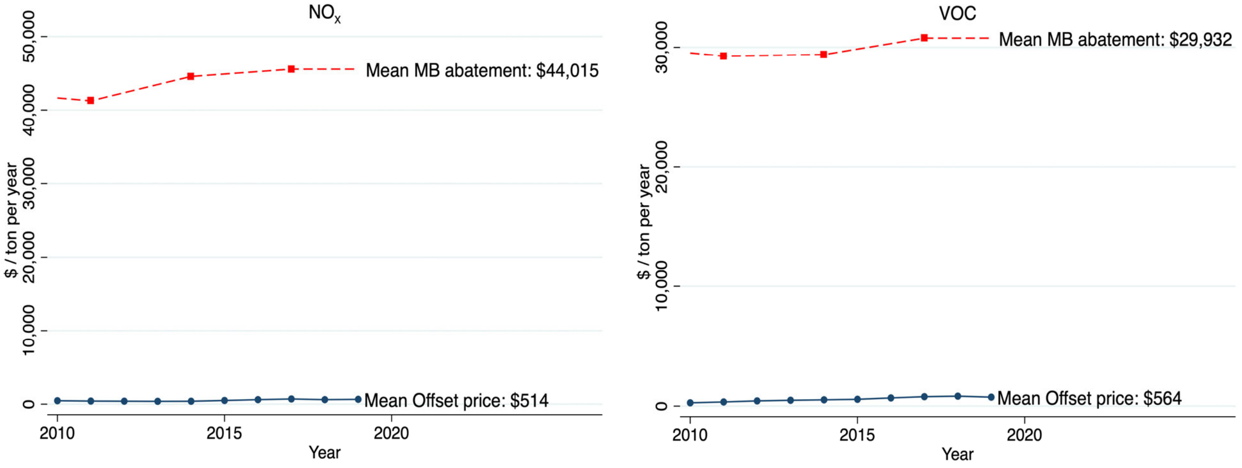
Notes: Shaded blue areas are in nonattainment in any years 1993-2019, and in states with offset markets. "Other pollutants" includes CO, PM, and SO_x. States with markets are identified by using a list from Emission Advisors (https://www.emissionadvisors.com/emissions-markets/; Accessed 4/16/2020) and verifying internet market listings.

Figure 2—Pollution Offset Prices Versus Marginal Benefits of Abatement, by Year

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



(B) Northeast



(C) South

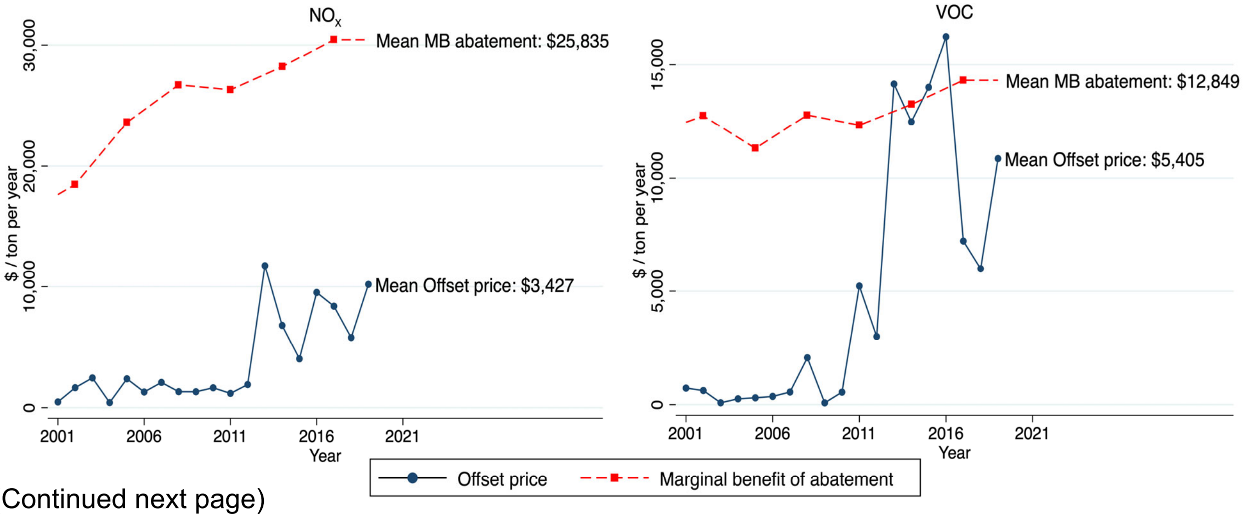


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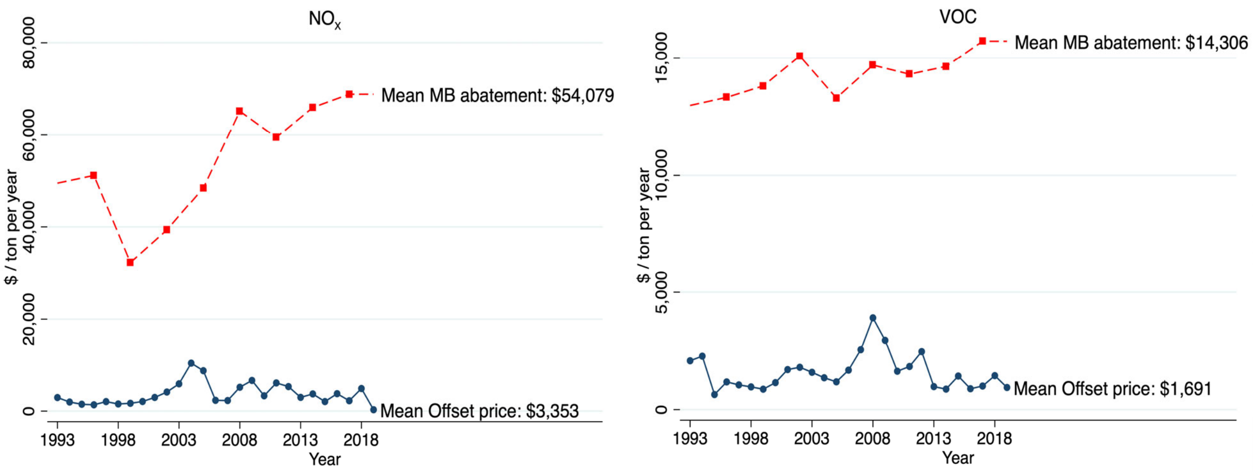
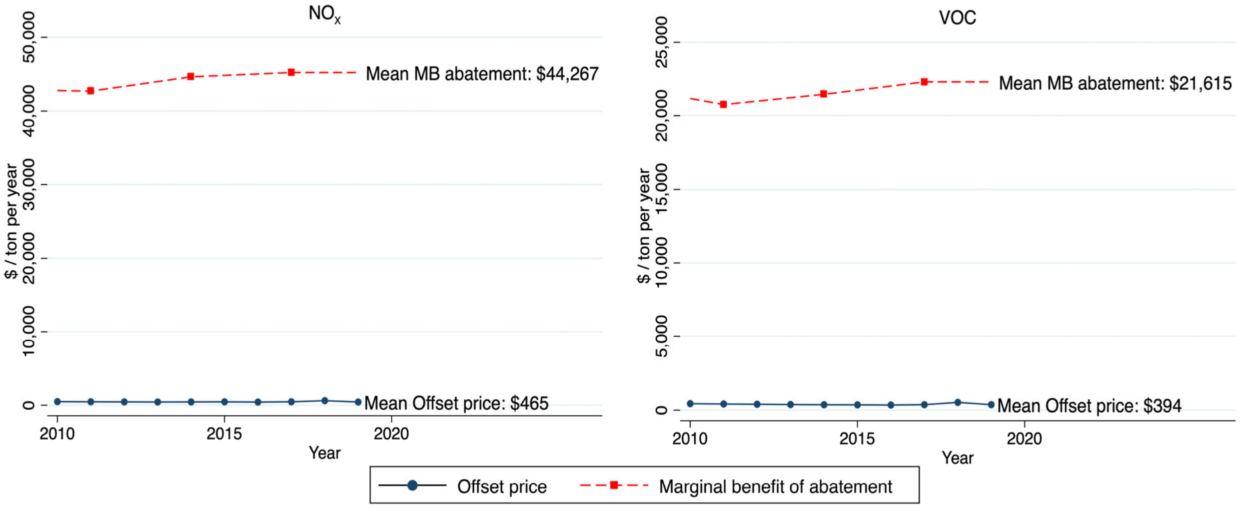
Figure 2—Pollution Offset Prices Versus Marginal Benefits of Abatement, by Year (Continued)

(D) West

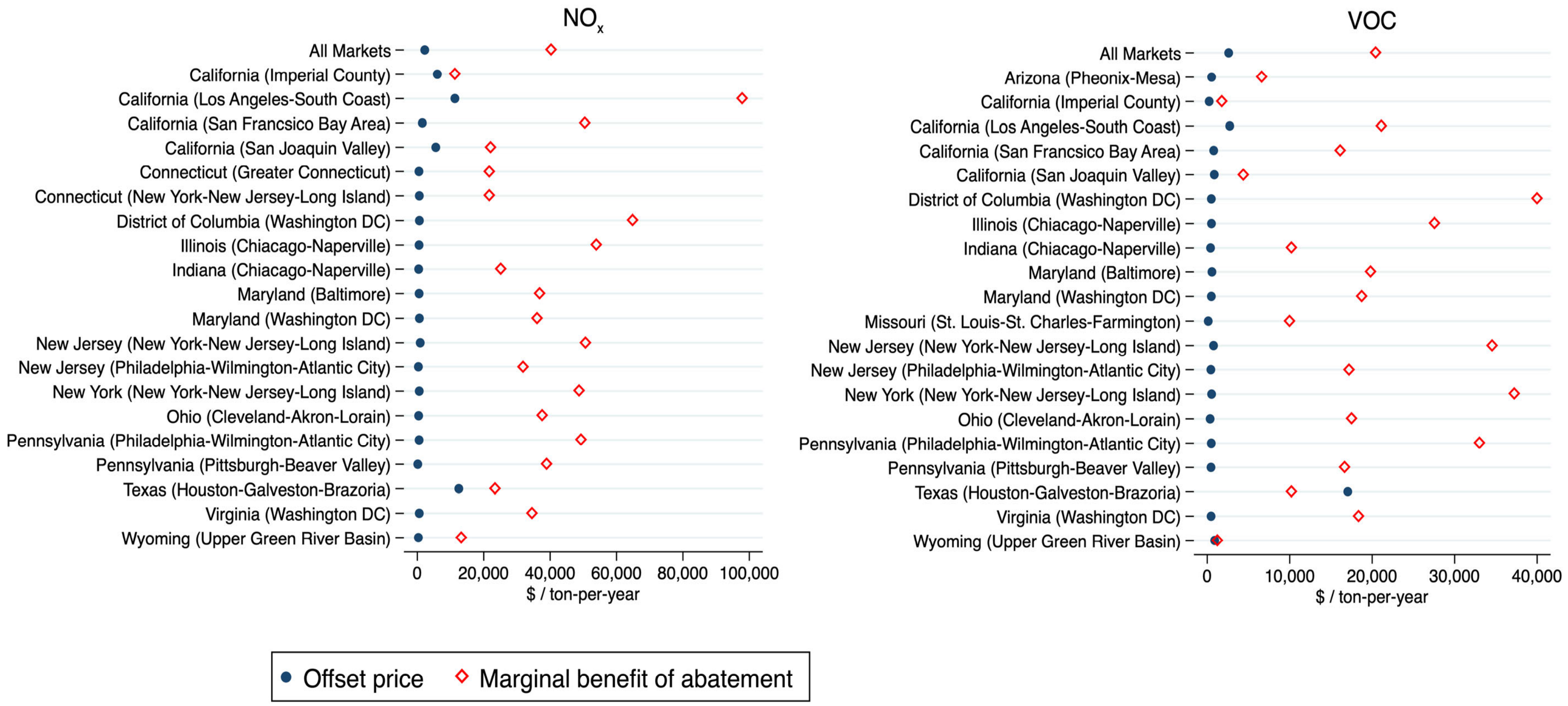


(E) Midwest



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 obsered 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.

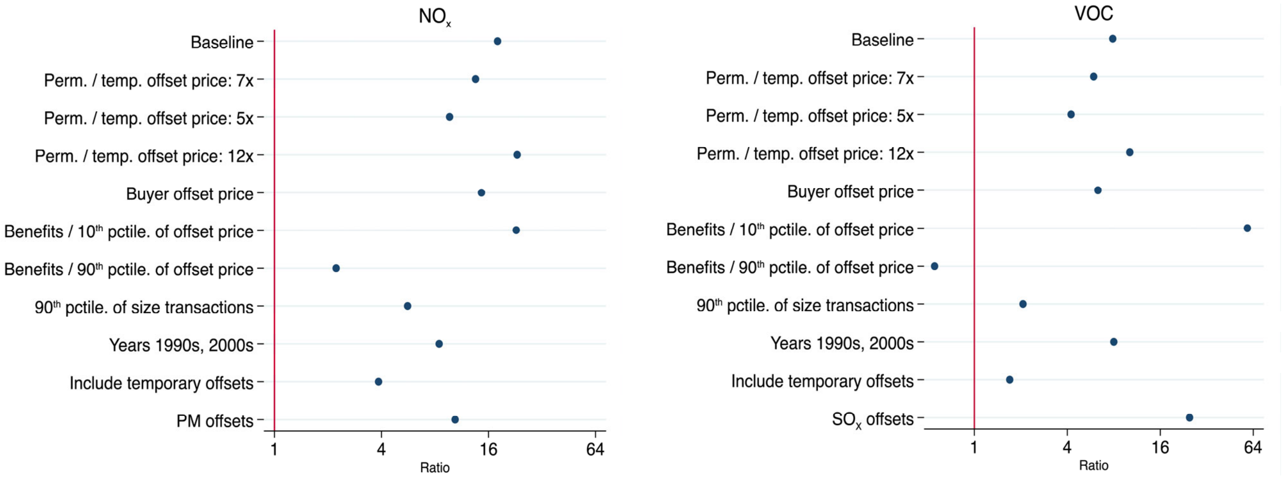
Figure 3—Offset Prices and Marginal Benefits of Abatement, Large Individual Markets



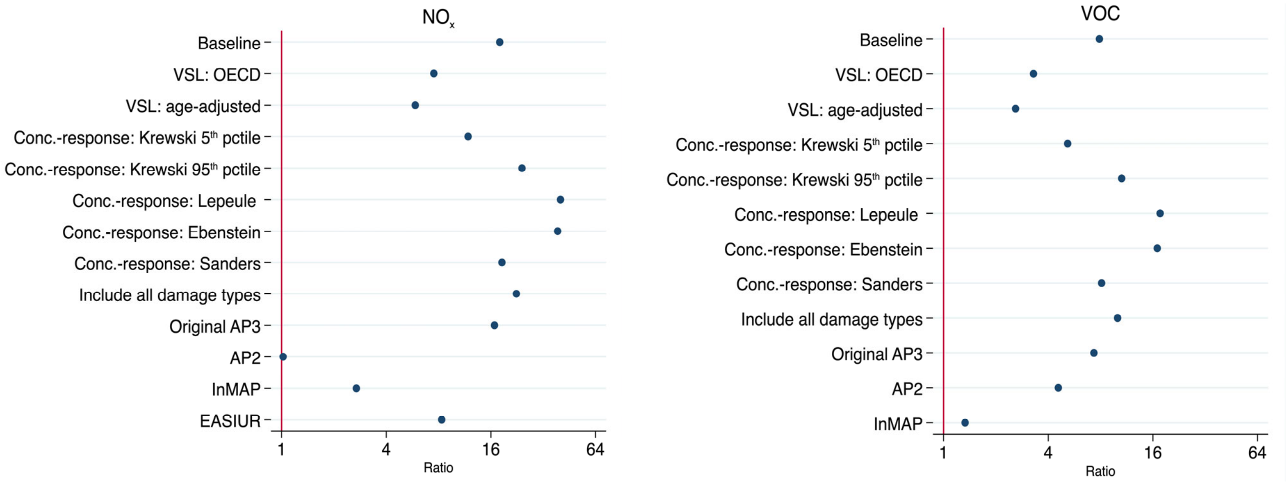
Notes: This figure compares offset prices and the marginal benefits of pollution abatement in individual market × pollutants, for a set of large markets with data. Data represents years 2010-2019. The vertical axis lists the state that the data represent, then in parentheses, the market's name. Offset 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.

Figure 4—Ratio Marginal Benefits of Pollution Abatement to Mean Offset Prices: Sensitivity Analysis

Panel A. Alternative offset price specifications



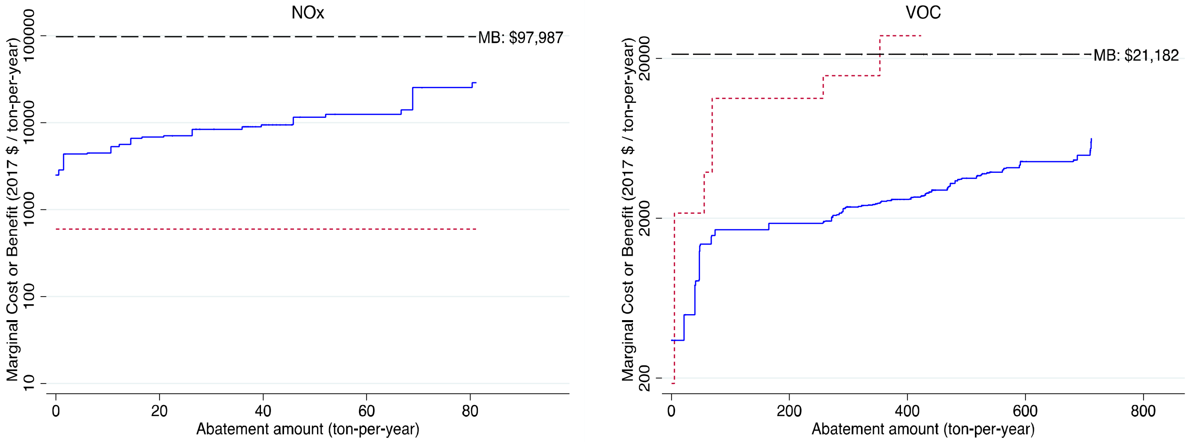
Panel B. Alternative estimates of the marginal benefits of abatement



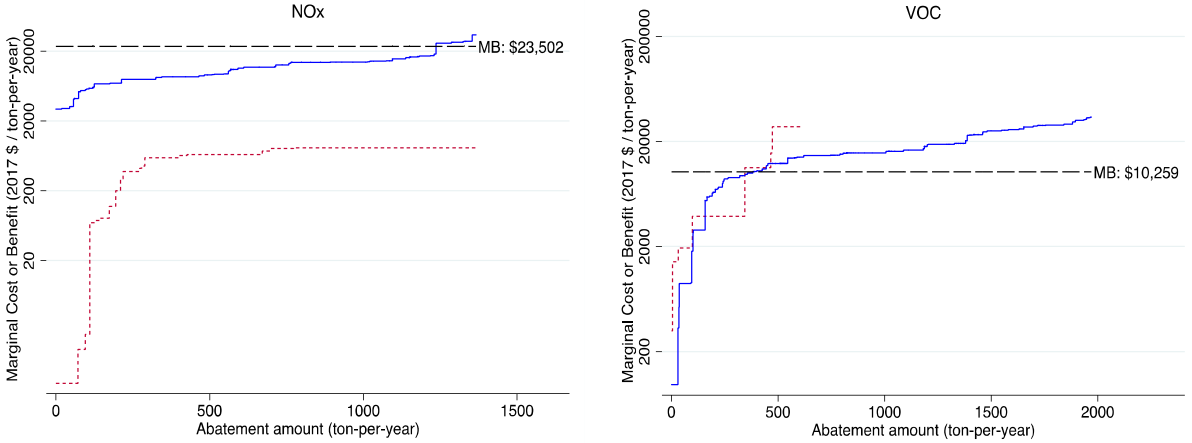
Notes. These figures present alternative ways of calculating the ratio marginal benefits of abatement to mean offset prices. Panel A presents alternate ways of calculating offset prices, while using the baseline estimates of marginal benefits of abatement. Panel B presents alternative ways of calulating 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.

Figure 5—Offset Prices, Engineering Estimates of Marginal Abatement Costs, and Marginal Abatement Benefits in Four Large Markets

(A) Los Angeles-South Coast, California



(B) Houston-Galveston-Brazoria, Texas



(C) San Joaquin Valley, California

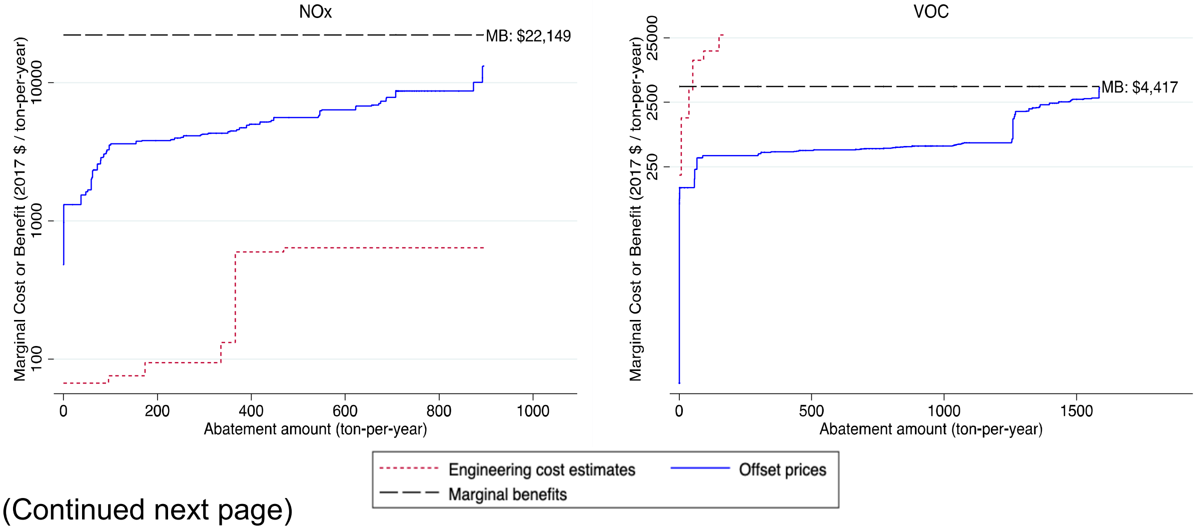


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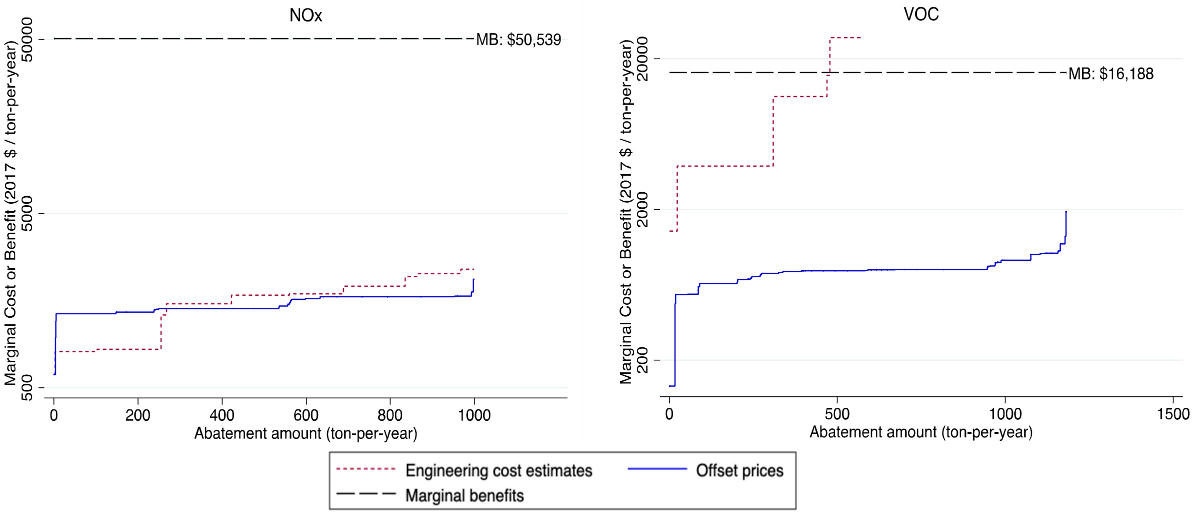
Figure 5—Offset Prices, Engineering Estimates of Marginal Abatement Costs, and Marginal Abatement Benefits in Four Large Markets

(D) San Francisco Bay Area, California



Notes: Each graph shows three curves, all describing the period 2010-2019. The solid line in each graph shows the ordered value of offset prices for the indicated market and pollutant. The short-dotted line in each graph shows engineering estimates of the marginal abatement cost curve, as estimated from EPA's Control Strategy Tool (CoST). The long-dashed line in each graph shows the marginal benefit of abatement curve. The marginal benefit of abatement curve is flat enough for these quantities of abatement that this curve appears linear and horizontal in these graphs. All currency are in 2017$, deflated by Federal Reserve's US GDP deflator. To pool estimated engineering costs, the amounts from control measures are aggregated up to the amount of offset traded in each individual nonattainment area. The engineering cost estimate line stops horizontally at the maximum quantity of abatement that the CoST model is able to identify for the indicated pollutant and market.

Online Appendix:
Is Air Pollution Regulation Too Stringent?

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Contents

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. We perform a similar exercise on the set of articles presented in the NBER Summer Institute session on environmental and energy economics for years 2000-2020 (see https://www.nber.org/summer-institute/; accessed 08/07/2020)

B Additional Institutional Details

The 1970 Clean Air Act (CAA) Amendments prohibit net increases in pollution emissions from stationary sources in nonattainment areas. The CAA initially forbid increases in pollution emissions from any large sources in these areas, which essentially prevented large polluting plants from opening in cities. Critics argued that this requirement was inhibiting economic development. In response, a 1976 EPA policy and the 1977 CAA Amendments began allowing large polluting firms to enter nonattainment areas only if their increase in pollution emissions was offset by decreases in emissions of the same pollutants from incumbent sources in the same areas.

Offset trading before 1990 was limited due in part to fairly strict rules (Foster and Hahn 1995). In the 1980s, regulators rejected some proposals to generate offsets due to inadequate documentation, inadequate abatement, or other reasons (General Accounting Office 1982). Also in the 1980s, regulators changed rules governing offsets in ways affecting their value. After 1990, these practices became less common.

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). Spurred by this increased flexibility, offset markets grew after 1990.

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 emissions 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 policies are fragmented, with hundreds of separate markets, whereas the U.S. has only a few cap-and-trade markets, which are typically large and each cover many sources and states.

Ozone nonattainment requires two separate markets (one for NO_x, one for VOCs, though some markets allow trading between these two pollutants under stringent restrictions). We consider PM_{10} and $PM_{2.5}$ to be a single market for particulate matter.

C Additional Data Details

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; and transaction-level data from California and Texas, 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 separate data points per year for the New York-New 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).[1] 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 Marginal Benefits of Abatement

We calculate county-level marginal benefits of pollution abatement from the AP3 model (Holland et al. 2020). 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 estimate of the value of a statistical life (VSL).

To calculate the marginal benefits of abatement using AP3, we start from the raw data files and programs that constitute AP3, which Nick Muller generously shared. 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.

C.2.1 Mortality Concentration-Response Function

The $PM_{2.5}$ concentration-adult mortality relationship accounts for a large majority of air pollution damages. Because we report several alternative versions of this relationship and fix a discrepancy in how AP 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

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[1] 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).

$\Delta E = E_1 - E_0$, 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

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

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:

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

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 U.S., and is measured in terms of PM_{10}, so requires translation to $PM_{2.5}$. Another quasi-experimental estimate focuses on the U.S., 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.2.2 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.2.3 Value of Statistical Life

Our baseline estimates use the USEPA (2010b)'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 specification 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 U.S., 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 U.S.

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. (2019), 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 U.S. 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.2.4 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 U.S. Census and mortality data from National Center for Health Statistics. 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.2.5 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 U.S. 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. Atmospheric chemists have developed extraordinarily detailed and computationally-intensive chemical transport models that assess how one specific change in emissions, such as closing 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.3 Engineering Estimates of Marginal Abatement Costs

The U.S. EPA uses a software system called Control Strategy Tool (CoST) to estimate engineering costs of counterfactual emission scenarios. The EPA uses this software to perform benefit-cost analyses of ambient pollutant standards (e.g., USEPA 2012, 2015).

CoST was created in 2006 but replaced earlier programs, AirControlNet and the Alternative Control Techniques Documents, which go back to at least the early 1990s.

CoST has two main data inputs—a baseline emission inventory for emission sources (e.g. USEPA 2019), and a database of pollution abatement measures, collected by the EPA through various federal, regional and local environmental agencies (USEPA 2010a). The software matches pollution sources with applicable abatement technologies and finds the lowest cost-per-abatement result. The software calculates the effectiveness of abatement technology based on source attributes such as flow rate and combustion efficiency. The software also distinguishes capital, operating, and maintenance cost of abatement investments.

We obtain the engineering estimates from CoST for each nonattainment area × pollutant where we have offset permit data, for the years 2011, 2014 and 2017. We use EPA's national emissions inventory for years 2011, 2014, 2017, and restrict the emission sources that are eligible for offset permits that we analyze. These typically includes electricity generation units, oil and gas facilities, and other industrial and nonindustrial point sources.

The CoST model requires users to pre-specify several choices about the characteristics of eligible abatement technologies. We make these choices to resemble those used in existing regulatory impact analyses that apply the CoST model (USEPA 2012, 2015), but adapted to reflect the setting of offset markets. We limit CoST to sources that exceed 5 tons of emissions, which is a typical range for firms trading offsets and is also the range at which the more stringent regulatory requirements under the Clean Air Act become binding. We require additional abatement technologies in CoST to reduce emissions by at least 0.1 tons (the minimum size CoST allows), since some offset transactions represent small quantities. We require additional abatement technologies to exceed existing abatement technologies by at least 10 percent, which is the standard setting in the CoST model; while we do not have detailed data on the relevant quantities of this measure for most offset transactions, we believe it accurately characterizes a reasonable share of offset transactions. To ensure that the control devices we analyze are comparable to the devices mandated by up-to-date air pollution regulation, we also restrict the menu of control devices selected by CoST to those used by EPA in their most recent benefit-cost analyses of ambient pollutant standards (USEPA 2012, 2015). Finally, we analyze CoST assuming a 10 percent discount rate, which corresponds with the discount rate used in the rest of the paper. In CoST, which outputs annualized costs, the discount rate affects the share of expenditures due to operating versus capital costs, but does not change the total annual cost.

D Additional Policy Discussion

The main text describes policy reforms that would decrease pollution emissions for incumbents and thereby bring marginal abatement costs and benefits closer. Here we discuss other reforms to offset markets that may provide welfare gains by increasing the flexibility of offset markets.

Regulations currently require offsets to come from other stationary sources within the same air region, but there may be cheaper abatement opportunities available in other sectors. Some air quality management districts are exploring the possibility of allowing offsets to come from mobile rather than stationary sources (e.g., city buses converting from diesel to natural gas), marine sources (e.g., boats arriving to a port being required to use ultra low-sulfur diesel), or agriculture. These reforms might increase the pool of low-cost offsets, lowering the equilibrium price. To the extent that marginal benefits of abatement vary across regions, trades between regions could also impose a trading ratio that is proportional to marginal damages (Tietenberg 1980). While lower offset prices would likely be welcome by producers, it also has implications for the optimal level of regulation and ambient pollution more generally; namely, the efficient level of pollution emissions should fall further to the point where the marginal benefits of emissions reductions are equal to the marginal cost of abatement.

Another type of reform would increase the flexibility of offset requirements. Most market-based instruments like taxes and cap-and-trade markets replace prevailing prescriptive standards. In offset markets, by contrast, sources must continue following command-and-control standards while also complying with offset requirements. Allowing sources to use offsets for achieving some of their regulatory requirements, even if in excess of emissions that prescriptive standards would allow, could improve liquidity and decrease prices in these markets. For example, a new source could emit more than prevailing requirements would allow if it purchases additional offsets for the extra emissions (Abbott and Brady 1990; Swift 2001).

A few air quality districts are experimenting with trades across pollutants, primarily between NO_x and VOCs. Trades between these two pollutants are complex, because they depend on the contribution of each pollutant to ground-level ozone. But streamlining procedures to analyze and allow trades between pollutants would also increase market liquidity.

An additional possible reform would allow trading between nonattainment areas. Because the marginal benefits of pollution abatement differ across markets, these inter-market trades would need to respect trading ratios, in which one ton of a pollutant from a given market is treated as equal to more than one ton of the pollutant from another market (Montgomery 1972). This may also generate potential equity concerns.

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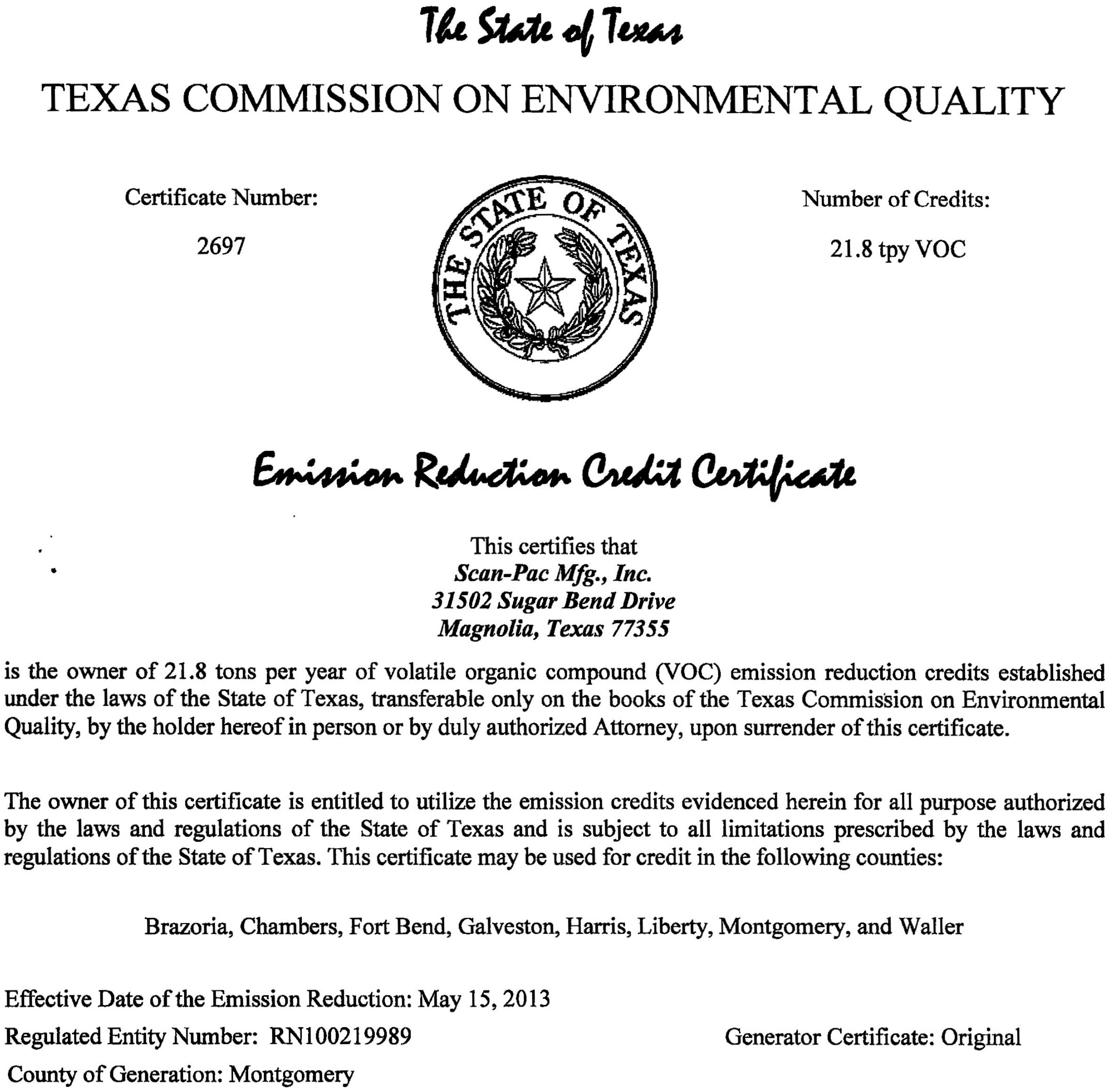
Appendix Table 1—Offset Prices Versus Engineering Estimates of Marginal Abatement Costs, by Market

	NO_x (1)	VOCs (2)
Arizona (Phoenix-Mesa)	—	—
California (Imperial County)	0.14	—
California (Los Angeles-South Coast)	0.05	4.96
California (San Francisco Bay Area)	1.04	12.77
California (San Joaquin Valley)	0.07	13.58
Connecticut (Greater Connecticut)	5.01	—
Connecticut (NY-NJ-Long Island)	1.32	—
District of Columbia (DC-MD-VA)	1.26	2.91
Illinois (Chicago-Naperville, IL-IN-WI)	1.01	2.58
Indiana (Chicago-Naperville, IL-IN-WI)	1.30	3.29
Maryland (Baltimore)	0.76	19.47
Maryland (Washington, DC-MD-VA)	1.26	2.91
Missouri (St. Louis-St. Charles-Farmington, MO-IL)	—	33.02
New Jersey (NY-NJ-CT-Long Island)	0.90	14.62
New Jersey (Philadelphia-Wilmington-Atlantic City PA-NJ-MD-DE)	1.79	9.18
New York (NY-NJ-CT-Long Island)	1.37	21.16
Ohio (Cleveland-Akron-Lorain)	1.71	12.54
Pennsylvania (Philadelphia-Wilmington-Atlantic City PA-NJ-MD-DE	1.04	8.22
Pennsylvania (Pittsburgh-Beaver Valley)	5.60	47.60
Texas (Houston-Galveston-Brazoria)	0.05	0.63
Virginia (Washington DC-MD-VA)	1.34	3.09
Wyoming (Upper Green River Basin)	0.52	—

Notes: The left-most column lists the state that the data represent then, in parentheses, the market. The numbers in the table represent the ratio of offset prices to the engineering estimates of abatement in each market, averaged over the years 2010-2019. Engineering estimates come from the EPA's Control Strategy Tool (CoST), which we apply using EPA's National Emissions Inventory for point sources for years 2011, 2014, and 2017. Table entries refer to quantity-weighted mean offset prices and estimated per-short ton abatement costs. All currency are in 2017$, deflated using the GDP deflator.

Appendix Figure 1—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.

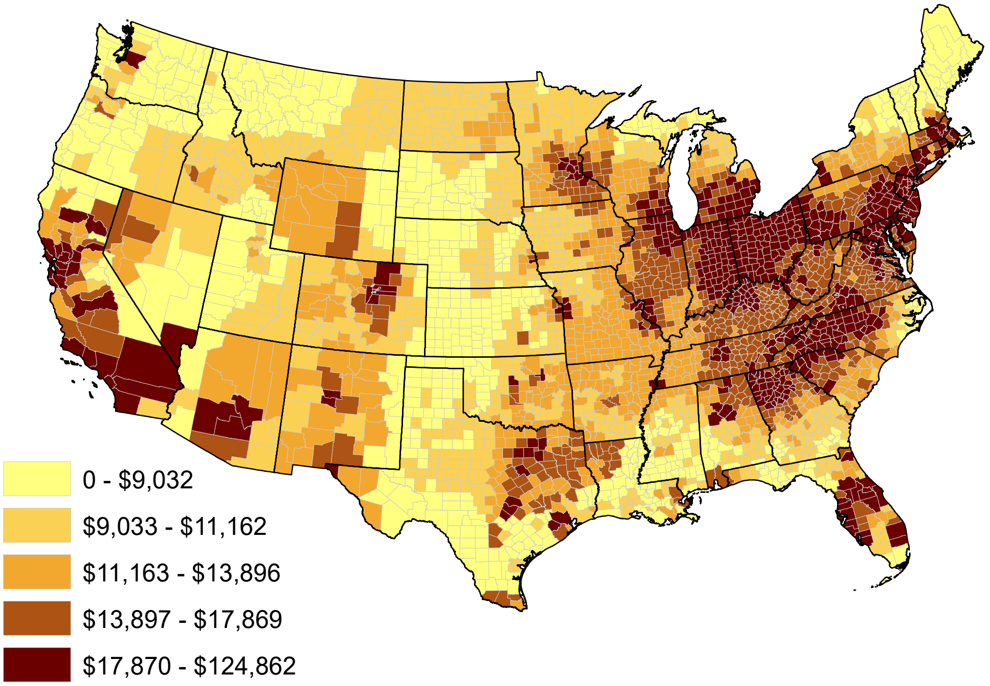
The owner of this certificate is entitled to utilize the emission credits evidenced herein for all purpose authorized by the laws and regulations of the State of Texas and is subject to all limitations prescribed by the laws and regulations of the State of Texas. This certificate may be used for credit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

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

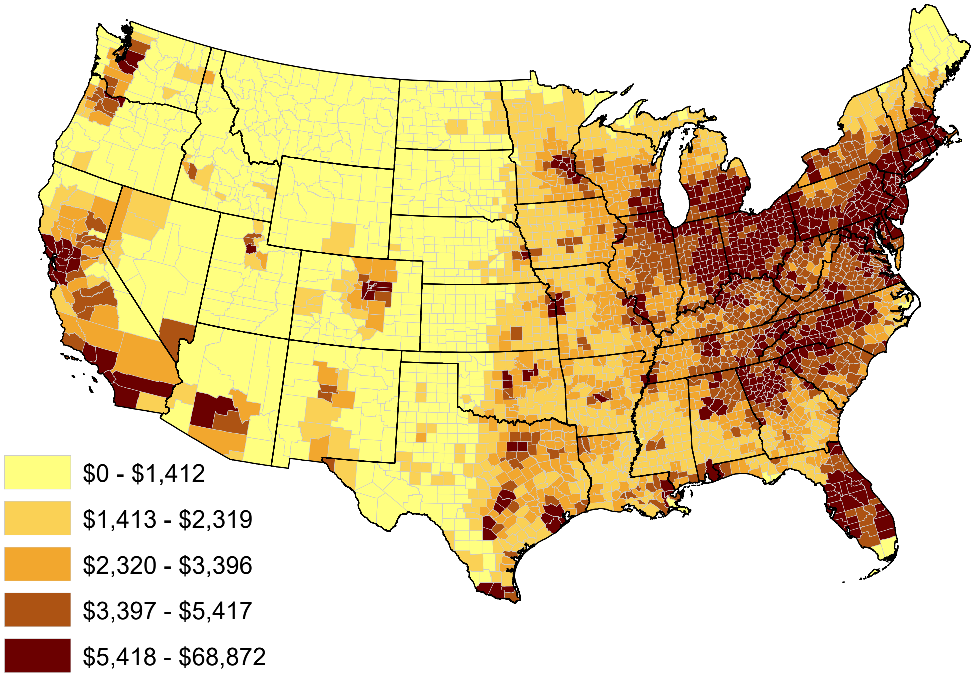
Effective Date of the Emission Reduction: May 15, 2013
Regulated Entity Number: RN100219989
Generator Certificate: Original
County of Generation: Montgomery

Appendix Figure 2—Marginal Benefits of Pollution Abatement, by Pollutant and County

(A) Nitrogen oxides (NO_x)

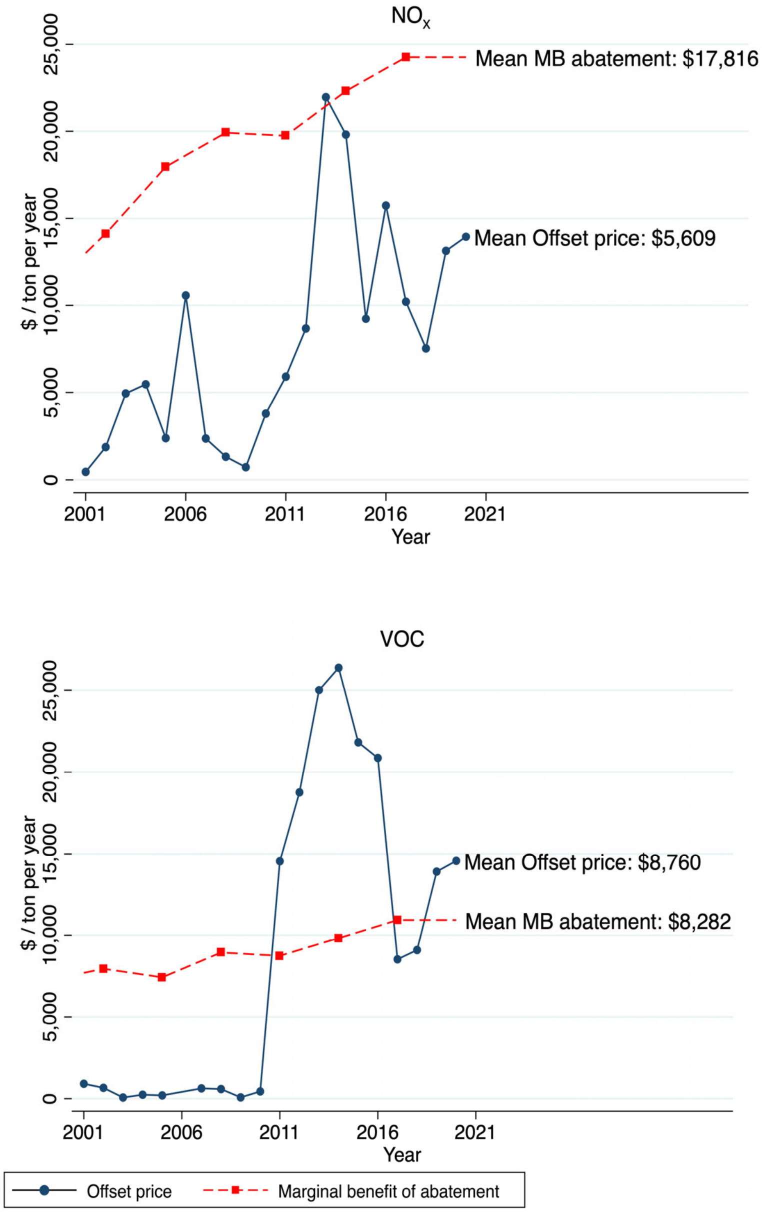


(B) Volatile organic compounds (VOCs)



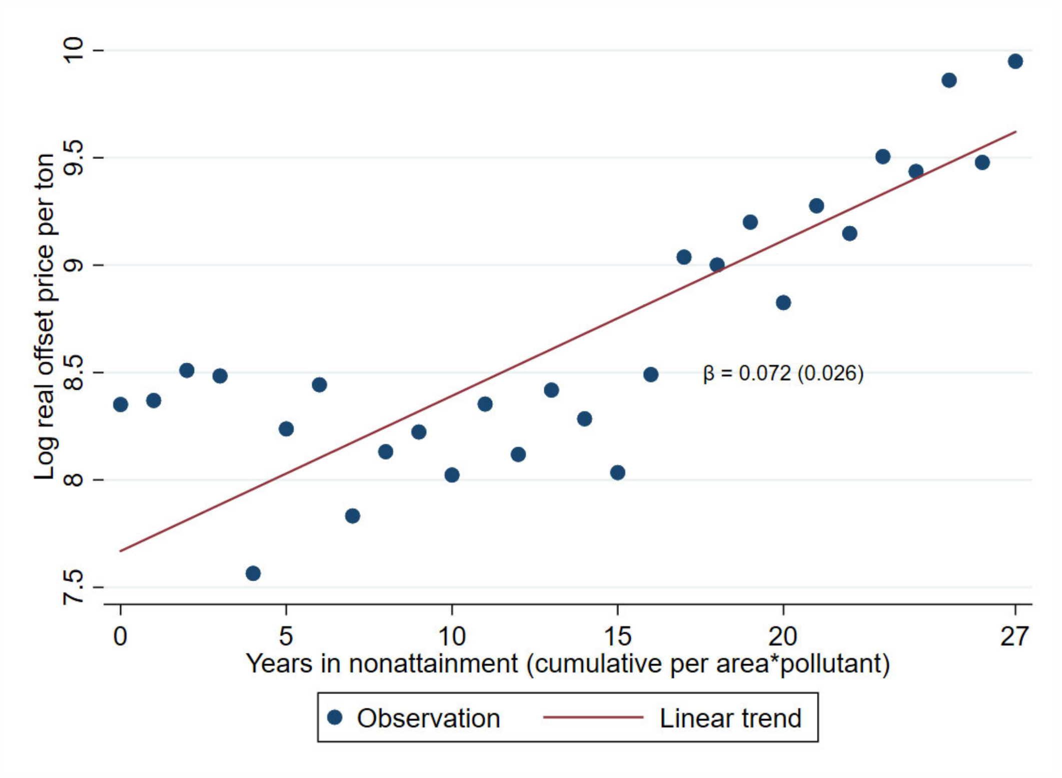
Note: Data shows the average marginal benefits over the years 2011, 2014 and 2017. Marginal benefits of abatement are the marginal external cost avoided per ton abated for the indicated nonattainment area and pollutant, as estimated by the AP3 model. Dollars are deflated to real 2017 values using the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

Appendix Figure 3—Pollution Offset Prices Versus Marginal Benefits of Abatement in Houston-Galveston-Brazoria, Texas



Notes: This figure graphs pollution offset prices and the marginal benefits of pollution abatement by year for the markets in Houston-Galveston-Brazoria, Texas. Blue solid line 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 the obsered 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 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 population in 2010 Census. All currency are in 2017$, deflated by Federal Reserve's US GDP deflator.

Appendix Figure 4—Offset Prices, by Years in Nonattainment



Note: This figure shows the relationship between offset prices and the time that an air region has been designated as nonattainment. Each dot represents the mean for all transactions occuring in areas that have been in nonattainment for the cumulative number of years indicated on the x-axis. Y-axis shows the real offset price per short ton. The figure averages across nonattainment areas, pollutants, and years.