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IS AIR POLLUTION REGULATION TOO STRINGENT?

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ABSTRACT

This paper describes a framework to estimate the marginal cost of air pollution regulation, then applies it to assess whether a large set of existing U.S. air pollution regulations have marginal costs exceeding their marginal benefits. The approach utilizes an important yet under-explored provision of the Clean Air Act requiring new or expanding plants to pay incumbents in the same or neighboring counties to reduce their pollution emissions. These “offset” regulations create several hundred decentralized, local markets for pollution that differ by pollutant and location. We show that these markets cover much US economic activity, experience search frictions, have rising prices over time, and reflect local regulatory stringency. We provide empirical and theoretical evidence consistent with the idea that offset transaction prices are close to the marginal cost of pollution abatement, and we compare offset prices to estimates of the marginal benefit of abatement from leading air quality models. We find that for most regions and pollutants, the marginal benefits of pollution abatement exceed mean offset prices more than ten-fold. In at least one market, however, estimated marginal benefits are below offset prices.

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A classic idea in economics is that firms may provide too much of an externality 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.

Political debates have questioned the optimal stringency of air pollution regulation. Two law professors, for example, summarized, “[The Environmental Protection Agency’s (EPA’s)] ozone standard is insufficiently stringent, not overly expensive” (Livermore and Revesz 2015). 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).

Economic analyses have also debated the net benefits of regulating ground-level ozone pollution, which is a focus of this paper. In revisions of its own regulations for ozone air pollution, for example, the US EPA has estimated that the benefit/cost ratio of tightening standards is between 0.2 and 2.2; other federal and academic analyses obtain similarly wide ranges (OMB 1998, 2009; Lange et al. 2018).

In part to help reconcile these disparate views, this paper develops a framework to estimate the marginal cost of pollution abatement separately by pollutant, county, and year. We utilize an important yet under-explored provision of the Clean Air Act that forbids increases in pollution emissions from large industrial sources in 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 nonattainment 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. 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. Our data cover over 80 markets, including the seven largest metro areas of the country, and representing about 60 percent of economic activity from U.S. offset trading areas.

We begin with several stylized facts on offset markets, which establish the structure of these important environmental markets and also clarify the relationship between offset prices and marginal abatement costs. We show that offset markets cover areas with about 60 percent of the US population, GDP, or manufacturing employment, representing 180 million people or \$11 trillion in GDP. Dispersion of offset prices within a market×year, and the prevalence of brokers and comments from market participants, suggest the presence of search frictions. Offset prices are rapidly rising in real terms. Finally, we compare offset prices against four well-known environmental aggregates: pollution abatement costs reported in the Census Bureau's Pollution Abatement Costs and Expenditures (PACE) survey; pollution emissions reported in the National Emissions Inventory; local economic activity in polluting industries; and the severity of Clean Air Act nonattainment designations. We also compare offset prices to engineering estimates of abatement costs from software the EPA has used. Most of these comparisons are consistent with an interpretation of offset prices as representing marginal abatement costs, although we find the greatest differences between offset prices and the engineering software, and suggestive evidence that the engineering estimates have some unreliable predictions.

Guided by these empirical patterns, we describe a theoretical interpretation of what offset prices represent. We work with two distinct frameworks, which impose different assumptions, though both end up concluding that offset prices are close to marginal abatement costs. The first framework, a neoclassical description of offset markets as a close variant of cap-and-trade markets, assumes thick markets and abstracts from imperfect competition and offset price dispersion. In this interpretation, offset prices equal marginal abatement costs. This reflects canonical views of environmental markets dating back to Dales (1968) and Crocker (1966) and formalized by Montgomery (1972), which suggest that emissions market prices reveal the marginal abatement costs of regulation.

We focus more on a second theoretical interpretation, which describes offset markets as a procurement auction in which a buyer procures bids for a particular type of offset and buys from the lowest-price bidder. The auction interpretation accommodates market power, search frictions, and offset price dispersion, though in some ways requires stronger assumptions than the price theoretic model. Using standard empirical auction tools, we recover an estimate of the marginal abatement cost curve for each market. We compare marginal abatement cost curves to the distributions of offset prices.

Finally, we use the relationship between offset prices and marginal abatement costs to construct an empirical test of policy efficiency. In markets where offset prices exceed the marginal benefits of abatement, we conclude that regulation is more stringent than efficiency would require. This reflects the definition of efficient environmental policy as equating the marginal costs to the marginal benefits of pollution abatement to society; the marginal benefits of abatement include health and other benefits from emissions reductions. In markets where the marginal benefits of abatement exceed mean offset prices, regulation is more lenient than efficiency would require.

Comparing offset prices with the marginal benefits of abatement indicates that for most pollutants and markets where we have data, regulation 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 ten times mean offset prices. We find similarly large ratios in each region of the country, in most individual markets, for one important other pollutant with more limited data availability (particulate matter), and in numerous sensitivity analyses. In the Houston market, however, the marginal benefits of abating VOCs are only about half of mean offset prices.

In part because these offset markets are not well known in the economics literature, our approach reflects extensive interviews with market participants. These conversations included regulators at the Environmental Protection Agency, California Air Resources Board, and local air districts; with the most active current intermediaries (brokers and traders) we could identify in several states and markets; and with environmental managers at firms that have sold and purchased offsets.[1]

This research builds on several literatures. This paper provides the first comprehensive empirical analysis of U.S. air pollution offset markets. Research on the Clean Air Act and nonattainment designations has had a large influence in environmental economics.[2] Given the central role of these markets in that Act, it is noteworthy that these offset markets have not been a focus of empirical research. Among market-based environmental policies, economists once described Clean Air Act offsets and related policies as "by far the most important of these programs in terms of scope and impact," (Cropper and Oates 1992), but the limited existing research mentioning offset markets mostly describes legal or policy details (Dudek and Palmisano 1988; 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.

We also provide a framework to estimate the marginal costs of air pollution abatement for

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[1] We found some of these contacts through multiple attempts to contact every firm employee or intermediary involved in purchasing an offset between 2018 and 2020 in Houston, which is one market where governments report contact information for market participants, and where we ended up interviewing participants involved in a third of transactions over the period 2018-2020, though in total our conversations included participants in many markets.

[2] A sampling of papers measuring Clean Air Act benefits includes Henderson (1996); Chay et al. (2003); Chay and Greenstone (2003, 2005); Isen et al. (2017); and Isen et al. (2017). A short list of other papers measuring total costs, though not marginal abatement costs, includes Becker and Henderson (2000); Greenstone (2002); Keller and Levinson (2002); List et al. (2003); Hanna (2010); Greenstone et al. (2012); Walker (2013).

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 straightforward to implement.[3] This focus is especially useful given that economic research has focused more on measuring the marginal benefits than the marginal costs of air pollution policy.[4] We also contribute to an emerging literature attempting to empirically quantify how regulatory stringency has evolved over time. 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). Our ability to track permit prices over time provides a useful and transparent way to consider trends in marginal abatement costs both nationally and market-by-market.

Before proceeding, a few clarifications may be useful. One natural question is how the existence of other environmental regulations affects our interpretation. While other environmental policies 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.[5]

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. 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 provide information about the marginal costs for the entire population of plants and not merely for those plants which choose to trade offsets.[6] In total we analyze thousands of transactions, across 9 to 25 years per market, the two most common criteria pollutants, and covering over 80 offset markets. These markets include the seven largest U.S. metro areas (New York, Los Angeles, Chicago, Dallas, Philadelphia, Houston, and

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[3] Our approach directly measures transactions in markets for pollution that report costs, while other approaches rely on engineering data or reported costs. 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 studies 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).

[4] For example, 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 the cost studies focused settings such as sulfur dioxide emissions from coal-fired power plants or vehicle environmental inspections in developing countries (see Appendix B for details).

[5] Appendix E.1 discusses other NO_x and VOC regulations operating in some areas we study.

[6] 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.

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 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 stylized facts on offset markets and their empirical relationship to regulatory stringency. Section 4 provides a theoretical interpretation of offset markets and applies the model quantitatively. Section 5 compares offset prices to the marginal benefits of abatement. Section 6 concludes.

1 History & Design of US Air 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).[7] Appendix C describes differences between offset and cap-and-trade market designs.

1.1 History of Offset Markets

The 1970 Clean Air Act Amendments directed the EPA to set National Ambient Air Quality Standards for ground-level ozone, particulate matter, and four other "criteria" air pollutants. The EPA operates air quality monitors in many US counties. If readings from a monitor violate these standards, the county is declared to be in "nonattainment," and polluting firms face stricter regulation.

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

While formally the EPA may not consider costs, political factors including costs may have some bearing on revising air quality standards. Each presidential administration can delay implementation of new standards, choose exact standards among several that the scientific committee proposes,

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[7] 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."

affect composition or deliberation of the scientific committee, and in other ways affect the choice of standards. Additionally, although the EPA does not directly consider costs in designing standards, it does publish detailed reports comparing costs and benefits of each reform (e.g., USEPA 2012), which are widely discussed in academic and public spheres.

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

The two main subsequent amendments to the Clean Air Act, in 1977 and 1990, changed the scope of offset markets. Since the 1970 Amendments, large polluting plants that are opening or undertaking significant modifications in nonattainment areas have been subject to New Source Review, a policy which requires that firms meet certain environmental requirements.[8] New Source Review prohibited net increases in pollution emissions from stationary sources in nonattainment areas. The EPA initially forbid increases in pollution emissions from any large sources in these areas, which essentially prevented large polluting plants from opening in cities in the early 1970s. Critics argued that this requirement was inhibiting economic development. In response, a 1976 EPA policy and the 1977 Clean Air Act Amendments allowed large polluting firms to enter nonattainment areas if their increase in pollution emissions was offset by decreases in emissions of the same pollutants from incumbent sources in the same areas. This reform created offset markets, which we describe in detail below.[9]

The 1990 Clean Air Act Amendments made two important changes. One was directing the EPA to set air quality standards for several types of nonattainment (called marginal, moderate, serious, severe, and extreme), and to impose stricter regulations on the higher types of nonattainment. These types of nonattainment affect trading ratios and coverage of offset markets.

The 1990 Clean Air Act Amendments also liberalized offset markets more broadly. 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

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[8] 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.

[9] 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).

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.

1.2 Design of Offset Markets

An incumbent in a nonattainment area 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. In some decentralized markets, brokers primarily serve the purpose of searching for lower prices. Environmental managers and selling and buying firms who we interviewed indicated this motivation is relevant for offsets—each broker maintains networks of potential sellers and buyers and has readily available information on potential prices and quantities, including for offsets in the process of being generated or that could be generated in the future. Some described additional motivations for using brokers. One benefit of brokers is confidentiality. Because transactions including buyer and seller names are a public record in some states, a company that trades offsets without a broker is publicly signaling its expansion or contraction plans, which may reveal sensitive business information to national and international competitors. Another benefit of brokers is expertise in managing regulators and contracts.

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." To quantify the abatement from a technology, firms provide detailed documentation that can include photos and serial numbers of each installed equipment, detailed blueprints and design specifications, certification from engineers, and emissions testing. Unlike the general estimates of pollution control in engineering cost estimates that regulators typically use and we analyze later, estimates for offsets are extremely specific to the individual firm and equipment. 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.[10]

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 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.[11] In December 2013, Scan-Pac sold this offset to an oil and gas processing and transportation firm, Enterprise Products, for \$3.6 million (=\$165,000 per ton).[12] Enterprise used the offsets to build a \$1.1 billion Houston-area facility that produces propylene, a common petrochemical, in the Houston area.

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

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[10] 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 trade off profits and pollution, and it is a source of abatement in cap-and-trade markets, pollution taxes, and other market-based environmental instruments. The theory we describe accommodates this type of abatement and shows how it still allows offsets to provide information on marginal abatement costs.

[11] 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.

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

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 is ambiguous on the importance of market power. In a typical snapshot where we have data from Houston and Los Angeles, for June 2014, both regions show large numbers of firms who could generate offsets. This ranges from a minimum of 274 firms in Houston-NO_x markets to a maximum of 828 firms in South Coast, CA. The number of firms with certified offsets available for sale ranges from 15 in Houston-NO_x to 218 in South Coast-VOCs. At the same time, as Section 4.1 discusses, most offset buyers receive only a few bids from potential sellers. In the presence of markups, incumbents would charge offset prices above their marginal abatement costs. This would strengthen our paper's main finding—it would imply that the ratio of the marginal abatement costs to the marginal benefits of abatement is even smaller than we estimate, and so would suggest that regulation is even more lenient than is efficient.

2 Data

This section describes key data; Appendix D 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.[13] 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

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

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 D.1 provides additional details).

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.[14] 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.[15]

What are the underlying economics which make permanent offsets sell at a price which is nearly ten times higher than temporary offsets? Firms should value the right to emit pollution in many years rather than just one year. Also, firms may discount future emissions rights according to their cost of capital or other prevailing discount rate. Firms may have expectations about future offset prices. Finally, offsets are a risky asset if the area where the firm is located exits nonattainment, then the firm no longer needs to hold or purchase offsets, and any offsets the firm holds lose their value. If one interpreted the ratio of permanent to temporary offsets as reflecting firms' discount rates, it would imply a discount rate of 8 to 10 percent, though the discount rate interpretation is not needed to apply the ratio of permanent to temporary offset prices (Appendix D.5). While

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[14] 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.

[15] 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.

8 to 10 percent is a on the high side of firm discount rates for many economic settings, it partly reflects the high volatility and risk of offset prices, including the possibility that if an area exits nonattainment, offset prices fall to zero.

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 models.[16] 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 D.3.2); 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 (2010b)'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 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 approx-

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

imate 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 used in AP3 (Smith and Huang 1995; Chay and Greenstone 2005; Bajari et al. 2012; Holland et al. 2020b). While there is uncertainty in each estimate from the literature, this suggests that AP3 does not dramatically understate the marginal benefits of pollution abatement relative to prevailing direct estimates of marginal willingness to pay for air quality.

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

A related issue is the question of how to quantify the benefits of policies that target one pollutant but affect others ("co-pollutants") (Aldy et al. 2020). The air quality models we use account for ways in which each emitted pollutant affects ambient concentrations of other pollutants (e.g., how NO_x emissions affect ambient $PM_{2.5}$). 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 Additional Data

Section 3.4 uses other datasets to characterize how offset prices relate to other direct or indirect measures of marginal abatement costs. We use various administrative survey datasets from the

U.S. Census Bureau on establishment-level inputs and outputs. We use data from the Census of Manufactures (CM), available in years ending in 2 and 7, and the Annual Survey of Manufactures (ASM), available in other years, to collect establishment-level information on the value of shipments and value added (equal to value of shipments minus materials and energy) for a large set of manufacturing establishments. We combine these data with other survey datasets to construct indirect measures of establishment pollution abatement costs. For example, we combine the 2005 ASM with the 2005 Pollution Abatement Costs and Expenditure Survey (PACE). PACE is the most comprehensive national source of pollution abatement costs for U.S. manufacturing. The Census Bureau last collected PACE in 2005, then discontinued it for budgetary reasons. We focus on the 2005 PACE only because it differs substantially from the 1999 or earlier PACE data, "making direct comparisons for most data items essentially meaningless" (EPA, 2005). We merge the 2005 PACE to the 2005 ASM using a unique establishment identifier. We then construct eight different abatement measures, which divide abatement investments, abatement capital stock, abatement operating costs, or sums of capital and operating costs, by an establishment's value added or value of shipments.

Additionally, we measure pollution emission rates (i.e., emissions per unit of output or emissions per unit of value added) by linking the EPA's National Emissions Inventory (NEI) to administrative micro data from the 2012 Census of Manufactures. The NEI reports emissions of criteria air pollutants for all stationary sources. Since the NEI and the Census of Manufactures have no establishment-level links, we aggregate each dataset to a county×6-digit North American Industry Classification System (NAICS) industry, then merge them. We link the 2011 NEI to the 2012 Census of Manufactures to maintain the larger sample size of a census rather than the 2011 ASM survey.

We also obtain engineering (i.e., accounting) estimates of marginal abatement costs using regulatory software from the EPA called the Control Strategy Tool (CoST; Appendix D.4 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 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 Describing Offset Markets

This section uses our data to describe stylized facts on offset markets, with two goals. First, offsets are important and little-studied environmental markets, so quantitatively describing their characteristics clarifies the structure of important US market-based environmental policies. Second, these empirical patterns provide some insight on the relationship between offset prices and marginal abatement costs, which guides later parts of the paper. The picture of offset markets that emerges from this section is that these markets are prevalent, have search frictions, have rising prices over time, and provide information about marginal abatement costs.

3.1 Offset Market Coverage

Table 1 describes US air pollution offset markets overall and the set of markets in our data. Panel A shows that the U.S. has several hundred offset markets that together cover areas with 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). Our analysis of offset markets represents a far larger number of distinct environmental markets than has been previously studied. 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. Economic efficiency of regulations addressing externalities requires equating marginal benefits and marginal costs of abatement by location. By analyzing many markets simultaneously, we are able to have a more comprehensive picture of 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 been part of a nonattainment area at any time over the period 2010 to 2019. Panel A of Figure 1 describes markets for NO_x and VOCs, corresponding to nonattainment for ground-level ozone.[17] 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 and sulfur oxides; the coverage is similar as for ozone. Appendix D.2 describes other measures of offset market size and importance.

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[17] 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.

3.2 Offset Price Dispersion and Search Frictions

A few pieces of evidence suggest that search frictions are an important feature of offset markets, a feature which guides the models Section 4 analyzes. Price dispersion provides one indication of search costs or frictions in these markets. After residualizing prices by district×pollutant and quantity, the 90-10 log price difference in offset prices is 2.02. For comparison, in one well-known study of prescription medications, the 90-10 log difference is 1.64 (Sorensen 2000). Research on markets with search costs more often report the coefficient of variation (standard deviation divided by mean). This is large in our setting since offset prices (raw or residualized) are approximately lognormally distributed. The average offset market×year has a coefficient of variation of 1.04. For comparison, other studies of specific markets report a coefficient of variation for prices of 0.19 to 0.25 (retail wine), 0.20 to 0.24 (waste hauling), and 0.22 (prescription medication) (Sorensen 2000; Jaeger and Storchmann 2011; Salz 2022). The average market×year in our data has a coefficient of variation of log prices of 0.101.

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

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

3.3 Trends in Offset Prices

Offset markets have evolved over time, and this section describes their trends. To the extent that offset markets provide information on marginal abatement costs, these trends provide information about the evolution of regulatory stringency. Table 5 uses versions of the following statistical model to estimate annual trends in mean offset prices:

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

Here O represents the ton-weighted mean log offset price for market m, pollutant p, and year y. We regress this measure of offset prices 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.

Table 5 presents estimates of the parameter β from this model. Panel A pools across pollutants and markets. These results suggest that mean offset prices are increasing by 5 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 5 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 5 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).

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.

3.4 Offset Prices Versus Environmental Aggregates

In part because the offset price data are new to research, we now relate them to well-established environmental data on county-level nonattainment, abatement expenditures, emission levels, polluting industrial activity, and engineering estimates. Appendix F discusses methodologies in detail. Prior research has interpreted many of these other variables in terms of the cost of abating pollution (Greenstone 2002; Becker 2005; Shapiro and Walker 2018), so these comparisons also provide empirical evidence consistent with the idea that mean offset prices behave as standard models would predict marginal abatement costs to behave.

We first compare offset prices to rates of industrial spending on pollution abatement, as reported by administrative versions of the Census Bureau's Pollution Abatement Control and Expenditures Survey. In standard models, stricter environmental regulation leads firms to spend more on abatement. We assess the extent to which offset prices follow this pattern.

Appendix Table 5 shows large and statistically significant positive relationships between offset prices and abatement expenditures. This is consistent with offset prices capturing information about the stringency of regulation. Row (1), column (1), implies that for plants that emit NO_x, a 1 percent increase in abatement operating expenditures per dollar of output is associated with a 1.79 percent increase in the NO_x offset price. Row (2) finds a larger elasticity of 3.48 when examining pollution abatement operating expenditures divided by value added. In general, most estimates are positive and statistically significant, though the magnitudes differ depending on the pollutant or independent variable in the regression.

Second, we compare offset prices to emissions. In standard models, stricter environmental regulation leads firms to emit less pollution, at least in part due to increased abatement spending. We assess the extent to which offset prices follow these patterns, using data from the EPA's National Emissions Inventory on the tons of pollution emitted per dollar or revenue or dollar of value added. These ratios are sometimes referred to as emissions intensity.

Appendix Table 6 suggests that regions with lower emissions intensity are also regions that have higher offset prices. For example, column (1) of Panel A implies that a ten percent increase in the emissions intensity of NO_x emitting establishments is associated with a 1.69 percent reduction in the NO_x offset price. These elasticities are similar across pollutants and when looking at emissions per unit of output or emissions per unit of value added, with an elasticity between 0.13 and 0.15.

Third, we compare offset prices to polluting economic activity. In standard models, growing demand for offsets siphons off the "low-hanging fruit" for abatement, and so offset prices rise as remaining abatement opportunities become more costly. Offset market participants in our interviews often noted this phenomenon. For example, lower natural gas prices due to hydraulic fracturing (fracking) increased demand for petrochemicals production in Houston, raising offset prices.

Panel A of Appendix Table 7 finds that offset prices are fairly elastic with respect to changes in local value added. Column (1) shows that a 10 percent increase in value added from NO_x emitting facilities is associated with a 13 percent increase in mean NO_x offset prices within an air district, or an elasticity of 1.3. Column (2) finds a slightly larger though imprecisely estimated elasticity for VOCs. Column (3) pools over pollutants and shows that the average long-run elasticity is in the range of 1.4. Panel B explores the relationship between the offset prices and output, or the total value of shipments. In contrast, the relationships between offset prices and output are a bit weaker and statistically insignificant, compared to estimates using industry value added.

Fourth, we compare offset prices against the stringency of nonattainment designations. Appendix Table 8 finds that more stringent nonattainment classifications have higher offset prices. This again suggests that offset prices provide information on regulatory stringency. Column (1) shows that counties in moderate nonattainment have 15 percent higher offset prices than counties in marginal nonattainment, though this difference is not statistically significant at conventional levels.[18] Offset prices increase monotonically with nonattainment stringency. Offset transactions in extreme nonattainment areas sell for nearly five times higher prices per ton than offsets in marginal nonattainment areas. Columns (2) through (4) obtain similar results from adding fixed effects for years, pollutants, or pollutant×year combinations.

Finally, we compare offset prices to engineering estimates of marginal costs from the EPA's own model and data. In principle, the EPA's Control Strategy Tool (CoST) provides estimates of actual marginal abatement costs for every facility in every air district. Table 6 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

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[18] This is calculated by exponentiating the regression coefficient $e^{0.142} - 1$.

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 6 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. For VOCs in columns (3) and (4), the opposite is true—engineering estimates are around six times larger than offset prices.

These differences 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 2 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. Given this graph pools data over the period 2010-2019, one should not interpret the solid blue line as the offset supply curve at a given moment in time, but rather simply characterizing the ordered distribution of offset prices. This figure shows large differences between offset prices and engineering estimates. For NO_x in Los Angeles, for example, Figure 2 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. In Houston, the engineering software predicts a distribution of prices under \$2,000, but actual offset prices exceed \$2,000 per ton.

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. Appendix I discusses reasons why engineering estimates and offset prices may differ so much; one likely explanation involves inaccurate input data for the engineering model.

4 Theory: What Do Offset Prices Represent?

In classic models of pollution markets, many competitive firms buy and sell pollution allowances at a single market-clearing price (Baumol and Oates 1988; Muller and Mendelsohn 2009), and some models incorporate a price wedge between sellers and buyers (Stavins 1995; Montero 1997). Appendix G adapts such models to our setting. Such standard frameworks provide a simple and useful interpretation—the market-clearing offset price equals the marginal abatement cost of both incumbents and entrants.

Some features of offset markets, however, differ from such standard models. Some offset markets are thin and have various forms of search costs, which can contribute to market power and price dispersion. To provide an interpretation of offset prices consistent with these features, and to clarify the relationship of offset prices to marginal abatement costs in the presence of these features, this section describes offset markets as a series of procurement auctions.[19]

While the simplicity of the price theory model from Appendix G is valuable, this model has a few appealing features. It provides a reasonable description of our setting, where a polluting industrial plant enters a regulated market and must purchase offsets to cover their emissions, and an incumbent in a market sells offsets to maximize profits. It also accommodates several types of frictions, including price dispersion within a market×year. Additionally, applying standard auction methods to this model can estimate the distribution of marginal abatement costs for incumbents in each market. Finally, this model echoes comments that market participants expressed in our interviews—offset buyers appear periodically; receive a certain number of bids, which is typically smaller than the number of firms on the offset registry; and buy from the lowest price bid. While any model abstracts from some features of reality, we believe this setting captures several important features of offset transactions and provides a useful, quantitative approach to consider how offset prices relate to marginal abatement costs. Appendix G.3 compares the price theory and auction models.

A few notes are worth highlighting. We estimate marginal abatement costs of incumbents, not entrants. This is tractable and also follows common practice in regulatory impact assessment, which focuses on compliance costs for existing firms. We observe offset prices, which we interpret as winning bids in the procurement auction, but lack information on non-winning bids. We have limited information on the number of price offers each entrant receives, though use summary information we gleaned from interviews with market participants. We use the data and limited information on number of participants in auctions to estimate the distribution of winning bids, and then the distribution of all bids.

Two additional details are relevant. First, we pool auctions for different amounts across years and markets, and therefore partial out auction-specific characteristics from the price data; Appendix H provides details. Second, estimated bids and valuations depend on the number of firms bidding in each auction. In our setting, this represents the number of price quotes each buyer receives. Our data do not report this number, so we use outside information on it. The Houston offset registry provides contact information for firms involved in offset transactions. In addition to interviewing other market participants we had found through various means, we contacted every firm or broker listed as participating in purchasing offsets between the years 2018 and 2020 in Houston by phone and email. Most were unresponsive, but we did receive descriptions of the number of bidders covering a third of transactions in this period in Houston. The descriptions did not list the number of bidders for individual transactions, but instead summarized groups of transactions of which respondents had direct knowledge.

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[19] In a procurement auction, a party purchases a good or service from the lowest bidder, whereas in a standard auction, a party sells a good or service to the highest bidder.

While we heard that different transactions can obtain a range of different numbers of price quotes, respondents indicated that three is a typical number of bids. One of the most active brokers in several states described three bids as "the magic number," representing the mean and median number of bids across auctions. Some buyers target this number since they believe three quotes is sufficient to capture the majority of price dispersion, and some firms or government agencies formally require obtaining three bids on large contracts as a mandatory institutional policy. Another active broker indicated that three or four bids are typical, and five would be a "healthy number" (i.e., uncommon).[20]

Thus, our baseline results assume that all buyers receive three bids. We also report a sensitivity analysis assuming that all buyers receive four bids, and another assuming five bids. In addition, we report a sensitivity analysis assuming that 40 percent of auctions have three bids, 40 percent have four bids, and 20 percent have five bids (with the number of bidders drawn randomly from these probabilities for each individual auction). While lacking precise data on bids for each individual auction leads us to interpret results carefully, we discuss the range and sensitivity to these exact numbers.

We briefly summarize what this model indicates about the relationship of offset prices to marginal abatement costs and social welfare. The model highlights several ways in which offset prices may differ from marginal abatement costs. Since buyers obtain price quotes from a limited number of incumbent sellers, the firm selling an offset may add a markup which equals the difference between the sale price (equal to the seller's bid) and the seller's valuation (equal to its marginal abatement cost). This channel makes offset prices exceed marginal abatement costs. Additionally, the incumbents that actually sell offsets have lower bids and marginal abatement costs than the average firm in a market. This channel makes offset prices lower than the marginal abatement cost for typical firms in a market. Finally, the incumbent firms that offer to sell offsets are a subset of all firms in the market. This implies that offset prices may not equal the lowest abatement opportunity in a market (the market's marginal abatement cost).

4.1 Model and Estimation

An entering firm (buyer) purchases Q_t tons of offsets for a given market and pollutant at time t. The buyer obtains bids from N_t sellers (incumbent firms). A bid represents an offer by an incumbent to sell the entrant Q_t tons of offsets. The number of potential sellers may exceed N_t, but, due to search costs, only a subset bid. The entrant purchases offsets from the lowest bidder (the auction winner) at price P_t. That winning bid equals the offset price which we observe in data.

Firms differ in their costs, bidding behavior, and valuations of pollution offsets. The valuation of an entrant (an offset buyer) represents its willingness to pay for offsets. The valuation of an incumbent (an offset seller) represents the minimum amount the incumbent must be paid to

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[20] We heard a range of explanations for why calling every firm with a registered offset, or with substantial emissions in the regulated area, was not a typical strategy. Most explanations involved various types of search frictions.

abate pollution corresponding to the offsets, i.e., the valuation represents the incumbent's marginal abatement cost.[21]

We seek to estimate four empirical distributions, which we describe in order: bids of winners, bids of all firms, valuations of incumbent winners, and valuations of all incumbents.

We begin by describing the distribution of winning bids. A winning bid equals the lowest-price bid in an auction, and therefore also equals an offset price we observe in data. Let G denote the cumulative distribution function (CDF) of all bids and g the corresponding density. Let $G_{(1:K)}$ represent the CDF of the lowest order statistic of K draws from G.[22] Because the winning price P_t equals the lowest among N_t bids, the winning price has CDF and density

$$G_{(1:N_t)}(x) = 1 - (1 - G(x))^{N_t} \tag{1}$$

$$g_{(1:N_t)}(x) = N_t g(x)[1 - G(x)]^{N_t - 1} \tag{2}$$

Equations (1) and (2) describe our data on winning bids. Winning bids equal offset prices, but might not equal the market's marginal abatement cost, for two reasons. A winning bid represents the lowest offered price, but we would like to learn about all firms in a market, not only firms that ultimately sell offsets. Additionally, an incumbent firm selling offsets may bid more than its valuation in order to profit from the sale, so markups drive a wedge between valuations and bids. We address each issue in turn.

The second empirical distribution we recover is the distribution of all bids, not only winning bids. Rearranging (1) and (2) shows that the distribution G and density g of all bids are as follows:

$$G(x) = 1 - [1 - G_{(1:N)}(x)]^{\frac{1}{N}} \tag{3}$$

$$g(x) = \frac{g_{(1:N)}(x)}{N[1 - G(x)]^{N-1}} \tag{4}$$

This is helpful because we can estimate these distributions using maximum likelihood (Paarsch et al. 2006).[23]

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[21] An incumbent's valuation represents its marginal abatement cost because for each offset, incumbents may submit a bid that weakly exceeds its valuation of the offset. The definition of the valuation is that for any offer below this amount, the incumbent will not abate pollution. Thus, the valuation is a payment which makes an incumbent indifferent between emitting pollution or abating in exchange for payment. Hence, it represents the incumbent's marginal cost to abate pollution.

[22] For example, $G_{(1:3)}$ is the CDF of the lowest bid (the winning bid, representing the price at which the offset is sold) from a series of auctions that have three bids each.

[23] The log likelihood of observing price and number of offer pairs $\{P_t, N_t\}$ is, from (2),

$$\begin{aligned} l(\theta) &= \sum_t \log\left[g_{(1:N_t)}(P_t|\theta)\right] \\ &= \sum_t \log\left[g(P_t|\theta)\right] + (N_t - 1)\log\left[1 - G(P_t|\theta)\right] \end{aligned} \tag{5}$$

The previous steps describe bids of winners and all firms, which can differ from a firm's abatement cost due to a markup. Hence, we then turn to the third empirical distribution, which describes winners' valuations. A seller's valuation is the minimum price the incumbent seller must receive to sell the offset. This is naturally interpreted as the incumbent's marginal abatement cost. Because the abatement is occurring through a market that requires paperwork and consultants together with the physical pollution control investment, we consider it all together as part of abatement.[24] A firm's bid minus its markup equals its valuation. We use estimated distributions of bids, $\hat{G}$ and $\hat{g}$, to recover the distribution of valuations V_t for winners.

The incumbent providing the lowest price bid and thus winning auction t values the offsets as the following price per ton (Guerre et al. 2000):

$$V_t = P_t - \frac{1}{N_t - 1} \frac{1 - G(P_t)}{g(P_t)} \tag{6}$$

We obtain an estimate of the winner's valuation $\hat{V}_t$ by substituting in estimates $\hat{G}$ and $\hat{g}$ for the distributions G and g in equation (6). The incumbent's value for the offsets equals the transaction price P_t minus a markup. This markup differs slightly from conventional auctions because this is a procurement auction where bidders are sellers rather than buyers. We estimate the distribution of winners' values by estimating a kernel density over the estimates $\{\hat{V}_t\}$ obtained from equation (6). This differs from the valuations of all firms due to search costs (i.e., the lowest valuation incumbents do not bid in every auction) and because entrants buy from the lowest-price bidder.

The fourth and final empirical distribution we estimate describes valuations for all incumbents, not merely winners. Because we lack data on bids from firms that lose an auction, we estimate the distribution of bids for all firms in auctions, as follows. For each auction t, we draw N_t bids $(P_t^1, \ldots, P_t^{N_t})$ from the estimated distribution of all bids, $\hat{g}$, estimated using equation (4). For each auction, we use equation (6) to compute the valuation of each bidder, $V_t^1, \ldots, V_t^{N_t}$. Finally, we smooth these valuations by using a kernel to estimate the density of $\{V_t^1, \ldots, V_t^{N_t}\}$.

The next subsection applies this model quantitatively to estimate the entire distribution of valuations in a market, which equals the market's marginal abatement cost curve. This deals with each challenge the previous paragraph mentions. Equations (3) and (4) show how we deal with offsets representing winners and not all bidders. Equation (6) shows how we estimate valuations from bids. Estimating the full marginal abatement cost curve for a market lets us assess how close offset prices are to marginal abatement costs. It is also useful because optimal policy would equate marginal costs and marginal benefits of pollution abatement, so we can compare these estimates to outside information on marginal benefits of abatement to learn about efficiency.

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[24] Similarly, when firms buy and sell allowances in a cap and trade market, or submit bids to generate electricity in an auction run by a dispatch operator, those prices may reflect the cost of both the physical engineering and the staff required to manage the engineering and interact with the market.

4.2 Quantification: What Do Offset Prices Represent?

Figure 3 graphs the offset prices and valuations that we recover from applying this model empirically. Panels A and B show the probability density functions (PDFs) while Panels C and D show the cumulative distribution functions (CDFs). Panels A and C describe nitrogen oxides pollution (NO_x) while panels B and D describe volatile organic compounds (VOCs). In each graph, the solid blue line describes offset prices while the dashed red line describes valuations. All values are in thousands of 2017 dollars per short ton of pollution. These estimates pool all markets and years with offset-level price data, and residualize market×year fixed effects and offset quantity, as described in Appendix H. We interpret the distribution of valuations as the marginal abatement cost curve. Comparing the two lines within each graph provides some insight as to how offset prices differ from marginal abatement costs.

The densities in Figure 3, Panels A and B, show that offset prices have similar support as valuations, with most values between $10,000 and $40,000 per ton. Offset prices are more tightly distributed, with median and mode around $25,000. Valuations have a wider distribution, with slightly higher median and mode. These differences between the distributions of offset prices and valuations are informative. Valuations have more low values than offset prices. To a limited extent, this is due to markups—a firm's bid exceed its valuation. To a larger extent, this is due to search costs—the lowest-valuation firms do not bid in most auctions, so offset prices reflect higher-cost incumbents. Valuations also have more high values than offset prices. This is because each offset price equals the lowest bid in an auction, so high-cost incumbents are unlikely to win an auction. For example, Panel D shows that while about ten percent of firms have VOC valuations above $35,000, these firms almost never successfully sell offsets, so few offset prices exceed $35,000.

Table 2 provides summary statistics corresponding to these graphs. In these statistics, typical valuations and offset prices are close, and in most cases within 5 to 10 percent. The difference ranges from under 1 percent in one case to 17 percent in the highest case.

Valuations and offset prices are less close in the tails. The 10th percentile of valuations is 21 to 49 percent below the 10th percentile of offset prices. By contrast, the 90th percentile of valuations is 16 to 23 percent above the 90th percentile of offset prices. The wider distribution of valuations than of offset prices can be seen in Figure 3. As discussed above, it reflects a combination of search, markups, and offset prices representing the lowest bid provided to a buyer.

Because we have limited information on the number of price quotes each buyer receives, Appendix Table 1 shows how our calculations vary under alternative assumptions about this number. Columns (1) and (4) assume that every offset buyer obtains four price quotes (bids). Columns (2) and (5) assume each buyer receives five price quotes. Columns (3) and (6) assume that 40 percent of buyers receive 3 price quotes, 40 percent of buyers receive 4 price quotes, and 20 percent of buyers receive 5 price quotes.

Appendix Table 1 shows that when buyers receive 5 price quotes, or three to five price quotes, mean and median offset prices and valuations remain fairly close. Panels A and B show that the difference between the means and medians of these distributions is generally below 20 percent, and in the majority of estimates this difference is below 10 percent. As above, Panels C and D show that offset prices and valuations differ somewhat more, on average by 20 to 30 percent, in the tails of the distributions.

Overall, these estimates show that typical offset prices are generally within 10 to 20 percent of valuations, or marginal abatement costs. Because valuations have similar mean but larger variance than offset prices, comparisons of offset prices to valuations out in the tails (e.g., at the 10th or 90th percentiles of the distributions) differ by up to 20 to 30 percent.

What does this tell us about what offset prices represent? Although we have a range of estimates, the relative proximity of mean offset prices and valuations in most cases provides some indication that mean offset prices are reasonably close to marginal abatement costs. As in many auction settings, having several bids (price quotes) is sufficient to limit the size of markups. While search costs can make the tails of offset prices and valuations somewhat different, the central tendencies are more similar.

5 Efficiency: Comparing Offset Prices to Marginal Benefits of Abatement

Table 3 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 marginal abatement costs, row 1 would be interpreted as the ratio of marginal benefits to marginal costs of pollution abatement. Appendix Tables 2 and 3 present estimates using the maximum offset price and median offset price within a district, respectively.

Table 3 shows that national mean marginal benefits of abatement substantially exceed offset prices. This provides our main finding that air pollution regulation in most of these markets is less stringent than is efficient. This conclusion is statistically precise at greater than 99 percent confidence for most pollutants and regions. On average for NO_x, mean marginal benefits of abatement are $43,000 to $52,000, depending whether the average is weighted by tons of pollution or population. Mean offset prices, however, are $1,100 to $4,300. Thus, the ratio of mean marginal benefits of abatement to mean offset prices is 12 to 38. Of course, this is far above a ratio of one. Similarly, for VOCs, we obtain a ratio of 9 to 29.

To interpret these ratios concretely, 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 $1,100 to $4,300 per ton for cleaning up pollution. At the same time, by decreasing emissions, the firm would be creating $42,000 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 3, 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. Markups would imply that marginal abatement costs are below offset prices and that the ratio of the marginal benefits of abatement to offset prices is even smaller than we estimate, which would suggest that regulation is even more lenient than is efficient. For NO_x in the Northeast, for example, the marginal benefits of abatement are approximately $44,000, but mean offset prices are only about $600. The ratios are modestly lower in the West, at 4.6 to 8.6. The ratios are the lowest in the South, at 2.3 to 19.

Figure 4 plots mean 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 3 essentially shows the mean value of these lines in the period 2010-2019, while these graphs show the underlying year-by-year averages, for all years.

A glance at the lines in Figure 4 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 4 are similar to the mean values over the entire last decade from Table 3.

Table 4 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 4, 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 couple 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 4 has a ratio below one—the market for VOCs in Houston.

What drives these differences? Figure 5 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 5 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 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 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 6, Panel A, investigates sensitivity to many alternative ways of summarizing offset prices. The main estimates assume that permanent offsets sell at a price of about nine times the price of temporary offsets; Figure 6 shows alternative values assuming the ratio of permanent to temporary prices is 7, 5, or 12.

The additional rows in Figure 6, Panel A, show alternative estimates for the markets where we have transaction-level offset prices. The Figure 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, analyze temporary offsets, and show results for a different pollutant with fewer offset transactions (particulate matter, listed in the NO_x graph for simplicity).

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 6, 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.

6 Conclusions

US air pollution offset markets are a key part of the Clean Air Act but have not been the subject of much empirical research. Using decentralized transactions data from a large set of these markets, we analyze these markets and describe how they can help estimate 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 straightforward to implement. Descriptive patterns in data suggest that offset markets are common, have search frictions, rising prices, and provide information about regulatory stringency and marginal abatement costs. A price theory and a procurement auction model of offset markets both suggest that offset prices are close to marginal abatement costs.

We find that the marginal benefit of pollution abatement is far above mean offset prices, as indicated by a wide range of air quality and valuation models. This leads to our main policy conclusion that policy is more lenient than is efficient in most markets, though regulation in one market, the Houston 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 may not be efficient.

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 E describes additional policies that could reform offset markets in ways to decrease marginal abatement costs, such as allowing trades between markets. While these reforms could 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.

One interesting question we leave for future work is the optimal choice of policy instrument. Under certainty, price and quantity policies (i.e., pollution taxes and cap-and-trade markets) have equivalent welfare consequences. Under uncertainty, the expected welfare consequences of these markets differ (Weitzman 1974); in some cases, price-quantity hybrids may have efficiency or political economy advantages. One possible interpretation of our results would be to suggest that the marginal benefit of abatement curve has relative steep slope; a reading of the epidemiology literature might suggest that the marginal benefits of abatement curve has relative flat slope (Krewski et al. 2009; Lepeule et al. 2012). A complete market design analysis could provide more comprehensive analysis of optimal policy instruments to use even given ultimate policy stringency.

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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7 Figures and Tables

Table 1: Prevalence of Offset Markets

	Number of markets (1)	Population (mn)		GDP (trn)		Manufacturing employment (mn)	
		People (2)	% (3)	$ (4)	% (5)	Workers (6)	% (7)
Panel A. National							
Any pollutant	491	182.1	59	11.08	66	6.44	56
Ozone	282	173.2	56	10.65	63	6.09	53
Particulate matter	83	121.2	39	7.58	45	3.97	34
Panel B. National—analysis period							
Any pollutant	226	158.1	51	9.74	58	5.38	47
Ozone	118	145.0	47	9.08	54	4.83	42
Particulate matter	63	114.3	37	7.11	42	3.74	32
Panel C. Full sample (16 states plus Washington, DC) as proportion of all national markets							
Any pollutant	42	94.5	60	6.14	63	3.00	56
Ozone	37	94.5	65	6.14	68	3.00	62
Particulate matter	5	30.3	27	1.83	26	1.05	28

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

Table 2: Offset Markets and Valuations

	NO_x (1)	VOCs (2)
Panel A. Mean		
Valuations	\$19.75	\$26.47
Offset Prices	\$23.80	\$28.40
Ratio: valuations / offset prices	0.83	0.93
Panel B. Median		
Valuations	\$24.32	\$29.78
Offset Prices	\$24.10	\$28.66
Ratio: valuations / offset prices	1.01	1.04
Panel C. 10^{th} *percentile*		
Valuations	\$10.56	\$21.16
Offset Prices	\$20.82	\$26.64
Ratio: valuations / offset prices	0.51	0.79
Panel D. 90^{th} *percentile*		
Valuations	\$31.64	\$34.46
Offset Prices	\$25.65	\$29.81
Ratio: valuations / offset prices	1.23	1.16

Notes: This table describes estimated valuations and offset prices using a version of equation (6), estimated separately by pollutant. Column (1) describes nitrogen oxides pollution (NO_x) while column (2) describes volatile organic compounds (VOCs). All values are in thousands of 2017 dollar per short ton of pollution. These estimates come from an auction with N=3 bidders. Data include all markets with transaction-level data for years 2010-2019.

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

	NO_x		VOCs	
	(1)	(2)	(3)	(4)
Panel A. Full sample (16 states plus Washington, DC				
1. Marginal benefits of abatement / Offset price	38.21	11.89	29.19	8.99
2. p-val: MBabatement / Offset price = 1	[0.00]	[0.00]	[0.00]	[0.00]
3. Mean marginal benefits of abatement	$43,044	$51,540	$24,934	$20,657
4. Mean offset prices	$1,126	$4,334	$854	$2,297
Panel B. Northeast				
1. Marginal benefits of abatement / Offset price	79.03	70.45	46.92	52.28
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	$567	$625	$622	$617
Panel C. South				
1. Marginal benefits of abatement / Offset price	20.84	5.97	11.67	2.30
2. p-val: MBabatement / Offset price = 1	[0.00]	[0.01]	[0.02]	[0.23]
3. Mean marginal benefits of abatement	$38,093	$29,155	$19,934	$13,464
4. Mean offset prices	$1,828	$4,884	$1,708	$5,852
Panel D. West				
1. Marginal benefits of abatement / Offset price	8.59	8.33	4.62	6.58
2. p-val: MBabatement / Offset price = 1	[0.00]	[0.00]	[0.00]	[0.00]
3. Mean marginal benefits of abatement	$36,940	$71,745	$7,389	$15,501
4. Mean offset prices	$4,302	$8,609	$1,601	$2,356
Panel E. Midwest				
1. Marginal benefits of abatement / Offset price	85.15	89.99	46.01	49.10
2. p-val: MBabatement / Offset price = 1	[0.04]	[0.02]	[0.02]	[0.01]
3. Mean marginal benefits of abatement	$44,504	$48,578	$19,856	$22,351
4. Mean offset prices	$523	$540	$432	$455
Weight:				
Tons	X		X	
Population		X		X

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

Table 4: Ratio of Marginal Benefits of Abatement to Offset Prices, by Market

	NO_x (1)	VOCs (2)
Arizona (Phoenix-Mesa)	—	11.49
California (Imperial County)	1.72	6.99
California (Los Angeles-South Coast)	7.86	7.05
California (San Francisco Bay Area)	30.53	18.81
California (San Joaquin Valley)	3.62	4.70
Connecticut (Greater Connecticut)	40.45	—
Connecticut (NY-NJ-Long Island)	33.12	—
District of Columbia (DC-MD-VA)	95.57	73.60
Illinois (Chicago-Naperville, IL-IN-WI)	96.42	49.96
Indiana (Chicago-Naperville, IL-IN-WI)	57.37	23.42
Maryland (Baltimore)	62.88	31.76
Maryland (Washington, DC-MD-VA)	53.33	34.59
Missouri (St. Louis-St. Charles-Farmington, MO-IL)	—	81.99
New Jersey (NY-NJ-CT-Long Island)	52.93	41.03
New Jersey (Philadelphia-Wilmington-Atlantic City PA-NJ-MD-DE)	93.46	35.79
New York (NY-NJ-CT-Long Island)	77.42	64.04
Ohio (Cleveland-Akron-Lorain)	74.86	45.00
Pennsylvania (Philadelphia-Wilmington-Atlantic City PA-NJ-MD-DE)	83.67	61.41
Pennsylvania (Pittsburgh-Beaver Valley)	275.84	33.26
Texas (Houston-Galveston-Brazoria)	1.71	0.54
Virginia (Washington DC-MD-VA)	54.13	35.94
Wyoming (Upper Green River Basin)	40.14	1.21

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 5: Trends in Offset Prices and Marginal Benefits of Abatement

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

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

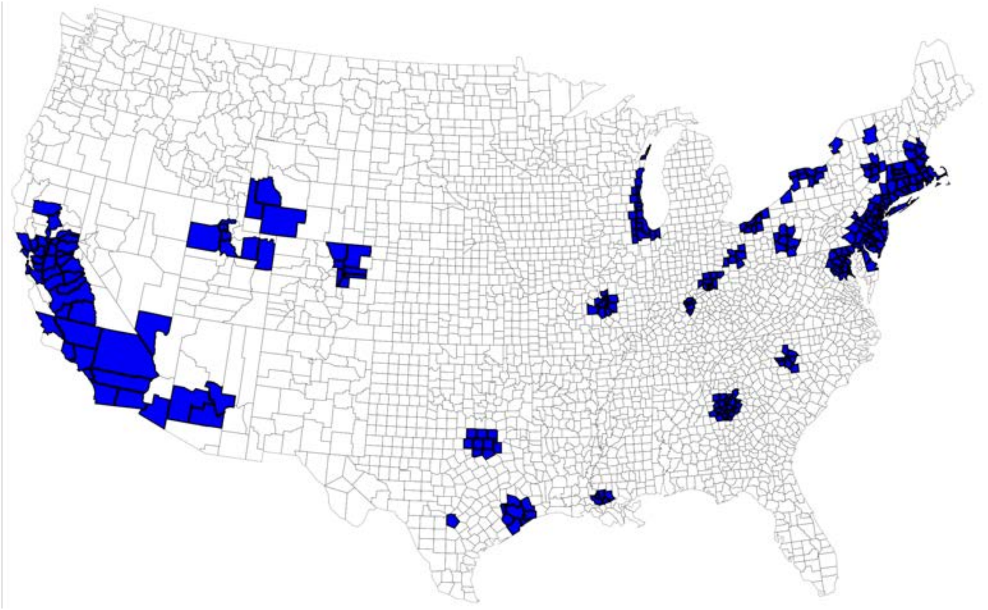
Table 6: Engineering Estimates of Marginal Abatement Costs Versus Offset Prices

	NO_x		VOCs	
	(1)	(2)	(3)	(4)
Panel A. Full sample (16 states plus Washington, DC)				
1. Engineering est. / offset price	0.29	0.27	4.18	6.04
2. p-val: engineering est. / offset price = 1	0.00	0.00	0.00	0.00
3. Mean engineering estimate	818	806	9,403	9,460
4. Mean offset prices	2,833	2,942	2,251	1,567
Panel B. Northeast				
1. Engineering est. / offset price	1.37	1.26	18.45	15.60
2. p-val: engineering est. / offset price = 1	0.00	0.00	0.00	0.00
3. Mean engineering estimate	777	836	11,471	10,161
4. Mean offset prices	567	665	622	651
Panel C. South				
1. Engineering est. / offset price	0.17	0.26	1.82	2.82
2. p-val: engineering est. / offset price = 1	0.00	0.00	0.34	0.01
3. Mean engineering estimate	647	668	10,725	8,585
4. Mean offset prices	3,778	2,589	5,886	3,049
Panel D. West				
1. Engineering est. / offset price	0.31	0.16	6.11	6.69
2. p-val: engineering est. / offset price = 1	0.00	0.00	0.00	0.00
3. Mean engineering estimate	1,158	940	11,318	12,620
4. Mean offset prices	3,718	5,917	1,852	1,887
Panel E. Midwest				
1. Engineering est. / offset price	1.05	1.07	3.30	3.42
2. p-val: engineering est. / offset price = 1	0.05	0.02	0.00	0.00
3. Mean engineering estimate	551	560	1,483	1,505
4. Mean offset prices	526	521	450	440
Weight:				
Tons	X		X	
Population		X		X

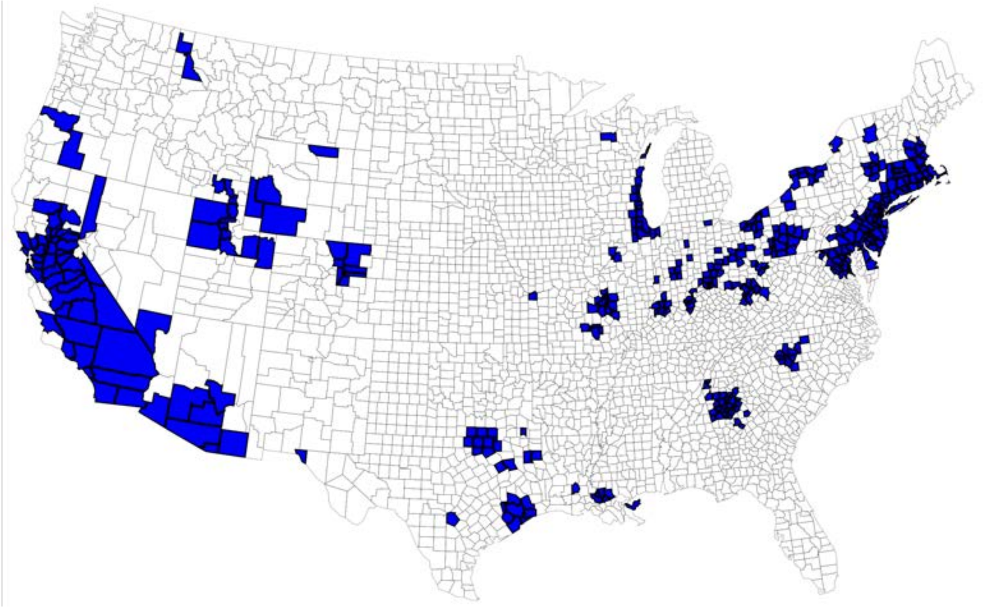
Notes: Row 1 in each panel shows the ratio of mean engineering estimate of abatement costs to the offset price in the specified census region. Row 2 in each panel shows the p-value for the test of the null hypothesis that this ratio equals one. Rows 3 and 4 show the engineering estimate of abatement 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)



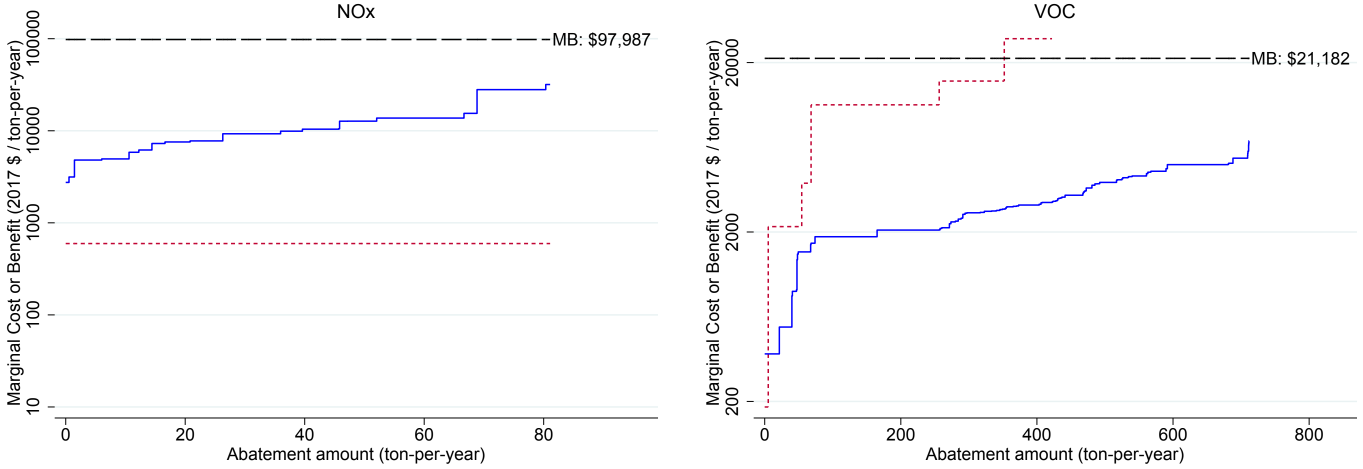
(B) Market areas for other pollutants



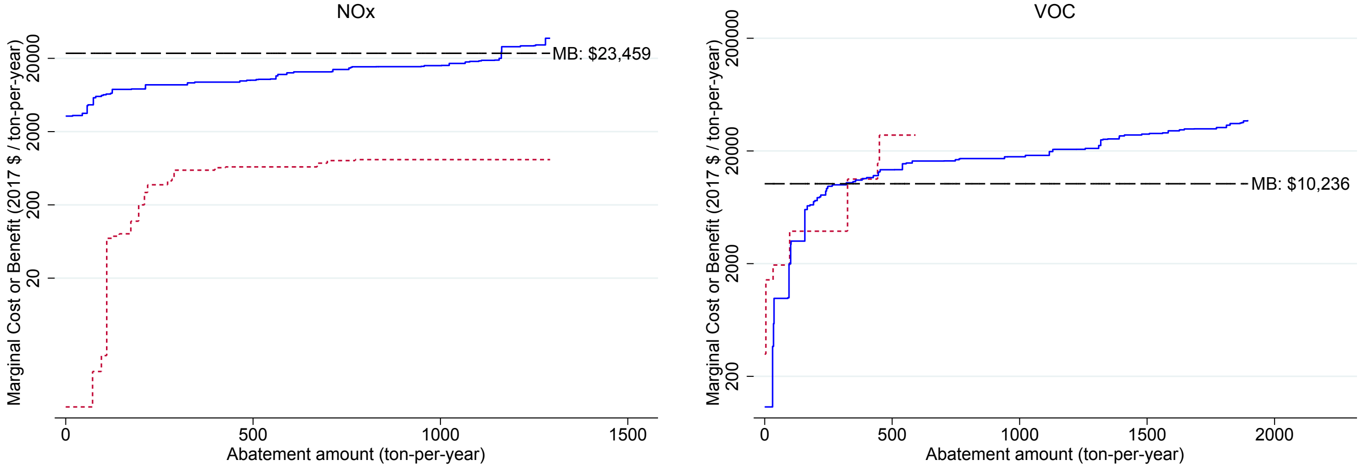
Notes: Shaded blue areas are in nonattainment in any years 2010-2019, and in states with offset markets. "Other pollutants" includes CO, PM, and SOx. States with markets are identified by using a list from Emission Advisors (https://www.emissionadvisors.com/emissions-markets/; Accessed 4/16/2020) and verifying internet market listings.

Figure 2: 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

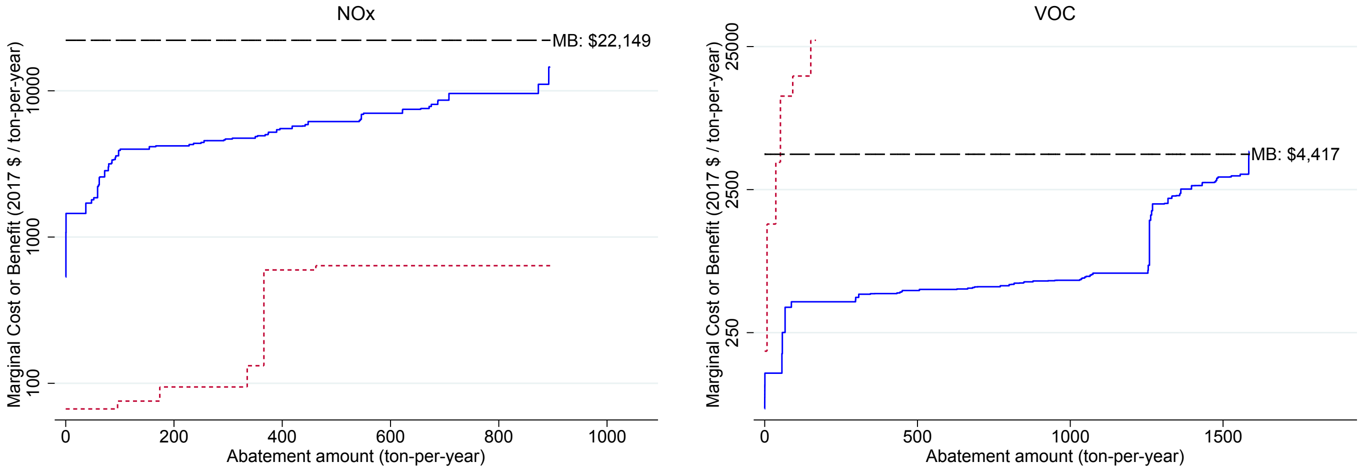


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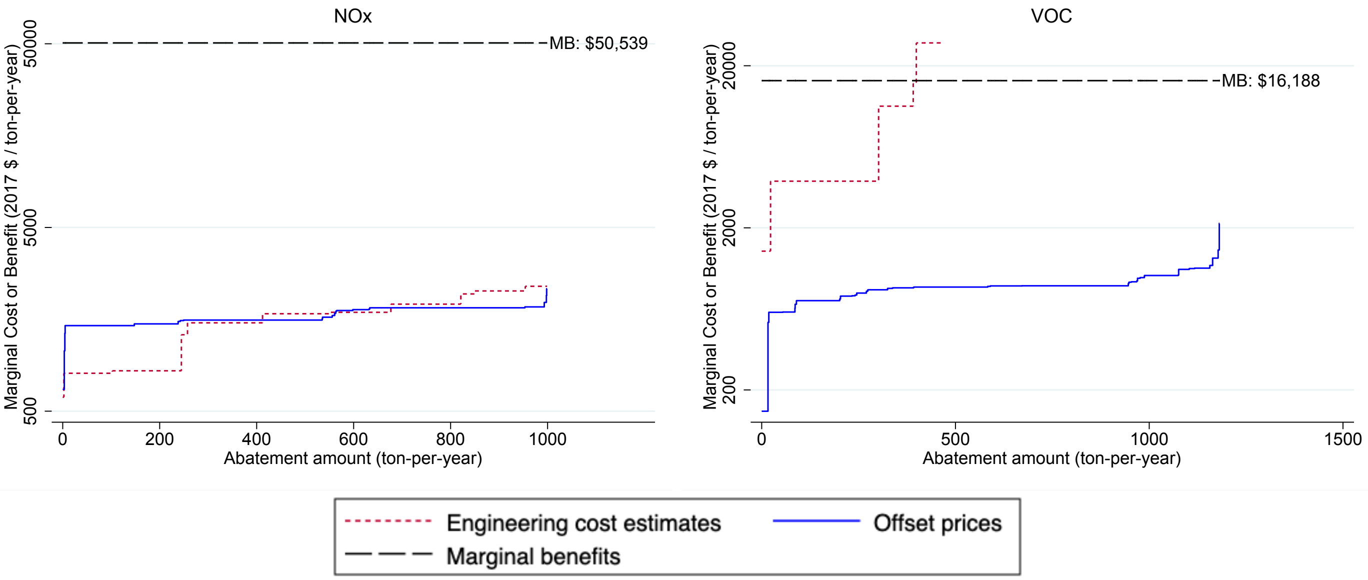
Figure 2: Offset Prices, Engineering Estimates of Marginal Abatement Costs, and Marginal Abatement Benefits in Four Large Markets (Continued)

(D) San Francisco Bay Area, California

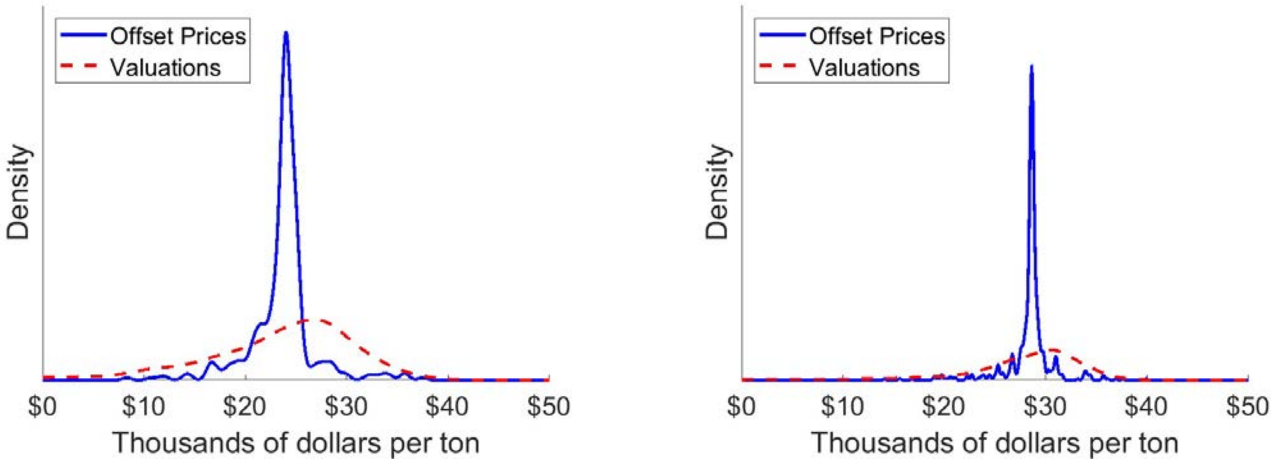


Notes: Each graph shows three curves, all describing the period 2010-2019. The solid line in each graph shows the ordered value of offset prices for the indicated market and pollutant. The short-dotted line in each graph shows engineering estimates of the marginal abatement cost curve, as estimated from 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.

Figure 3: Offset Prices and Valuations, Densities and Cumulative Distributions

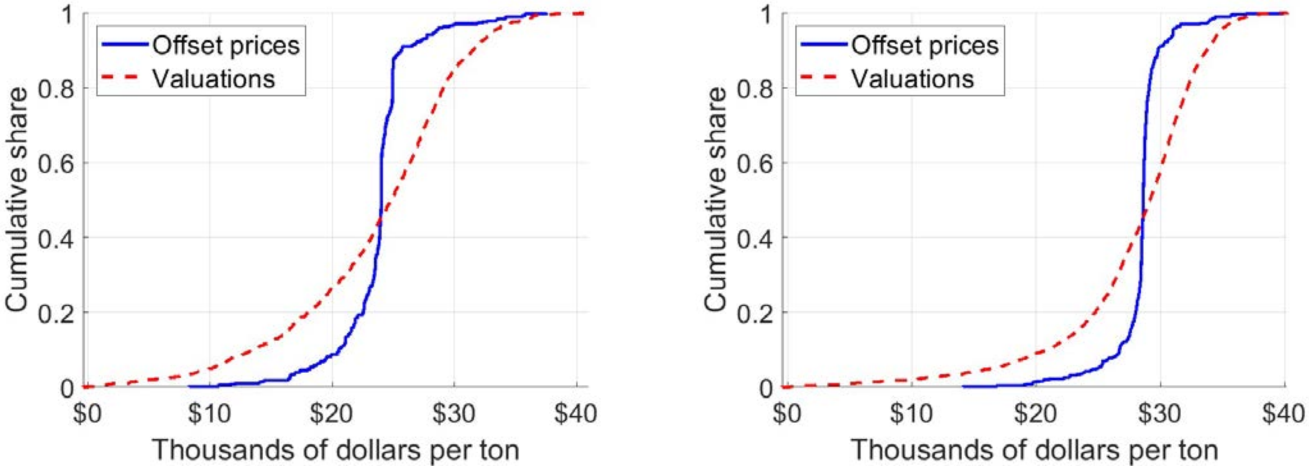
(A) NO_x Density

(B) VOC Density



(C) NO_x cumulative distribution

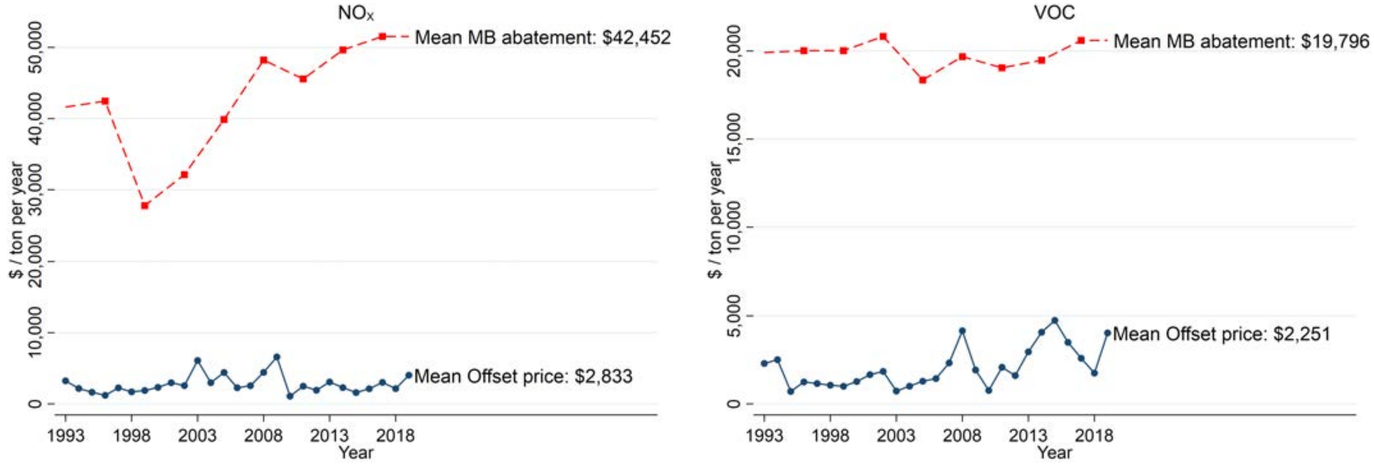
(D) VOC cumulative distribution



Notes: These figures plot estimated valuations and offset prices using a version of equation (6) and estimated separately by pollutant. Panels A and B show the probability density functions (PDFs) while Panels C and D show the cumulative distribution functions (CDFs). Panels A and C describe nitrogen oxides pollution (NO_x) while panels B and D describe volatile organic compounds (VOCs). In each graph, the solid blue line describes offset prices while the dashed red line describes valuations. All values are in thousands of 2017 dollar per short ton of pollution. These estimates come from an auction with N=3 bidders. Data include all California and Texas markets for years 2010-2019.

Figure 4: Pollution Offset Prices Versus Marginal Benefits of Abatement, by Year

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



(B) Northeast

(C) South

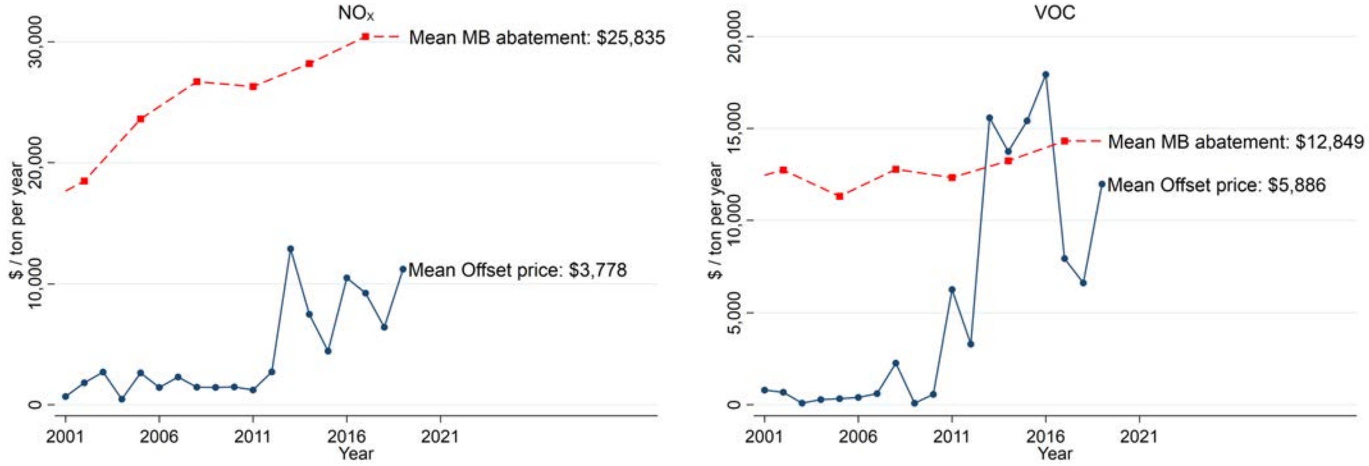


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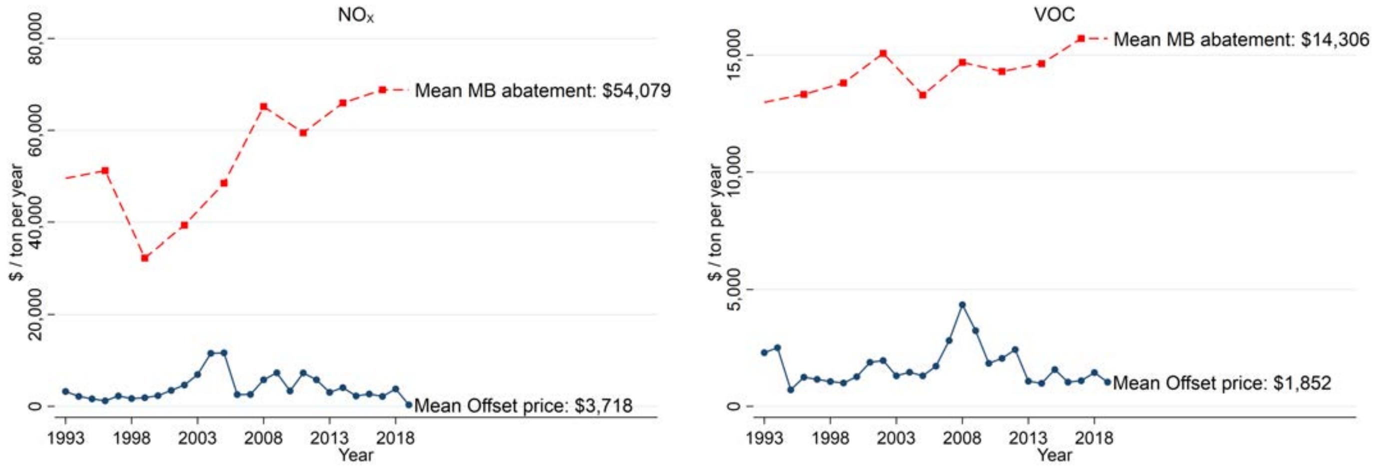
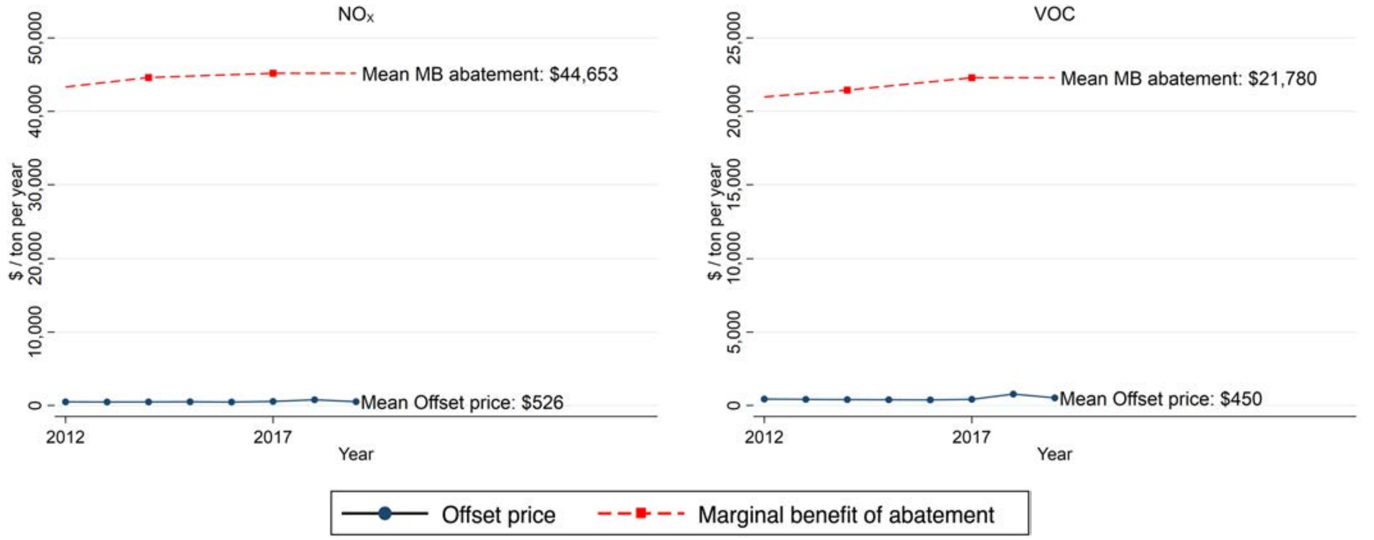
Figure 4: Pollution Offset Prices Versus Marginal Benefits of Abatement, by Year (Continued)

(D) West

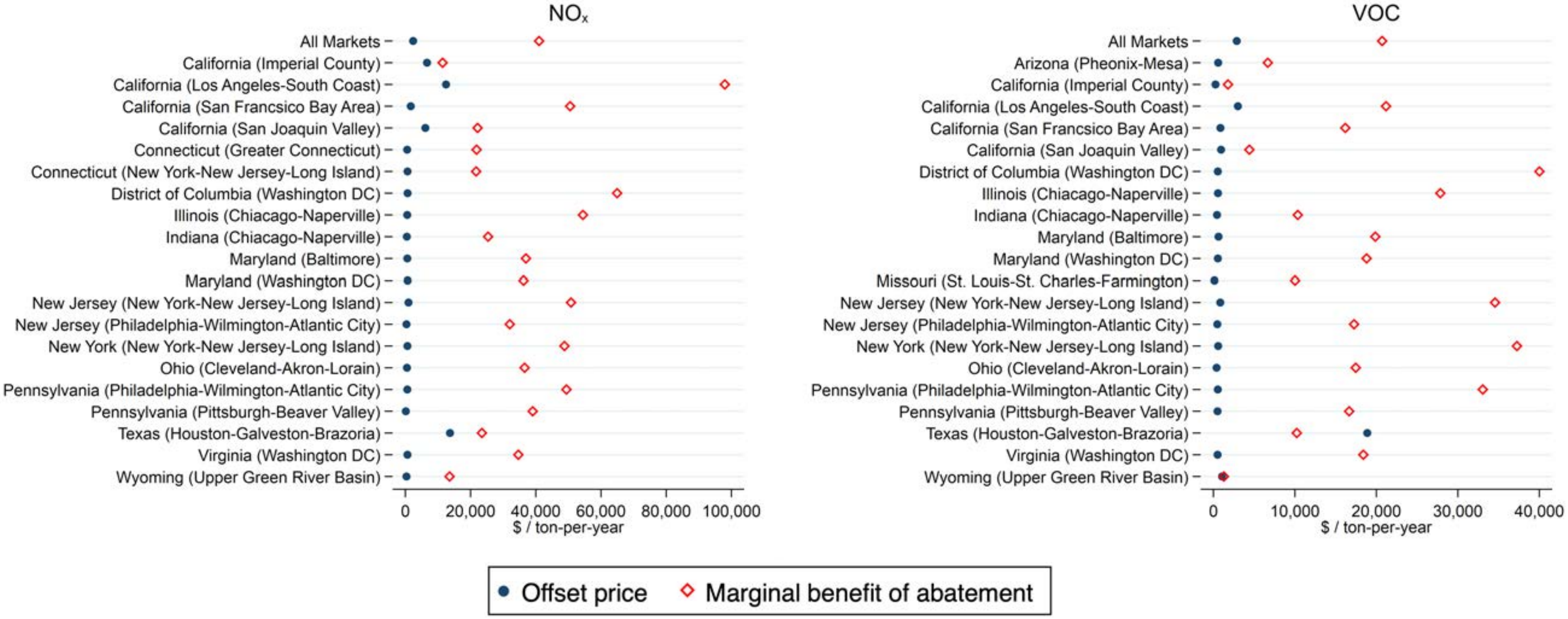


(E) Midwest



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

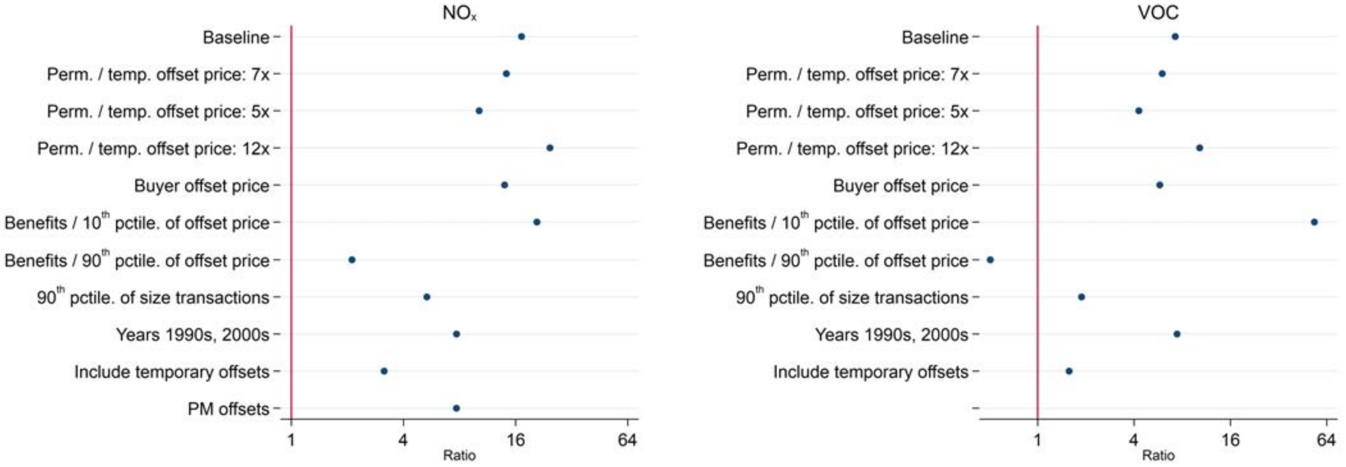
Figure 5: Offset Prices and Marginal Benefits of Abatement, Large Individual Markets



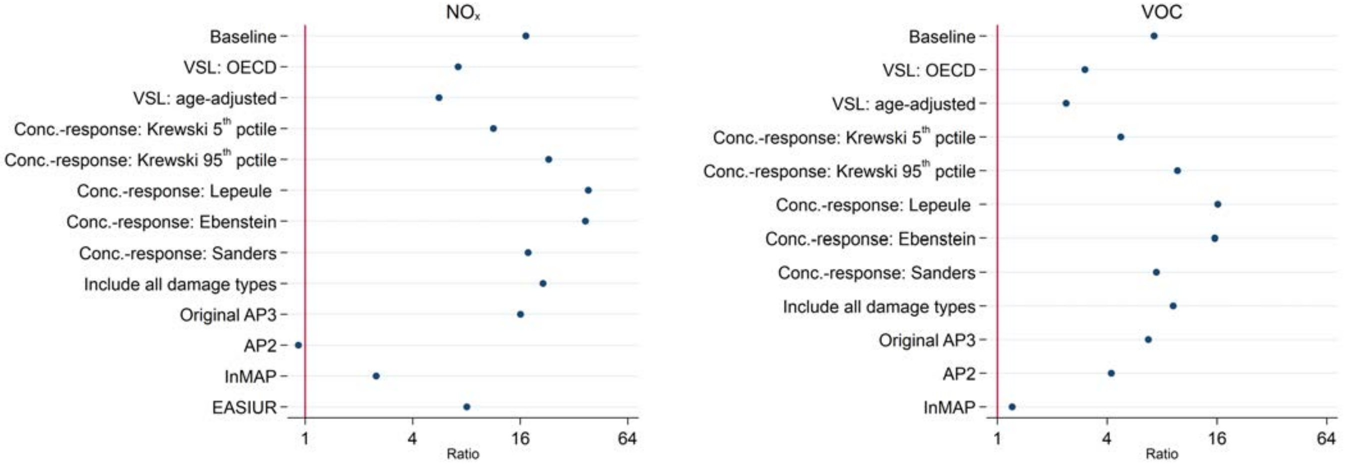
Notes: This figure compares offset prices and the marginal benefits of pollution abatement in individual market × pollutants, for a set of large markets with data. Data represents years 2010-2019. The vertical axis lists the state that the data represent, then in parentheses, the market's name. Offset 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 6: Ratio Marginal Benefits of Pollution Abatement to Mean Offset Prices: Sensitivity Analysis

Panel A. Alternative estimates using different parameterizations of offset prices



Panel B. Alternative estimates of the marginal benefits of abatement



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

Online Appendix:
Is Air Pollution Regulation Too Stringent?

A Interpreting EPA's Cost-Benefit Analysis of Air Pollution

The EPA's Regulatory Impact Analysis for the NAAQS ozone revision in 2008 considers four possible revised ozone standards (0.075, 0.079, 0.070, or 0.065 parts per million).[25] The EPA ultimately chose a standard of 0.075 ppm. For each standard, the EPA describes several methods of estimating benefits, multiple discount rates, and a range of costs and benefits for each approach. The benefit/cost ratios reported in the main text represent the lowest and highest range across scenarios for the standard of 0.075 ppm which the EPA actually chose. For the other standards, the range of benefit/cost ratios ranges from 0.1 to 4.6.

B 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.

C Offset Versus Cap and Trade Market Designs

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

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[25] https://www3.epa.gov/ttnecas1/regdata/RIAs/452_R_08_003.pdf

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.

D Additional Data Details

D.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).[26] 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).

D.2 Market Coverage and Offset Sources

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

A second statistic assesses how the emissions in offset transactions compare to total emissions. This ratio should be far below one since offsets reflect large entrants while total emissions in the market reflect all incumbents and entrants. Across markets, the mean ratio between annual offset quantity transacted in our data and total emissions in the National Emissions Inventory for the corresponding markets, weighted by market transaction quantity, is 7 percent. This statistic compares the flow of new pollution (entry, reflected in offsets) versus the stock of pollution from entrants an incumbents (reflected in NEI). Across markets, maximum ratio of 19 percent is in the San Joaquin air district.

A third statistic calculates the total value of transactions in offset markets. We observe 47 market × pollutant pairs with offset price and quantity data between 2012-2016. For this market size calculation, we take the weighted mean of these offset transactions, weighting by the traded quantity. Multiplying these mean offset prices by the total emissions in each market gives a mean offset market value of \$86 million for an air-district×pollutant. The total value summed across these 47 markets corresponds to \$2.1 billion. As a point of comparison, the market size of the NO_x Budget Program, a prominent cap-and-trade market for NO_x in 19 Eastern States, was about \$1 billion per year (Deschenes et al. 2017). Hence, the offset markets in our data have similar market size as at least one other important environmental market.

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

The Houston offset data identify which offsets originate from plant shutdown, and so let us

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[26] 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).

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

D.3 Marginal Benefits of Abatement

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

D.3.1 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 $\Delta E = E_1 - E_0$, and the concentration-response parameter, β:

$$\frac{r_1}{r_0} = \exp(\beta \times \Delta E) \tag{7}$$

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

$$r_1 - r_0 = r_0 \times \Bigg[\exp(\beta \times \Delta E) - 1\Bigg] \tag{8}$$

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

$$\Delta\text{Deaths} = \text{Population} \times (r_1 - r_0) \tag{9}$$

Substituting (8) into (9) gives the following response function:

$$\Delta\text{Deaths} = \text{Population} \times r_0 \times \Bigg[\exp(\beta \times \Delta E) - 1\Bigg] \tag{10}$$

Each epidemiological study reports the relative risk $\frac{r_1}{r_0}$ and the change in concentration ΔE ; we substitute these into equation (7) to recover the coefficient β. Given β, we can then use equation (10) 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 $\mathrm{PM}_{2.5}$ 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 $\mathrm{PM}_{2.5}$ 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 $\mathrm{PM}_{2.5}$, we use estimates from Zhou et al. (2016), which suggests a ratio of 0.61 unit of $\mathrm{PM}_{2.5}$ 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 $\mathrm{PM}_{2.5}$ 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 $\mathrm{PM}_{2.5}$ 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 $\mathrm{PM}_{2.5}$ 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 $\mathrm{PM}_{2.5}$. 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 $\mathrm{PM}_{2.5}$ 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.

D.3.2 Addressing One Discrepancy

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

$$D_0 = \text{Population} \times r_0 \times \left[1 - \frac{1}{\exp(\beta E_0)}\right] \tag{11}$$

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:

$$D_1 = \text{Population} \times r_0 \times \left[1 - \frac{1}{\exp(\beta E_1)}\right] \tag{12}$$

The new damage is $D_1 \times WTP$.

Equations (11) and (12) imply that in the original version of AP3, the change in deaths is calculated as

$$\begin{aligned}
\Delta\text{Deaths} &= D_1 - D_0 \\
&= \text{Population} \times r_0 \times \left[\frac{1}{\exp(\beta E_0)} - \frac{1}{\exp(\beta E_1)}\right] \\
&= \text{Population} \times r_0 \times \left[\frac{\exp(\beta E_1)}{\exp(\beta E_0)\exp(\beta E_1)} - \frac{1}{\exp(\beta E_1)}\right] \\
&= \text{Population} \times r_0 \times \left[\frac{1}{\exp(\beta E_1)} \times \exp(\beta \underbrace{(E_1 - E_0)}_{\Delta E} - 1)\right] \qquad (13)
\end{aligned}$$

Comparing equations (13) and (10) 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 (10) everywhere, rather than equation (13), to calculate pollution damages.

D.3.3 Value of Statistical Life

Our baseline estimates use the USEPA (2023)'s preferred VSL of \$8.8 million (in 2017 dollars). This estimate primarily reflects hedonic models of the labor market which assess how a worker's wage increases as the worker's occupational fatality risk increases. An alternative 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.

D.3.4 Other Inputs to Estimate Marginal Benefits of Abatement

AP3's estimates use data on the baseline population and mortality rates in each county. We use population data from the 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.

D.3.5 Alternative Models for the Marginal Benefits of Abatement

We also show sensitivity analyses using the three main other integrated assessment models besides AP3 which estimate the marginal damages of emitting a ton of each pollutant in each 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.

D.4 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.5 Implied Discount Rates

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

We use the following standard annuity formula:

$$P_{permanent} = P_{temporary}\left[\frac{1-(1+r)^{-n}}{r/(1+r)}\right] \tag{14}$$

Here, $P_{permanent}$ is the price of a standard offset, $P_{temporary}$ is the price of a temporary offset, r is the discount rate firms implicitly use, and n is the duration that firms expect offsets to last. Regulatory analyses of air pollution abatement regularly assume an average region will be in nonattainment for 20 years. We therefore calculate discount rates assuming $n = 20$, though we report sensitivity to assuming $n = 10$ and $n = \infty$. We limit the analysis of discount rates to permanent offsets that are in the same market, pollutant, and year as a traded temporary offset. Practically, we calculate the ratio of permanent and temporary offset prices in these markets, then numerically solve nonlinear equation (14) for r.

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

E Additional Policy Discussion

E.1 Other Existing Environmental Regulations

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

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

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

E.2 Other Potential Policy Reforms

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.

F Relating Offset Prices to Other Environmental Aggregates

Throughout Section 3.4, an industry represents a 6-digit North American Industry Classification (NAICS) code. Additionally, we define polluting plants to include all plants in industries that account for at least 0.5 percent of national, stationary-source emissions for that pollutant, where emissions are measured from the EPA's National Emissions Inventory (NEI).

Pollution Abatement Costs and Expenditures

We report estimates of the following equation:

$$ln(P_c) = \beta ln\left(\frac{A_{ci}}{Y_{ci}}\right) + \mu_i + \epsilon_{ci} \tag{15}$$

Each observation in this regression represents a county c and industry i. Here A_{ci} represents either total dollars of spending on pollution abatement in a county×industry, measured from PACE; or short tons of pollution emissions, measured from the NEI. The variable Y represents output of polluting plants, measured from the 2005 ASM (corresponding with the 2005 PACE) or 2012 CM (corresponding with the 2011 NEI). The term P_c represents mean offset prices in county c for the corresponding Census year. We aggregate abatement expenditures or emissions A_{ci} to the county×industry level, in part to avoid zeros before taking logs. The regression includes fixed effects for each industry, μ_i to control for differences across industry in abatement expenditures and/or emissions intensity. We weight each regression by the total value of shipments in a county×industry cell. We estimate different versions of equation (15), where Y represents value added or output; P is the price of offsets for different pollutants; and where A represents different versions of abatement expenditures or pollution emissions. The coefficient β in equation (15) represents the elasticity of offset prices with respect to abatement costs or emission rates. For example, we test how NO_x offset prices are related to survey measures of abatement costs for NO_x emitting firms. While these are cross-sectional regressions that are correlational in nature, they provide some insight on the association of abatement costs and emissions rates.

Appendix Table 5 presents 24 separate estimates of equation (15). Each entry shows one estimate of the elasticity β. Columns (1) and (2) show pollutant-specific regressions. Column (3) pools estimates across all pollutants. Parentheses show standard errors clustered by air district.

Pollution Emissions

Appendix Table 6 estimates a version of Equation (15), where A_{ci} represents the short tons of air pollution emissions from a county×industry, divided by output or value added. Each column and panel shows a separate regression. Panel A measures emission rates per dollar of shipments, and Panel B measures emissions per dollar of value added. Each column shows a different pollutant, and column (3) combines pollutants. For example, column (1) of Panel A shows an estimate of the relationship between the NO_x offset price in that air district×year and NO_x emissions per dollar of shipments in NO_x-emitting establishments.

Polluting Industrial Activity

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

$$lnP_{dt} = \sum_{l=0}^{2} \gamma_l lnY_{d,t-l} + \alpha_d + \eta_t + \epsilon_{dt} \tag{16}$$

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

Nonattainment Designations

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

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

$$lnP_{dpt} = \sum_{g} \psi_g 1[d \in g] + \epsilon_{dpt} \tag{17}$$

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

Appendix Table 8 presents results from four separate regressions, one per column. The excluded (reference) category for nonattainment severity is "marginal". Regressions are weighted by average tons of offsets transacted for a district×pollutant.[27] Parentheses show standard errors clustered by district×pollutant.

G Price Theory Model of Offset Markets

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.[28] 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 uncertainty 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 ($dC_i(X_i)/dX_i < 0$, $dT_i(X_i)/dX_i < 0$, and $dD(X)/dX_i > 0$).

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

[28] 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.

G.1 The Planner's Problem

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

$$min_X \sum_i C_i(X_i) + T(X_i) + D(X) \tag{18}$$

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

$$-\frac{dC_i(X_i)}{dX_i} - \frac{dT(X_i)}{dX_i} = \frac{dD(X)}{dX_i} \quad \forall\, i \tag{19}$$

The first term in equation (19), 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 (19), the marginal benefits of abatement, describes how a marginal increase in emissions affects the damages from pollution. Equation (19) 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 (19), 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 (19) 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 (19) shows that policies with high transaction costs have a downside for the environment because they decrease the efficient amount of abatement.

G.2 Decentralization

We assume firm i chooses its emissions to maximize profits:

$$max_{X_i} P_y Y(X_i) - E_i(X_i) - PX_i - T_i(X_i) \tag{20}$$

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 $T_i(\cdot)$. One could think of $E_i(X_i)$ as the optimal quantity of abatement investment given emissions X_i.

Differentiating equation (20) with respect to emissions X_i for an operating firm, and defining a firm's marginal control costs as $-\frac{dC_i(X_i)}{dX_i} = P_y \frac{dY(X_i)}{dX_i}$ gives the condition for production efficiency:

$$-\frac{dC_i(X_i)}{dX_i} - \frac{dT_i(X_i)}{dX_i} = P \tag{21}$$

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 (19) with the firm's production efficiency condition from equation (21) shows a simple condition for efficient offset prices:

$$P = \frac{dD(X)}{dX_i} \tag{22}$$

Equation (22) 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 (21) shows the two additional classes of policy reforms that could then increase welfare—decreasing marginal control costs $dC_i(\cdot)/dX_i$ or decreasing transaction costs $dT_i(\cdot)/dX_i$.

G.3 Comparing Price Theory and Auction Interpretations

Because auctions provide an atypical interpretation of pollution markets, we highlight differences between this and classic models. The largest difference is the interpretation of dispersion in offset prices. In the auction model, offset price dispersion arises from varying markups, search frictions, and heterogeneity of incumbents' marginal abatement costs. The price theory model does not provide an obvious interpretation of price dispersion, though alternative versions of that model could assume that reported transaction prices vary in the extent to which they include transaction costs or in the sharing of transaction costs between sellers and buyers.

The models also differ in the interpretation of intermediation frictions. In the auction model, search costs make entrants unable to obtain price quotes from every incumbent, so entrants need not buy from the lowest-cost seller. The price theory model describes transaction costs as a component of offset prices, though does not measure them.

Third, auction and price theory models differ in their interpretation of market thickness. The auction framework describes markets with a limited number of entrants or buyers periodically appearing and purchasing offsets from a large number of potential sellers. The price theory framework assumes a large number of similar sellers and buyers, so demand and supply functions are smooth. Typical offset markets have dozens to hundreds of incumbents but fewer entrants.

Fourth, the models quantify different types of outputs. The auction model recovers the distribution of reservation prices for all bidders and for winners. This provides one estimate of the entire marginal abatement cost curve. The price theory model describes one moment of the distribution of offset prices as the marginal abatement cost. Because the price theory model is silent on the causes of price dispersion, it does not explain which moment to use.

Fifth, the models provide different interpretation and quantification of markups. In the auction model, an incumbent chooses a markup to compare the additional revenue from a higher bid against the consequent lower probability of winning the auction, and this markup is straightforward to quantify. Price theory models generally abstract from market power.

A few more general differences are worth noting. The price theory model allows for a transparent interpretation of prevailing offset prices as equal to the marginal cost of pollution abatement in the market. The auction theory requires model-based estimates to quantify the marginal cost of pollution abatement. Data demands also differ—because the price theory assumes a single offset price, it requires only one summary statistic for offset prices. Quantification with the auction model requires offset-level prices. Both models accommodate differences in abatement costs between entrants and incumbents (e.g., if entrants face more strict regulations, as they do under the Clean Air Act). The auction model only estimates marginal abatement cost curves for incumbents, though that is the usual focus of regulatory analysis.

We believe the appropriate model of a pollution market depends on its institutional features. A price theory interpretation well describes thick markets with centralized exchanges and low intermediation and search costs, like the Acid Rain Program or the EU Emissions Trading System. An auction interpretation may fit better for thinner, decentralized markets where search costs play a larger role, like US air pollution offset markets.

H Auctions with Homogenization

This section describes how we account for observable auction heterogeneity. Assume the valuation of bidder i in auction t is an additively separable function of observed auction-variables z_t:

$$u_{it} = z_t'\gamma + a_{it} \tag{23}$$

We further assume that the distribution of bids G conditional on auction covariates z_t is normal:

$$G(\cdot|z_t) = \Phi(\cdot|z_t'\gamma|\sigma)$$

Equivalently, residual bids $b_{it}^h = b_{it} - z_t'\gamma$ are normal with mean zero and standard deviation σ. From the main text, rewrite the density of offset prices conditional on covariates z_t and number of bids N_t as

$$g_{(1:N_t)}(x|z_t) = N_t \times \phi(x|z_t'\gamma, \sigma) \times [1 - \Phi(x|z_t'\gamma, \sigma)]^{N_1 - 1}$$

The log-likelihood for the parameters γ and σ is then

$$\begin{aligned} \ell(\gamma, \sigma|\{P_t, N_t, z_t\}) &= \sum_t log[g_{(1:N_t)}(P_t|z_t)] \\ &= \sum_t \Big\{ log[\phi(P_t|z_t'\gamma, \sigma)] + (N_1 - 1)log[1 - \Phi(P_t|z_t'\gamma, \sigma)] \Big\} \end{aligned}$$

Estimating this with maximum likelihood provides estimates $\hat{\gamma}$,$\hat{\sigma}$, and the conditional distribution $\hat{G}(\cdot|z_t) = \Phi(\cdot|z_t'\hat{\gamma}, \hat{\sigma})$.

To estimate the distribution of winners' valuations, we use (23) to write the residual bid of the winner of auction t as

$$b_t^h = P_t - z_t'\hat{\gamma}$$

The valuation formula described in the main text then implies the winner's residual valuation is

$$\hat{a}_t = b_t^h - \frac{1}{N_t - 1} \frac{1 - \Phi(P_t|z_t'\gamma, \sigma)}{\phi(P_t|z_t\gamma, \sigma)}$$

Finally, the valuation is calculated as

$$\hat{u}_t = z'\hat{\gamma} + \hat{a}_t$$

We estimate a kernel density of $\{\hat{u}_t\}$ and plot it, as in the main text. Finally, we calculate the distribution of all valuations and plot it as in the main text, substituting $\phi(\cdot|z'\hat{\gamma}, \hat{\sigma})$ for $\hat{g}$.

I Engineering Estimates Versus Offset Prices

Why do the engineering and revealed preference estimates differ so much? This Appendix section discusses several reasons why the EPA's engineering estimates of marginal abatement costs may differ from our estimates derived from offset prices. 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.

Appendix Table 1: Offset Prices and Valuations, Sensitivity Analysis

Pollutant	NO_x			VOCs		
Assumed Number of Bidders	4 (1)	5 (2)	[2, 5] (3)	4 (4)	5 (5)	[2, 5] (6)
Panel A. Mean						
Valuations	\$23.74	\$25.29	\$22.20	\$28.18	\$29.32	\$26.47
Offset Prices	\$24.20	\$24.53	\$23.31	\$28.77	\$29.00	\$28.40
Ratio: valuations / offset prices	0.98	1.03	0.95	0.98	1.01	0.93
Panel B. Median						
Valuations	\$26.80	\$28.41	\$25.33	\$30.80	\$31.66	\$29.78
Offset Prices	\$24.57	\$24.95	\$23.53	\$29.02	\$29.28	\$28.66
Ratio: valuations / offset prices	1.09	1.14	1.08	1.06	1.08	1.04
Panel C. 10^{th} *percentile*						
Valuations	\$14.83	\$17.46	\$14.21	\$23.13	\$24.70	\$21.16
Offset Prices	\$21.20	\$21.48	\$20.20	\$27.05	\$27.28	\$26.64
Ratio: valuations / offset prices	0.70	0.81	0.70	0.86	0.91	0.79
Panel D. 90^{th} *percentile*						
Valuations	\$34.00	\$35.14	\$32.02	\$35.41	\$36.23	\$34.46
Offset Prices	\$26.00	\$26.27	\$25.21	\$30.19	\$30.44	\$29.81
Ratio: valuations / offset prices	1.31	1.34	1.27	1.17	1.19	1.16

Notes: This table describes estimated valuations and offset prices using a version of equation (6), estimated separately by pollutant. Columns (1)-(3) describe nitrogen oxides (NO_x) while columns (4)-(6) describes volatile organic compounds (VOCs). The column headings describe the number of bidders assumed when estimating valuations. In columns (3) and (6), an auction is assumed to have 3 or 4 bidders with 40 percent probability each or 5 bidders with 20 percent probability. All values are in thousands of 2017 dollars per ton of pollution. Data include all California and Texas markets for years 2010-2019.

Appendix Table 2: Ratio of Marginal Benefits of Abatement to Maximum Offset Prices, 2010-2019

	NO_x		VOCs	
	(1)	(2)	(3)	(4)
Panel A. California and Texas				
1. Marginal benefits of abatement / Offset price	24.16	5.33	17.38	4.53
2. p-val: MBabatement / Offset price = 1	[0.00]	[0.00]	[0.00]	[0.00]
3. Marginal benefits of abatement	$43,085	$51,729	$24,938	$20,642
4. Max offset prices	$1,783	$9,711	$1,435	$4,552
Panel B. California				
1. Marginal benefits of abatement / Offset price	6.03	3.76	2.25	3.04
2. p-val: MBabatement / Offset price = 1	[0.00]	[0.00]	[0.02]	[0.00]
3. Marginal benefits of abatement	$40,831	$72,309	$8,730	$16,484
4. Max offset prices	$6,766	$19,226	$3,873	$5,426
Panel C. Texas				
1. Marginal benefits of abatement / Offset price	1.86	1.21	0.81	0.48
2. p-val: MBabatement / Offset price = 1	[0.62]	[0.85]	[0.92]	[0.66]
3. Marginal benefits of abatement	$23,613	$23,562	$8,301	$8,952
4. Max offset prices	$12,716	$19,432	$10,233	$18,792
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 the maximum offset price per ton of emissions. Row 2 shows the p-value for testing the null hypothesis that the ratio in Row 1 equals one. Rows 3 and 4 show the mean marginal benefits of abatement and maximum offset price, respectively. Data represent years 2010-2019. Offset prices are the maximum price of pollution offsets per ton for the indicated region, pollutant, and time period. When combining maximum amounts across markets, we weight by transaction amount in tons or by population in offset markets. Data on marginal benefits are available for years 2008, 2011, 2014, 2017, and linearly interpolated between years. All currency are in 2017$, deflated using the GDP deflator. Abatement marginal benefits for each region are weighted across counties within a market according to county population in 2010 Census, and weighted across markets by transaction amount in tons or by population in offset markets.

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

	NO_x		VOCs	
	(1)	(2)	(3)	(4)
Panel A. California and Texas				
1. Marginal benefits of abatement / Offset price	41.95	13.85	29.81	9.48
2. p-val: MBabatement / Offset price = 1	[0.00]	[0.00]	[0.00]	[0.00]
3. Marginal benefits of abatement	$43,085	$51,729	$24,938	$20,642
4. Median offset prices	$1,027	$3,734	$837	$2,176
Panel B. California				
1. Marginal benefits of abatement / Offset price	8.78	9.79	4.01	6.31
2. p-val: MBabatement / Offset price = 1	[0.00]	[0.00]	[0.00]	[0.00]
3. Marginal benefits of abatement	$40,831	$72,309	$8,730	$16,484
4. Median offset prices	$4,651	$7,385	$2,176	$2,613
Panel C. Texas				
1. Marginal benefits of abatement / Offset price	5.32	3.63	1.93	1.09
2. p-val: MBabatement / Offset price = 1	[0.16]	[0.20]	[0.62]	[0.93]
3. Marginal benefits of abatement	$23,613	$23,562	$8,301	$8,952
4. Median offset prices	$4,441	$6,494	$4,299	$8,185
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 the median offset price per ton of emissions. Row 2 shows the p-value for testing the null hypothesis that the ratio in Row 1 equals one. Rows 3 and 4 show the mean marginal benefits of abatement and median offset price, respectively. Data represent years 2010-2019. Offset prices are the median price of pollution offsets per ton for the indicated region, pollutant, and time period. When combining median amounts across markets, we weight by transaction amount in tons or by population in offset markets. Data on marginal benefits are available for years 2008, 2011, 2014, 2017, and linearly interpolated between years. All currency are in 2017$, deflated using the GDP deflator. Abatement marginal benefits for each region are weighted across counties within a market according to county population in 2010 Census, and weighted across markets by transaction amount in tons or by population in offset markets.

Appendix Table 4: Offset Prices Versus Engineering Estimates of Marginal Abatement Costs, by Market

	NO_x (1)	VOCs (2)
Arizona (Phoenix-Mesa)	—	—
California (Imperial County)	0.13	—
California (Los Angeles-South Coast)	0.05	4.50
California (San Francisco Bay Area)	0.96	10.45
California (San Joaquin Valley)	0.07	12.32
Connecticut (Greater Connecticut)	4.56	—
Connecticut (NY-NJ-Long Island)	1.20	—
District of Columbia (DC-MD-VA)	1.15	2.64
Illinois (Chicago-Naperville, IL-IN-WI)	0.88	2.22
Indiana (Chicago-Naperville, IL-IN-WI)	1.13	2.80
Maryland (Baltimore)	0.69	17.44
Maryland (Washington, DC-MD-VA)	1.15	2.64
Missouri (St. Louis-St. Charles-Farmington, MO-IL)	—	8.93
New Jersey (NY-NJ-CT-Long Island)	0.82	13.16
New Jersey (Philadelphia-Wilmington-Atlantic City PA-NJ-MD-DE)	1.64	8.46
New York (NY-NJ-CT-Long Island)	1.25	19.05
Ohio (Cleveland-Akron-Lorain)	1.29	4.52
Pennsylvania (Philadelphia-Wilmington-Atlantic City PA-NJ-MD-DE)	0.95	7.57
Pennsylvania (Pittsburgh-Beaver Valley)	5.09	37.98
Texas (Houston-Galveston-Brazoria)	0.05	0.57
Virginia (Washington DC-MD-VA)	1.22	2.80
Wyoming (Upper Green River Basin)	0.48	—

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 Table 5: Relationship Between Offset Prices and Abatement Expenditures

	(1) Offset Price NO_x	(2) Offset Price VOC	(3) Offset Price Combined
$\frac{\text{Operating Costs}}{\text{Output}}$	1.791*	1.015***	1.424***
	(0.753)	(0.314)	(0.337)
$\frac{\text{Operating Costs}}{\text{Value Added}}$	3.475***	1.222**	1.851***
	(0.821)	(0.445)	(0.409)
$\frac{\text{Total Costs}}{\text{Output}}$	1.298*	0.611***	0.890***
	(0.531)	(0.167)	(0.199)
$\frac{\text{Total Costs}}{\text{Value Added}}$	2.189***	0.720***	1.109***
	(0.529)	(0.180)	(0.214)
$\frac{\text{Capital Stock}}{\text{Output}}$	1.303*	0.502**	0.789***
	(0.575)	(0.202)	(0.210)
$\frac{\text{Capital Stock}}{\text{Value Added}}$	2.223**	0.541*	0.927***
	(0.685)	(0.256)	(0.255)
$\frac{\text{Operating+Capital Stock}}{\text{Output}}$	1.303*	0.606***	0.888***
	(0.540)	(0.172)	(0.201)
$\frac{\text{Operating+Capital Stock}}{\text{Value Added}}$	2.213***	0.712***	1.105***
	(0.550)	(0.191)	(0.217)
N	129	339	603

Note: This table presents regression results from 24 separate regressions, 4 per row. An observation is a county×NAICS-6 industry, where the independent variable corresponds to a different measure of abatement expenditures per dollar of output or value added, as indicated in the row heading. The dependent variable in all regressions is the price of emissions reduction credits or offset prices. All dependent and independent variables are in logs. Observations are limited to industries that account for at least 0.5 percent of national, stationary-source emissions for the pollutant specified in each Column (NO_x, VOC). All regressions are weighted by the total value of shipments and control for NAICS-6 industry fixed effects. Standard errors clustered at the district-level are in parentheses. Abatement expenditures and capital stock come from the 2005 Pollution Abatement Costs and Expenditure Survey, and output and value added come from the 2005 Annual Survey of Manufacturers.

Appendix Table 6: Relationship Between Offset Prices and Plant-level Emissions Intensity

	(1) NO_x	(2) VOC	(3) Combined
	Panel A: Emissions Per Unit of Output		
$\frac{\text{Emissions}}{\text{Output}}$	-0.169*	-0.143	-0.137***
	(0.083)	(0.093)	(0.045)
N	1599	2266	4497
	Panel B: Emissions Per Unit of Value Added		
$\frac{\text{Emissions}}{\text{Value Added}}$	-0.149*	-0.139	-0.130***
	(0.085)	(0.085)	(0.043)
N	1599	2266	4497

Note: This table presents regression results from 6 separate regressions, 3 per panel. An observation is a county×NAICS-6 industry, where the independent variable is calculated as the output-weighted average of emissions per dollar of shipments (Panel A) or emissions per dollar of value added (Panel B). The dependent variable in all regressions is the price of emissions reduction credits or offset prices. All dependent and independent variables are in logs. Observations are limited to industries that account for at least 0.5 percent of national, stationary-source emissions for the pollutant specified in the column heading. All regressions control for NAICS-6 industry fixed effects and are weighted by the total value of shipments; column (4) also includes pollutant fixed effects. Standard errors clustered at the district-level are in parentheses. Emissions data come from the 2011 National Emissions Inventory, and output and value added come from the 2012 Census of Manufacturers.

Appendix Table 7: Relationship Between Offset Prices and Value Added

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

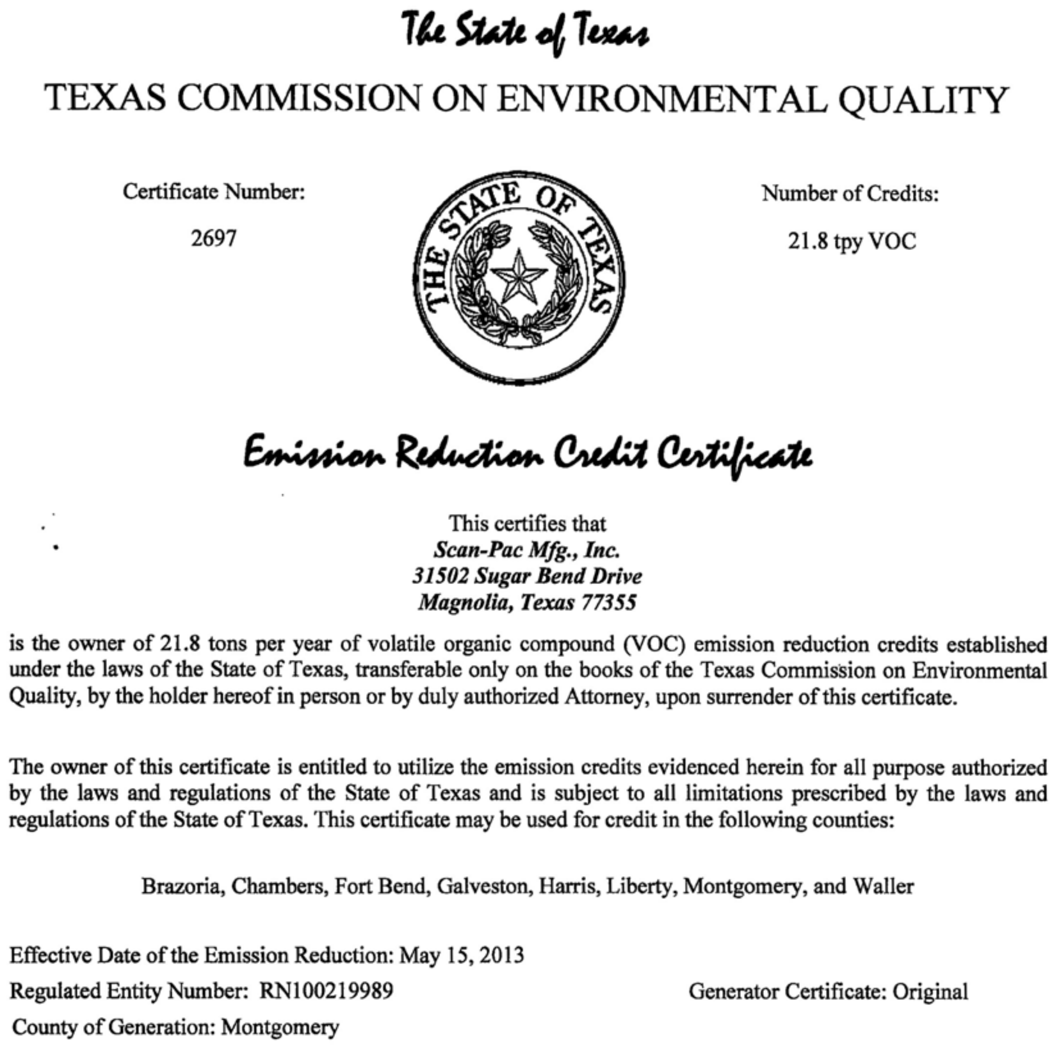
Note: This table presents regression results from 6 separate regressions, 1 per column in each panel. An observation is a district×year, where the dependent variable is the mean log offset price for a given pollutant, as indicated in the column headings. The independent variable in Panel A is the log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

Appendix Table 8: Relationship Between Offset Prices and Stringency of Nonattainment Designation

	(1) Offset Price	(2) Offset Price	(3) Offset Price	(4) Offset Price
1[Extreme Nonattainment]	1.726^{***}	1.654^{***}	1.654^{***}	1.644^{***}
	(0.468)	(0.516)	(0.522)	(0.475)
1[Severe Nonattainment]	1.387^{***}	1.369^{***}	1.369^{***}	1.358^{***}
	(0.451)	(0.484)	(0.485)	(0.461)
1[Serious Nonattainment]	0.734^{*}	0.776^{*}	0.773^{**}	0.764^{**}
	(0.373)	(0.393)	(0.373)	(0.360)
1[Moderate Nonattainment]	0.142	0.312	0.310	0.292
	(0.291)	(0.306)	(0.292)	(0.268)
Constant	8.174^{***}	8.125^{***}	8.126^{***}	8.134^{***}
	(0.329)	(0.343)	(0.329)	(0.309)
N	480	480	480	480
Year FE		X	X	
Pollutant FE			X	
Pollutant×Year FE				X

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

Appendix Figure 1: Example of a Pollution Offset



The State of Texas

TEXAS COMMISSION ON ENVIRONMENTAL QUALITY

Certificate Number:
2697

Number of Credits:
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.

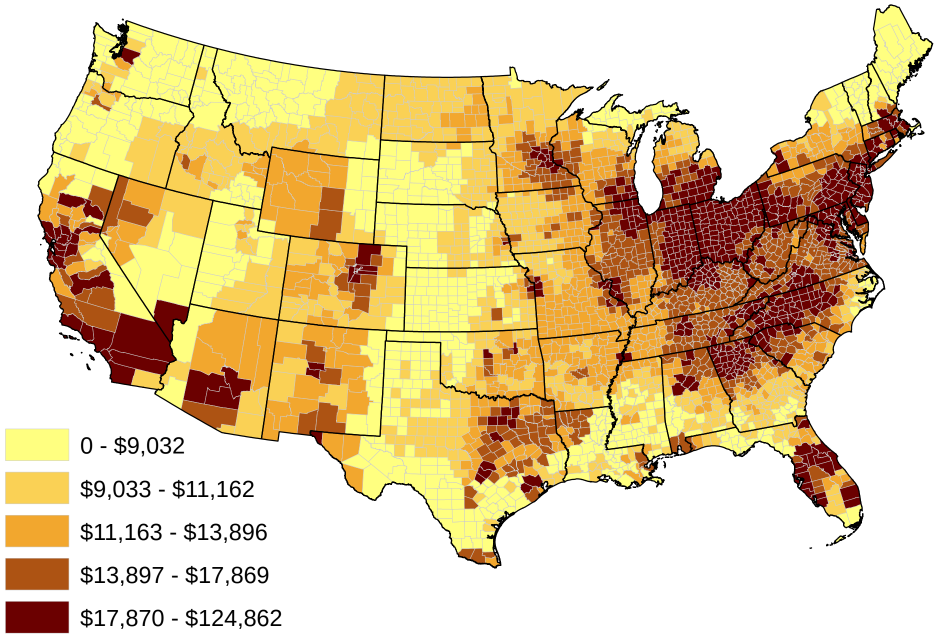
The owner of this certificate is entitled to utilize the emission credits evidenced herein for all purpose authorized by the laws and regulations of the State of Texas and is subject to all limitations prescribed by the laws and regulations of the State of Texas. This certificate may be used for credit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

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

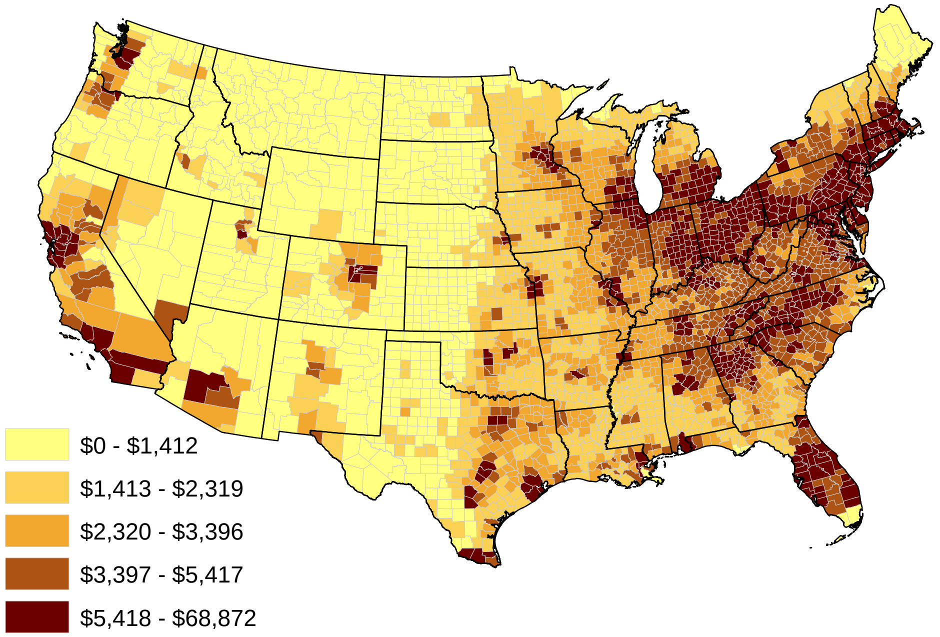
Effective Date of the Emission Reduction: May 15, 2013
Regulated Entity Number: RN100219989
Generator Certificate: Original
County of Generation: Montgomery

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

(A) Nitrogen oxides (NO_x)

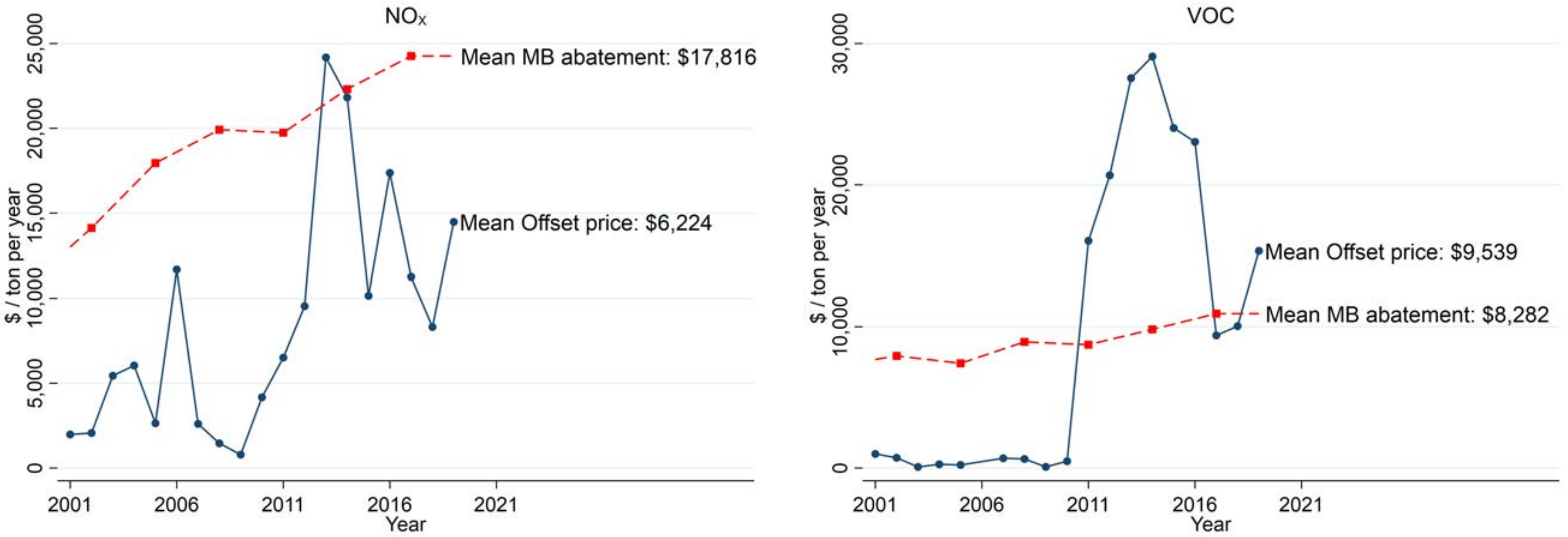


(B) Volatile organic compounds (VOCs)



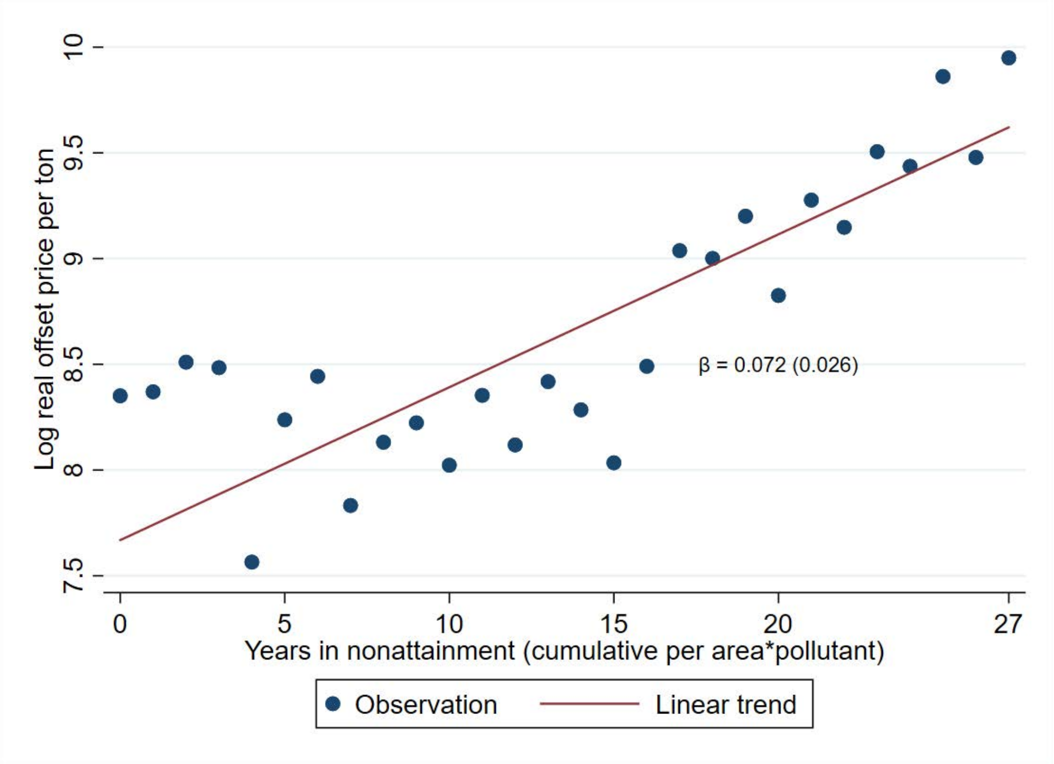
Notes: Data shows the average marginal benefits over the years 2011, 2014 and 2017. Marginal benefits of abatement are the marginal external cost avoided per ton abated for the indicated nonattainment area and pollutant, as estimated by the AP3 model. Dollars are deflated to real 2017 values using the 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 observed price ratio between permanent and temporary offsets. Marginal benefits of abatement are the marginal external cost avoided per short ton abated for the indicated nonattainment area and pollutant for years 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 occurring 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.