Carbon Pricing and Heterogeneous Abatement Responses: Evidence from Seven U.S. Cities

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Abstract

This paper examines whether carbon-pricing policies accelerate greenhouse gas reductions beyond those achieved by disclosure-based programs. Using a building-level panel from seven U.S. cities, we compare New York City's Local Law 97, an emissions-penalty regime, with disclosure-focused policies elsewhere. A difference-in-differences design finds modest but statistically significant average reductions, with substantial cross-building heterogeneity. We document a nonmonotonic, inverted U-shaped response to expected penalties: abatement rises with anticipated penalty salience up to a threshold and then flattens. Taken together, the estimates imply that the prevailing penalty is below the response-maximizing range.

JEL codes: Q40; Q52

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Do we need more aggressive policies to meet U.S. greenhouse-gas reduction targets? Environmentalists argue that the United States will not meet its Paris pledge to achieve a 50-52 percent cut by 2030 as the current emissions are only about 17 percent below 2005 levels (King et al., 2024). They argue that each year of delay would increase the cost of the reduction effort, making future cuts costlier and more disruptive, or risking an overshoot of the temperature ceiling. In contrast, conservatives favor market-based approaches, warning that stringent regulations would impose excessive costs and overstep the authority of the relevant agencies.

This paper addresses this debate using a novel dataset of building-level greenhouse gas emissions across seven U.S. cities: New York City, Philadelphia, San Francisco, Chicago, Seattle, Denver, and Los Angeles. While all seven adopted energy-disclosure policies for large buildings, New York City took another step and implemented a pricing-based regime that imposes penalties on emissions above building-specific caps. Specifically, New York City enacted Local Law 97 (LL97) of 2019 under the Climate Mobilization Act, which sets legally enforceable emissions caps for most buildings larger than 25,000 gross square feet and for covered building groups on a single tax lot or under one condominium board that exceed 50,000 square feet. Owners whose buildings exceed the applicable limit are subject to a penalty of $268 per metric ton of CO_2e above the cap, with additional fines for late reporting and false statements.[1] We leverage this cross-city policy variation to identify the impact and effectiveness of carbon pricing in the building sector.

In the first part of the paper, we assess the effect of the pricing-based regime. Using a difference-in-differences model comparing buildings in the treatment city (New York City) with those in disclosure-focused cities, we find mixed results on the effects of carbon pricing. We additionally employ a triple difference estimator to control important confounding factors, such as COVID-19. For example, COVID-19 affected building types

[1]Buildings meeting these size thresholds were already subject to energy benchmarking and disclosure under Local Law 84, so the net policy change introduced by LL97 is the per-ton exceedance penalty (LL84, LL97).

unevenly; offices were more severely affected than other property types (Gupta et al., 2022; Ling et al., 2020; Rosenthal et al., 2022). After controlling for office-sector dynamics, the estimates indicate reductions in greenhouse gas emissions of about 0.08 percent (CO_2e metric tons) and in energy use intensity of about 3.77 kBtu per sqft. Although statistically meaningful, this average effect is modest given the stringency of the pricing policy. To understand this magnitude, we examine how penalties interact with building-level emissions and allow for nonmonotonic responses, since a building's response depends on the penalty it expects to face. We first document substantial heterogeneity in expected penalties among covered buildings and, correspondingly, in their emissions responses. Using a multi-level difference-in-differences design, we find that buildings in the third quartile of the expected-penalty distribution (50th to 75th percentile) reduce emissions the most: about 5.5 percent overall and about 11.47 percent for offices.

In the next section, motivated by the nonmonotonic effects documented above, we estimate the causal response to carbon pricing using a flexible continuous difference-in-differences design in the spirit of Acemoglu and Finkelstein (2008). We pool buildings across the seven cities and define treatment intensity as the building's pre-policy expected penalty. The estimated average causal response on emission cut exhibits an inverted U-shaped pattern with respect to penalty intensity (Dijkstra & Gil-Moltó, 2018; Lambertini et al., 2017; Perino & Requate, 2012). In elasticity terms, a 1 percent increase in the expected penalty (total dollars) reduces emissions by about 0.012 percent; expressed per sqft, a 1 percent increase in penalty per sqft reduces emissions by about 0.33 percent. The marginal treatment effect becomes flat at expected-penalty levels of roughly $2.34 million for carbon emission (log) and $2.39 million for energy-use intensity (kBtu per sqft). Beyond about $2.3 to $2.4 million, additional expected penalties deliver little extra abatement, consistent with diminishing returns at high penalty exposure. We interpret this result as emissions falling most for buildings with mid-range expected penalties, with weaker responses for very low-exposure buildings that face little financial pressure and

for very high-exposure buildings that appear constrained by technology, capital, or occupancy. These results imply modest average effects with sizable abatement where the penalty is most salient.

The primary contributions of this paper are twofold. First, we estimate the price elasticity of building-level CO_2e using a new dataset that links emissions reduction and penalty intensity for large buildings across seven U.S. cities. Second, we assess how a pricing policy compares with disclosure-based or voluntary programs in reducing emissions. To our knowledge, this is the first study to estimate the effect of an explicit carbon price on emissions using building-level data across multiple large U.S. metropolitan areas. Given the scale of the building sector in U.S. energy use and greenhouse gas emissions, understanding whether pricing complements or substitutes for disclosure is an important open question [2]. Our results show that pricing policies deliver statistically and economically meaningful reductions in CO_2e.

Our paper finds that carbon pricing is effective, but the response is nonmonotonic and hinges on the financial incentives that buildings anticipate. Carbon emission reduction is limited when expected penalties are minor relative to retrofit costs or when owners expect to delay compliance; responses strengthen once anticipated penalties exceed thresholds that make upgrades privately cost-effective. This pattern is consistent with lumpy investment, option value of waiting, and financing frictions. Together, these results motivate future work that isolates the penalty mechanism itself by testing how expected compliance costs and penalty salience drive retrofit adoption, which is outside the scope of this paper.

[2] Homes and businesses account for about 31% of total U.S. greenhouse gas emissions when counting direct and indirect emissions from energy use (U.S. Environmental Protection Agency, 2025). U.S. General Services Administration reports that buildings use roughly 40% of U.S. energy and are responsible for about 35% of national greenhouse gas emissions, depending on boundary definitions (U.S. General Services Administration, 2025).

Literature Review

We contribute to the debate on pricing-style instruments (penalties tied to emissions) versus non-price approaches such as disclosure and voluntary programs (US EPA, 2014). Canonical reviews find that carbon pricing is typically the least-cost way to cut emissions while highlighting political and distributional constraints (Aldy & Pizer, 2016; Gillingham & Stock, 2018; Goulder & Parry, 2008). Although the literature reports varied aggregate impacts of carbon pricing,[3] we provide building-level evidence from seven large U.S. cities with quantifiable policy measures. Rather than issuing a single verdict on whether pricing dominates disclosure, we offer nuanced evidence on the effects of a pricing-style regime.

Our paper speaks directly to the carbon tax and carbon-pricing literature. Building on foundational work (Gillingham & Stock, 2018), a growing empirical literature examines pricing policies in Sweden (Andersson, 2019; Runst & Thonipara, 2020), Canada (Lawley & Thivierge, 2018; Murray & Rivers, 2015; Pretis, 2022), and cross-country settings (Rafaty et al., 2025; Sen & Vollebergh, 2018). We differ in two ways. First, we move from national or sector-aggregate analyses to building-level data across multiple large U.S. cities, which allows us to estimate emissions responses within narrowly defined property types while holding local conditions fixed. This adds evidence to the elasticity literature, which is largely country- or sector-level. Second, we provide a direct micro-level comparison of buildings with similar characteristics (size and type) under a pricing-style regime versus a disclosure-based policy, avoiding comparisons across fundamentally different units.

This paper also builds on the literature on nonlinear relationships between regulation and emissions, which emphasizes threshold effects. Environmental effort can be non-

[3]Causal evaluations show that carbon taxes and emissions trading systems reduce emissions with limited macroeconomic side effects and can stimulate clean innovation (Andersson, 2019; Calel & Dechezleprêtre, 2016; Freyre et al., 2020; Martin et al., 2014; Metcalf & Stock, 2023; Ramos et al., 2015; Rivers & Schaufele, 2015). Voluntary and disclosure-based programs also produce measurable reductions where reputational and information channels are strong. However, average effects are heterogeneous and often smaller (Anderson & Newell, 2004; Arimura et al., 2012; Khanna & Damon, 1999; Konar & Cohen, 1997).

monotonic, often failing to reduce emissions at low stringency but lowering them once a threshold is crossed, with possible reversals at very high levels. Wang and Zhang (2022) and Wolde-Rufael and Mulat-Weldemeskel (2021) show an inverted U-shaped relationship at aggregate scales (regions or countries). Our paper adds to this literature by studying buildings in the United States and by strengthening the causal interpretation of the policy-emissions link by employing a difference-in-differences design.

1 Building Carbon Emission Laws in the U.S.

Buildings account for roughly 31 percent of total U.S. greenhouse gas emissions when direct on-site fuel combustion and the sector's share of electricity generation are combined (U.S. Environmental Protection Agency, 2025). Because buildings use about three-quarters of U.S. electricity, allocating power-sector emissions to end uses further raises the share attributable to buildings (U.S. Environmental Protection Agency, 2025). In response, cities and states have adopted a broad set of building policies. Table 1 shows building energy policies across U.S. cities. Broadly, two regulatory schemes have emerged. First are information-based policies that require benchmarking, periodic reporting, and public transparency to address information frictions and enable market or administrative follow-up (Institute for Market Transformation, 2024; U.S. Department of Energy, 2019). Second are performance-based policies, which build on benchmarking by setting binding energy-use or emissions targets and attaching consequences for noncompliance, including financial penalties.

1.1 Carbon Pricing: New York City

Among U.S. cities that have implemented or plan to adopt pricing-style emissions standards, New York City has the most ambitious policy. New York City's Local Law 97 (LL97) of 2019, enacted under the Climate Mobilization Act, sets legally enforceable

emissions caps for most buildings larger than 25,000 gross square feet and for covered building groups on a single tax lot or under one condominium board that exceed 50,000 square feet. Owners whose buildings exceed the applicable limit are subject to a penalty of $268 per metric ton of CO_2e above the cap, with additional fines for late reporting and false statements. LL97 covers roughly 50,000 properties —about 5 percent of New York City's building stock —but these properties account for nearly 60 percent of citywide floor area and roughly half of building emissions.

Before this pricing policy, New York City implemented Local Law 84 (LL84), an energy-disclosure requirement. Enacted in 2009, LL84 requires covered buildings to benchmark their annual energy and water use. This energy disclosure came with a mile financial penalty capped at $500 per quarter, up to $2,000 per year [4]. Because LL84's expanded coverage closely matches LL97's thresholds, the disclosure-covered stock substantially overlaps with the buildings subject to LL97, which enables analysis of pricing effects within a standard coverage set.

1.1.1 Carbon Emission Penalty

The key component of New York City's carbon-pricing policy is the penalty. This financial enforcement applies to buildings whose emissions exceed their allowable limit, determined by each building's current CO_2e and floor area by occupancy type. Under LL97, the annual penalty equals the amount a building's actual emissions exceed its allowable limit multiplied by the per-metric-ton rate. The formula for the penalty is:

[4]Coverage initially applied to buildings 50,000 square feet and larger, and was expanded by Local Law 133 of 2016 to include buildings 25,000 square feet and larger, plus specific multi-building campuses

$$
\begin{aligned}
\text{Annual Penalty} &= \$268 \times \max\Big\{0, (E_{Actual} - E_{Limit})\Big\} \\
E_{Actual} &= \sum_{s} \text{Annual Energy Use}_s \times \text{Emission Factor}_s \\
E_{Limit} &= \sum_{o} \text{Floor Area}_o \times \text{Limit Factor}_o
\end{aligned} \tag{1}
$$

One notable feature of this penalty regime is that it does not apply a single standard to all buildings. Under this calculation, actual emissions E_{Actual} are computed as the sum across energy sources s of annual site energy use multiplied by the corresponding emission factors. Table 2 and Table 3 report the emission factors for electricity, natural gas, No. 2[5] and No. 4[6] fuel oil, district steam, and other additional fuel types, respectively. Many large buildings are mixed-use and therefore include multiple occupancy types. LL97 assigns property-type-specific emissions-intensity limits, so enforcement is based on a weighted standard that reflects the building's internal space mix rather than a single uniform threshold for all spaces.

The emissions limit E_{Limit} is computed as the sum across occupancy types o of floor area (sqft) multiplied by the applicable LL97 emissions-intensity limit factor ($\text{tCO}_2e/\text{sqft}$). Table 4 lists the factors used to construct these building-specific limits. Any positive excess $E_{\text{Actual}} - E_{\text{Limit}}$ is multiplied by \$268 per metric ton of CO_2e to obtain the annual penalty. In practice, this requires allocating each building's floor area to its EPA property types[7], applying the corresponding factors, and summing to form the allowable emissions total before comparing to measured CO_2e.

LL97 also provides a few limited tools that can lower a building's reported emissions or reduce penalties. First, renewable energy credits can be applied only to the electricity

[5]No. 2 fuel oil is a distillate fuel oil used for space heating (closer to diesel).

[6]No. 4 fuel oil is made by blending distillate and residual fuel oil.

[7]These limits tighten over time to advance decarbonization. For 2024 to 2029, the factors align with the EPA property types. Beginning in 2027, the program references factors set in the New York City Building Code, and stricter intensity requirements take effect after 2029 and again in 2035 (New York City Department of Buildings, 2024).

portion of a building's emissions, and they must be linked to power delivered into New York City. Second, a beneficial electrification credit gives credit for qualifying heat pump installations recorded with the city, with a larger benefit for equipment that is operating before 2027. Third, buildings can use Affordable Housing Reinvestment Fund offsets for up to 10 percent of their annual emissions limit, purchased through the city's program. These tools do not change the cap itself, but they can reduce the calculated overage and the resulting penalty.

1.2 Cities with Energy Disclosure or Interim Penalty

Energy disclosure programs are based on voluntary participation with low financial incentives. They require large buildings to benchmark whole-building energy and, often, water in EPA's ENERGY STAR Portfolio Manager, submit data on a fixed schedule, and disclose results publicly through websites or on-site placards. Energy disclosure differs from carbon pricing in two key respects. First, monetary enforcement is modest. For example, in Chicago, the maximum penalty for noncompliance is capped at $9,200 per year, and other cities have similar penalty features[8]. Second, fines target paperwork failures, such as failing to file, filing late, or failing to post a scorecard. There is no binding emissions cap and no per-ton penalty. Compliance incentives operate through transparency and reputational pressure that can influence tenants, investors, and access to incentives, while investment timing and technology choices remain with owners. Chicago, Philadelphia, San Francisco, and Los Angeles illustrate this model: broad coverage with public scoring or benchmarking, limited fines focused on non-reporting, and supportive measures such as audits, tune-ups, or retro-commissioning that encourage rather than compel upgrades.

[8]Philadelphia assesses 300 dollars after the first 30 days and 100 dollars per day thereafter; San Francisco sets 100 dollars per day for buildings above 50,000 square feet and 50 dollars per day for smaller covered buildings, each capped at 25 days; Los Angeles applies a 202 dollar noncompliance fee with possible additional administrative charges.

Seattle has adopted a performance standard with penalties, but it is not a carbon-pricing regime for our analysis period. Its 2023 Building Emissions Performance Standard covers existing commercial and multifamily buildings larger than 20,000 square feet and sets greenhouse-gas intensity targets beginning in 2031, using 2027 to 2030 data to stage compliance. Missed intervals trigger per-square-foot penalties that vary by use type: 10.00 dollars per sqft for nonresidential, 7.50 dollars per sqft for other multifamily, and 2.50 dollars per sqft for low-income or low-rent multifamily. Because the compliance targets begin in 2031 and penalties apply thereafter, we do not classify Seattle as a carbon-pricing jurisdiction in the present study window as it remains a disclosure-first jurisdiction with a future performance standard.

2 Data: Building Emission

We combined multiple building-level datasets across seven cities, New York, Chicago, Los Angeles, Denver, Philadelphia, Seattle, and San Francisco[9]. In each city, building owners or their consultants benchmark by entering property characteristics and whole-building energy and water use into EPA's ENERGY STAR Portfolio Manager (ESPM), a national reporting platform adopted by many state and local ordinances. Utilities can transmit aggregated whole-building data directly into Portfolio Manager via EPA web services. Portfolio Manager calculates greenhouse gas emissions using electricity grid emission factors for each eGRID subregion and supports both location-based and market-based accounting. Local governments then require owners to submit or share their Portfolio Manager records with the jurisdiction on an annual schedule, with program details and enforcement handled by each city. Figure 1 shows the overall CO_2e for the treated (NYC) and control (all other cities) before and after 2019.

[9]Our data collection about extensive building energy reports is from NYC Open Data, Chicago Data Portal, Los Angeles Open Data, Denver Open Data Catalogue, Open Data Philly, Seattle Open Data, and San Francisco Data, accordingly.

Table 5 reports summary statistics for carbon emissions, emissions intensity, energy use, gross floor area, and penalties by group and period. Units are metric tons of CO_2e for emissions, tCO_2e per sqft for intensity, kBtu per sqft for EUI, and thousand square feet for floor area.

For greenhouse gas emissions and energy use in buildings, EPA's Portfolio Manager uses two scopes to convert reported energy use into emissions. Scope 1 covers direct emissions from on-site fuel combustion. On-site fuels such as natural gas, fuel oils, and propane use EPA default factors expressed per unit of energy (e.g., kBtu). For each fuel, Portfolio Manager multiplies energy use by gas-specific emission factors[10] for CO_2 (carbon dioxide), CH_4 (methane), and N_2O (nitrous oxide), then converts to carbon dioxide equivalent (CO_2e) using global warming potentials (GWP).[11]

Scope 2 emissions arise from purchased electricity and district energy. Portfolio Manager assigns each property to an eGRID subregion using ZIP code or the serving electric utility, then applies the subregion's average emission rate for electricity that combines CO_2, CH_4, and N_2O into CO_2e. District steam, hot water, and chilled water are also treated as Scope 2 and use EPA default indirect factors. Emission rates are drawn from EPA's eGRID, which aggregates measured power-plant data and updates factors by reporting year.

For New York City buildings, we apply the LL97 rule exactly in Section 1.1.1. For buildings in other cities, we construct the same LL97-style overage and the associated "shadow penalty" using their floor-area mix and carbon emissions, but we treat it as a counterfactual measure. Figure 2 depicts the penalty (in USD) distribution of buildings in treated (NYC) and control (all other cities). In the estimation sample, we set their realized penalty to zero and retain the shadow overage and shadow penalty for comparability, scaling, and heterogeneity analysis. This aligns limit construction across cities

[10] Described in Table 2 and Table 3.

[11] Global Warming Potential (GWP) compares how much heat a greenhouse gas traps in the atmosphere relative to carbon dioxide over a specified time horizon, typically 100 years.

while preserving the fact that only New York City faced an enforceable per-ton charge in our study window.

For the continuous difference-in-differences analysis, we avoid mechanical endogeneity by fixing treatment intensity from the pre-policy period. Specifically, after computing building-year penalties, we calculate each building's pre-2019 average shadow penalty and use this baseline measure as the continuous treatment interacted with the post indicator. Realized penalties remain zero outside New York City. This design captures differential exposure to pricing while holding pre-policy emissions behavior constant.

3 Carbon Pricing: Substitute vs. Complement

In this section, we investigate the effects of the carbon-pricing policy. First, we test whether carbon pricing has an additional (complementary) effect beyond energy-disclosure policies or only a minimal (substitutive) effect on carbon-related outcomes. To do so, we estimate the average treatment effect by comparing treated buildings (in New York City) with control buildings (in other cities). We first check the parallel trend of carbon emission across cities, which is described in Figure 3. The regression is:

$$Y_{i,j,t} = \beta Post_t \times Treated_i + X_{i,j}\Gamma + FE + \epsilon_{i,j,t} \tag{2}$$

Here, $Y_{i,j,t}$ is the outcome for building i of property type j in year t. We consider three outcomes tied to emissions: greenhouse gas emissions (log metric tons), emissions intensity (metric tons per sqft), and energy use intensity (kBtu per sqft). $Post_t$ indicates the post-policy period, which we set to begin in 2019, the year of the Local Law 97 announcement. $Treated_i$ equals 1 for buildings located in New York City and 0 for buildings in the comparison cities; treatment status is time invariant and reflects exposure to Local Law 97. $X_{i,j}$ includes building gross floor area (GFA). FE denotes fixed effects; we include building, zipcode, and time fixed effects.

The parameter of interest is β, which represents the causal effect of the carbon-pricing policy. If carbon pricing incentivizes building owners to reduce emissions, then $\beta < 0$, indicating that the policy lowers emissions. A positive or statistically insignificant estimate would suggest limited effectiveness.

A potential threat to identification is the COVID-19 pandemic. Although COVID-19 depressed economic activity nationwide, the pace of recovery varied across cities (Gupta et al., 2022; Ling et al., 2020; Rosenthal et al., 2022). This pattern potentially induces city-specific emission trends that bias difference-in-differences estimates. To address this concern, we estimate Eq. (2) with interactions by property type. The premise is that pandemic-related fluctuations in emissions were concentrated in office buildings, whereas residential buildings were less affected. Allowing for property-type heterogeneity (and including property-type-by-time controls as needed) mitigates bias from differential pandemic dynamics.

Table 6 reports the estimates. The baseline specifications (columns 1, 3, and 5) indicate that, after the policy, NYC buildings emit about 3 percent more CO_2e (log metric tons) but use less energy (about -3.8 kBtu/sqft). This seeming paradox is addressed in columns 2, 4, and 6, which add an office-by-treatment interaction to capture COVID-19 dynamics by property type. For non-office properties, the average treatment effect on log CO_2e is small and negative (-0.86 percent, column 2). Offices exhibit an additional +6.9 percent, implying a net impact of roughly +6.0 percent for offices and -0.86 percent for non-office buildings. For CO_2e per sqft, the baseline positive effect shrinks to approximately 0.0085, and the office interaction is not statistically different from zero. For site EUI, the treatment effect becomes more negative when the office control is added (from -3.7719 to -5.0284 kBtu/sqft), and the office interaction remains statistically insignificant.

Taken together, these results suggest that the carbon-pricing policy reduces emissions for non-office buildings, but office-sector dynamics dampen aggregate estimates during COVID-19.

4 Heterogeneous Carbon Pricing Effect

4.1 Multi-Level Difference-in-difference

In this section, we investigate heterogeneous effects of carbon pricing. As noted in Section 2, only 21% of large NYC buildings are liable for penalties, and potential penalty amounts vary widely. This variation in incentive strength implies that a binary treated-versus-control difference-in-differences may mask policy effects, because the financial motive to reduce emissions differs across buildings.

To address this, we estimate a more flexible version of Eq. (2) that replaces the single treatment indicator with multi-level penalty exposure. First, we interact $Post_t$ with indicators for discrete penalty tiers (no penalty, low, medium, high). This lets the estimated effect scale with the strength of the pricing signal each building faces. The working hypothesis is that buildings that face (in New York City) or would have faced (in other cities) higher penalties under the pricing regime should exhibit larger reductions in emissions.

Implementation proceeds in two steps. We construct an expected penalty using pre-policy emissions and the Local Law 97 schedule, and assign each building to one of five groups: no penalty and the four quartiles of the positive expected-penalty distribution. We then estimate a DID with $Post_t$ interacted with these tier indicators, comparing changes in emissions within buildings across penalty tiers. Building and time fixed effects remain in place, and the omitted group is the no-penalty tier, shown up in the dataset after 2020. We estimate the following regression:

$$Y_{i,j,t} = \beta Post_t \times Treated_i \times Tier_g + X_{i,j}\Gamma + FE + \epsilon_{i,j,t} \tag{3}$$

Here, $Y_{i,j,t}$ is the same three outcome (log of tCO_2e, tCO_2e/sqft, and EUI (kBtu/sqft) for building i of property type j in year t. $Post_t$ indicates the post-policy period, which we set to begin in 2019, the year of the Local Law 97 announcement. $Treated_i$ equals 1 for buildings located in New York City and 0 for buildings in the comparison cities; treatment

status is time invariant and reflects exposure to Local Law 97. $X_{i,j}$ includes building gross floor area (GFA). FE denotes fixed effects; we include building, zipcode, and time fixed effects.

Table 7 reports the multi-level difference-in-difference estimates for Eq. (3). First, the ATET is opposite to a reduction or not significant by property type: it is positive and significant for offices and not significant for multifamily. Second, emission reductions concentrate in the upper-middle penalty tier: for offices, the Q75 interaction is negative and significant (-0.0319); penalty-tier interactions for multifamily are positive and significant except at Q75, which is negative and not significant. Third, the combination of no detectable effect at Q25 and Q100 with sizable negatives at Q50 and Q75 for offices suggests non-monotonic carbon-pricing effects across penalty exposure tiers.

4.2 Continuous Difference-in-difference

In the multi-level difference-in-difference model, we discretize the penalty into 5 categories, and this risks losing within-group variation and making the estimates sensitive to arbitrary cut-off choices. To address this econometrics issue, we estimate the elasticity of carbon emissions with respect to penalties and investigate the nonlinear shape of this relationship in this section.

To estimate the elasticity, we use a continuous difference-in-difference framework in which the treatment intensity varies across buildings. In line with the canonical framework in Acemoglu and Finkelstein (2008), we interact a building-specific pre-policy anticipated penalty with a post-treatment indicator.

Our estimating equations are:

$$Y_{i,j,t} = \beta Post_t \times log(Penalty_i) + X_{i,j}\Gamma + FE + \epsilon_{i,j,t} \tag{4}$$

$$Y_{i,j,t} = \beta_1 Post_t \times Penalty_i + \beta_2 Post_t \times Penalty_i^2 + X_{i,j}\Gamma + FE + \epsilon_{i,j,t} \tag{5}$$

where $y_{i,j,t}$ is either the log of total emission or emissions intensity for building i in year t and ZIP code z. Just as the other models, three fixed effects are included: building fixed effects, time fixed effects, and ZIP code fixed effects.

Table 8 reports the DID estimation results of Eq. (4) and (5). In the columns (1) and (2), the estimate suggests that for log emission, the elasticity is -0.0098, implying that a 1% higher penalty reduces emissions by 0.01%. Columns (3) and (4) allow for nonlinear responses by including penalty levels and their square. Both the penalty term, β_1, and the penalty with square term, β_2, coefficients are significant. For the log emission, the estimates are $\beta_1 = -1.1534$ and $\beta_2 = 0.2475$. For the emission intensity, the estimates are $\beta_1 = -1.1454$ and $\beta_2 = 0.2424$. This estimation suggests the inverted U-shape relationship between penalty intensity and emission reduction. Figure 4 depicts this pattern. Using the estimates, we find that the turning point where the marginal effect crosses zero is $\frac{-\beta_1}{2\beta_2} \approx \$2.36M$ for log emission and $\$2.33M$. Hence, the marginal abatement declines as the penalty rises, with the marginal effect being almost zero around \$2.33-\$2.36M. Beyond the \$2.33-\$2.36M penalty, further increases in penalty have low or zero incentives to reduce emissions. The last two columns use log site energy use intensity (EUI) as the dependent variable. The results confirm that reductions in carbon emissions are driven mainly by lower energy use following the adoption of carbon pricing. This pattern is consistent with buildings' immediate response being to cut energy use to avoid penalties.

Our calculation for the optimal level of the per-ton penalty rate suggests that the current per-ton penalty, \$268, is too low, and to maximize the carbon reduction impact, the optimal penalty is approximately \$25,111.45, which is far above the current penalty.

$$Y_{i,j,t} = \sum_{k=2015}^{2022} \beta_k \left[\log(\text{Penalty}_i) \times \mathbf{1}\{k = t\}\right] + X_{i,j}\Gamma + FE + \epsilon_{i,j,t} \tag{6}$$

We also estimate an event-study specification in Eq. (6) that interacts the log of the baseline penalty exposure with time indicators, using 2015 as the reference year. In the Figure 5, the coefficients on the interaction terms represent how the relationship between emis-

sions and penalty exposure evolves relative to benchmark. The estimates show no significant differences before 2019, indicating that buildings with higher expected penalties followed similar pre-policy trends as others. Post-2019 coefficients become statistically significant and negative, growing in magnitude through 2022. This pattern suggests that buildings facing higher penalties reduced their emissions more substantially in the years following the policy's introduction.

5 Conclusion

This study provides the first empirical evidence on how carbon penalties influence building-level emissions in major U.S. cities. Using a novel panel dataset covering over 200,000 large buildings across seven metropolitan areas, we evaluate the effects of New York City's LL97 in comparison with disclosure-only regimes. Our findings show that the carbon penalty impact statistically significantly reduces the building carbon emission, but its impact is highly heterogeneous and nonmonotonic across the distribution of penalties.

On average, a one percent increase in the expected carbon penalty reduces total emissions by approximately 0.01 percent and energy use intensity by about 0.34 percent per sqft. The response follows an inverted U shape, where buildings facing mid-range penalties exhibit the most significant reductions. In contrast, those with either very low or very high expected penalties show weaker responses. This pattern suggests that moderate penalties effectively motivate reducing carbon emissions, while diminishing returns emerge once financial or technological constraints dominate.

Overall, carbon penalties complement rather than substitute for disclosure-based programs. The results imply that pricing mechanisms can enhance existing transparency policies by making emissions reductions financially salient, but the magnitude of their effect depends critically on penalty design and enforcement. Future research should examine the behavioral and financing channels through which penalty expectations translate

into abatement investments, as well as the longer-term dynamics of compliance beyond initial policy implementation.

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Table 1: Summary of Building Energy and Performance Policies in Major U.S. Cities

City	Policy Type	Start Year	Building Coverage	Penalty
NYC	Performance (LL97)	2019	Single buildings $\geq$ 25,000 sqft; groups of buildings on one lot $\geq$ 50,000 sqft	\$268 per metric ton of CO_2e over the emissions cap.
	Rating (LL33)	2018		Fines for failure to post the energy efficiency grade.
	Disclosure (LL84)	2011		Fines for late, false, or missing benchmarking reports.
Seattle	Performance (BPS)	2023	Existing non-residential and multifamily buildings $\geq$ 20,000 sqft	Fines per sqft for missed performance intervals (\$2.50-\$10.00).
	Disclosure	2010		Flat fines for reporting failures.
Denver	Performance	2021	Generally $\geq$ 25,000 sqft Buildings 5,000-24,999 sqft have elective pathways.	Penalty based on site-energy target shortfall (typically \$0.30-\$0.70 per kBtu/year).
	Disclosure	2016		Fines for failure to submit benchmarking report.
Chicago	Rating	2019	City, commercial, and multifamily buildings $\geq$ 50,000 sqft	Fine for failure to display the energy placard.

Continued on next page

City	Policy Type	Start Year	Building Coverage	Penalties for Non-Compliance
	Disclosure	2014		Initial fine of $100 plus $25 per day until corrected (caps apply).
Philadelphia	Performance	2019	Benchmarking for buildings $\geq$ 50,000 sqft Tune-ups for most non-residential of the same size.	Penalties for failure to submit a tune-up report.
	Disclosure	2013		$300 initial fine plus $100 per day after deadline for late reports.
San Francisco	Performance	2011	Benchmarking for non-residential $\geq$ 10,000 sqft Renewable electricity for commercial $\geq$ 50,000 sqft	Penalties for non-compliance with renewable electricity requirements.
	Disclosure	2011		Daily fines up to $100 for late reporting (capped annually).
Los Angeles	Performance	2017	Privately owned $\geq$ 20,000 sqft; City-owned $\geq$ 7,500 sqft	Fines for failure to complete required audits or retro-commissioning.
	Disclosure	2017		Fines up to $202 per building for late reporting; significant late fees apply.

Notes: **BEPS/BPS:** Building Energy Performance Standard. **BERDO:** Building Energy Reporting and Disclosure Ordinance. **CO_2e:** Carbon Dioxide Equivalent. **EBEWE:** Existing Buildings Energy and Water Efficiency Ordinance. **LL:** Local Law (New York City).

Table 2: LL97 Emission Factors by Compliance Period (Administrative Code §28-320.3.1.1)

Energy Source	**Unit**	**Emission Factor**
Panel A: 2024–2029		
Electricity (utility grid)	tCO_2e per kWh	0.000288962
Natural gas	tCO_2e per kBtu	0.00005311
No. 2 fuel oil[a]	tCO_2e per kBtu	0.00007421
No. 4 fuel oil[b]	tCO_2e per kBtu	0.00007529
District steam	tCO_2e per kBtu	0.00004493
Panel B: 2030–2034		
Electricity (utility grid)	tCO_2e per kWh	0.00014500
Natural gas	tCO_2e per kBtu	0.00005311
District steam	tCO_2e per kBtu	0.00004320
No. 2 fuel oil[a]	tCO_2e per kBtu	0.00007421
No. 4 fuel oil[b]	tCO_2e per kBtu	0.00007529

Source: NYC Department of Buildings, Rule 1 RCNY §103-14. The rule also permits a time-of-use method for electricity using hourly consumption per §103-14(d)(3)(iii).

[a] No. 2 fuel oil is a distillate heating oil that meets ASTM D396 specifications; see the U.S. Energy Information Administration Glossary.

[b] No. 4 fuel oil is a blend of distillate and residual fuel oils that conforms to ASTM D396 and is commonly used in commercial and industrial burners; see U.S. Energy Information Administration definitions.

Table 3: Additional On-site Fuel Emission Factors per DOB Rule (tCO_2e per kBtu)

Fuel	**Factor**	**Fuel**	**Factor**
Biofuel	0.00007389	Kerosene	0.00007769
Butane	0.00006502	Naphtha $< 401°F$	0.00006827
Butylene	0.00006897	Other oil $> 401°F$	0.00007647
Coke oven gas	0.00004689	Pentanes plus	0.00007027
Diesel	0.00007421	Propane	0.00006425
Distillate fuel oil No. 1	0.00007350	Propylene	0.00006802
Ethane	0.00005985	Special naphtha	0.00007259
Ethylene	0.00006621	Fuel gas	0.00005925
Gasoline	0.00007047	Isobutane	0.00006519
Isobutylene	0.00006911		

Source: NYC Department of Buildings, Rule 1 RCNY §103-14, Tables of emission coefficients applicable under LL97 compliance. For fuels not listed, owners must request approval of a coefficient under §103-14(d)(3)(i)(c).

Table 4: LL97 emissions–intensity limit factors by ESPM property type, reporting years 2024 to 2029

Property type	tCO_2e/sf	Property type	tCO_2e/sf	Property type	tCO_2e/sf
Adult Education	0.00758	Enclosed Mall	0.01074	Performing Arts	0.00846
Ambulatory Surgical Center	0.01181	Financial Office	0.00846	Personal Services (Health/Beauty, Dry Cleaning, etc.)	0.00574
Automobile Dealership	0.00675	Fitness Center/Health Club/Gym	0.00987	Pre-school/Daycare	0.00675
Bank Branch	0.00987	Food Sales	0.01181	Refrigerated Warehouse	0.00987
Bowling Alley	0.00574	Food Service	0.01181	Repair Services (Vehicle, Shoe, Locksmith, etc.)	0.00426
College/University	0.00987	Hospital (General Medical & Surgical)	0.02381	Residence Hall/Dormitory	0.00758
Convenience Store without Gas Station	0.00675	Hotel	0.00987	Residential Care Facility	0.01138
Courthouse	0.00426	K–12 School	0.00675	Restaurant	0.01181
Data Center	0.02381	Laboratory	0.02381	Retail Store	0.00758
Distribution Center	0.00574	Library	0.00675	Self-Storage Facility	0.00426
Mailing Center/ Post Office	0.00426	Lifestyle Center	0.00846	Senior Care Community	0.01138
Manufacturing/ Industrial Plant	0.00758	Medical Office	0.01074	Social/Meeting Hall	0.00987
Medical Office	0.01074	Movie Theater	0.01181	Strip Mall	0.01181
Movie Theater	0.01181	Multifamily Housing	0.00675	Supermarket/ Grocery Store	0.02381
Multifamily Housing	0.00675	Museum	0.01181	Transportation Terminal/ Station	0.00426
Non-Refrigerated Warehouse	0.00426	Office	0.00758	Urgent Care/Clinic/ Other Outpatient	0.01181
Office	0.00758	Other - Education	0.00846	Vocational School	0.00574
Other - Education	0.00846	Other - Entertainment/ Public Assembly	0.00987	Wholesale Club/ Supercenter	0.01138
Other - Entertainment/ Public Assembly	0.00987	Other - Lodging/Residential	0.00758	Worship Facility	0.00574
Other - Lodging/Residential	0.00758	Other - Mall	0.01074		
Other - Mall	0.01074	Other - Public Services	0.00758		
Other - Public Services	0.00758	Other - Recreation	0.00987		
Other - Recreation	0.00987	Other - Restaurant/Bar	0.02381		
Other - Restaurant/Bar	0.02381	Other - Services	0.01074		
Other - Services	0.01074	Other - Specialty Hospital	0.02381		
Other - Specialty Hospital	0.02381	Other - Technology/ Science	0.02381		
Other - Technology/ Science	0.02381	Outpatient Rehabilitation/ Physical Therapy	0.01181		
Outpatient Rehabilitation/ Physical Therapy	0.01181	Parking	0.00426		
Parking	0.00426	Performing Arts	0.00846		

Notes: Values are emissions–intensity limits in metric tons CO_2e per sqft used to compute covered-building limits for calendar years 2024 to 2029. For authoritative definitions, property-type mapping rules, and any updates, see 1 RCNY §103-14 (New York City Department of Buildings, 2025).

Table 5: Pre- and Post-2019 Summary Statistics by Treatment Status

	Control: Non-NYC Cities			Treated: NYC		
Variable	Mean	SD	P50	Mean	SD	P50
Panel A. Pre-2019						
CO_2e Emissions (tCO_2e)	714.30	1772.06	190.00	675.48	1423.63	355.60
CO_2e Emissions (tCO_2e/ft^2)	0.37	0.31	0.28	0.54	0.21	0.52
EUI ($kBtu/ft^2$)	52.73	27.12	47.00	82.84	32.17	82.40
GFA (thousand ft^2)	144.73	228.29	67.32	123.48	221.92	68.20
Multifamily	0.73	0.44	1.00	0.89	0.31	1.00
Office	0.27	0.42	0.00	0.10	0.31	0.00
Penalty (USD)	20,747.94	115,345.94	0.00	7,523.82	56,588.52	0.00
Number of Buildings		11,795			22,039	
Panel B. Post-2019						
CO_2e Emissions (tCO_2e)	521.28	1293.74	138.50	546.29	1191.98	292.90
CO_2e Emissions (tCO_2e/ft^2)	0.31	0.24	0.25	0.48	0.19	0.47
EUI ($kBtu/ft^2$)	48.06	24.68	42.70	75.01	30.57	74.60
GFA (thousand ft^2)	137.76	229.48	60.17	115.56	206.78	61.31
Multifamily	0.77	0.42	1.00	0.89	0.30	1.00
Office	0.23	0.42	0.00	0.10	0.30	0.00
Penalty (USD)	4,507.06	51,178.02	0.00	4,008.41	38,106.90	0.00
Number of Buildings		12,771			23,033	

Notes: Table reports summary statistics for buildings in Non-NYC cities (control) and NYC (treated), split into pre-2019 and post-2019 periods. CO_2e denotes carbon-dioxide equivalent emissions; EUI is energy use intensity; GFA is gross floor area. Means (Mean), standard deviations (SD), and medians (P50) are shown. Binary indicators (Multifamily, Office) are reported as shares. Monetary values are in USD.

Table 6: Difference-in-Differences

	Log CO_2e		CO_2e/ft^2		Site EUI ($kBtu/ft^2$)	
	(1)	(2)	(3)	(4)	(5)	(6)
Post × Treat	0.0315***	-0.0086**	0.0085***	-0.0035**	-3.7719***	-5.0284***
	(0.0038)	(0.0038)	(0.0015)	(0.0015)	(0.1977)	(0.2045)
Post × Treat × Office		0.0690***		0.0056		-0.0596
		(0.0107)		(0.0048)		(0.5843)
Building FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Zipcode FE	Yes	Yes	Yes	Yes	Yes	Yes
N	194,226					
F	78.20	240.73	16.57	198.59	182.19	315.53
Adjusted R^2	0.96	0.96	0.81	0.82	0.77	0.77

Notes: Entries are DID coefficients with standard errors in parentheses. Outcomes are log total CO_2e emissions, CO_2e per square foot, and site energy use intensity (EUI). All specifications include building, year, and zipcode fixed effects. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

Table 7: Multi-Level Difference-in-Differences

	Log CO_2e		
	(1)	(2)	(3)
Post × Treat	0.0338***	-0.0071	0.0679***
	(0.0043)	(0.0043)	(0.0113)
Post × Penalty(Q25) × Treat	0.0333*	0.0358**	0.0039
	(0.0179)	(0.0157)	(0.0706)
Post × Penalty(Q50) × Treat	0.0045	0.0333**	-0.1336**
	(0.0158)	(0.0147)	(0.0556)
Post × Penalty(Q75) × Treat	-0.0319**	-0.0043	-0.1244***
	(0.0146)	(0.0152)	(0.0425)
Post × Penalty(Q100) × Treat	0.0189	0.0312**	-0.0112
	(0.0133)	(0.0143)	(0.0315)
All Building	Yes	No	No
Multifamily Only	No	Yes	No
Office Only	No	No	Yes
FE	Yes	Yes	Yes
N	185,318	155,594	29,578
F	148.21	144.32	19.86
Adjusted R^2	0.96	0.96	0.97

Notes: Outcome is log total CO_2e emissions. Columns (1)–(3) report DID estimates for all buildings, multifamily only, and office only, respectively. "Penalty(Qq)" indicates indicators for being in the qth percentile bin of the penalty distribution interacted with Post and Treat. All specifications include fixed effects (FE) as indicated. Standard errors in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

Table 8: Continuous Diff-in-Diff

	Log CO_2e	CO_2e/ft2	Log CO_2e	CO_2e/ft2	Log Site EUI	Log Site EUI
	(1)	(2)	(3)	(4)	(5)	(6)
Post × Log(Penalty+1)	-0.0098***	-0.0085***			-0.0126***	
	(0.0006)	(0.0003)			(0.0006)	
Post × Penalty (millions)			-1.1534***	-1.1454***		-1.3612***
			(0.1472)	(0.1216)		(0.1636)
Post × Penalty^2 (millions^2)			0.2475***	0.2424***		0.2900***
			(0.0305)	(0.0250)		(0.0339)
N	185,318	185,318	185,318	185,318	185,318	185,318
F	150.61	485.67	56.80	32.13	354.40	158.25
Adjusted R^2	0.96	0.81	0.96	0.81	0.74	0.74

Notes: Entries are DID coefficients with standard errors in parentheses. Columns (1)–(2) and (5) use the log transformation of the penalty, $\log(\text{Penalty} + 1)$; columns (3)–(4) and (6) use the penalty in millions of USD and its square;Outcomes are log total CO_2e emissions, CO_2e per square foot, and energy use intensity in Column (1)-(2), (3)-(4), and (5)-(6), respectively. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

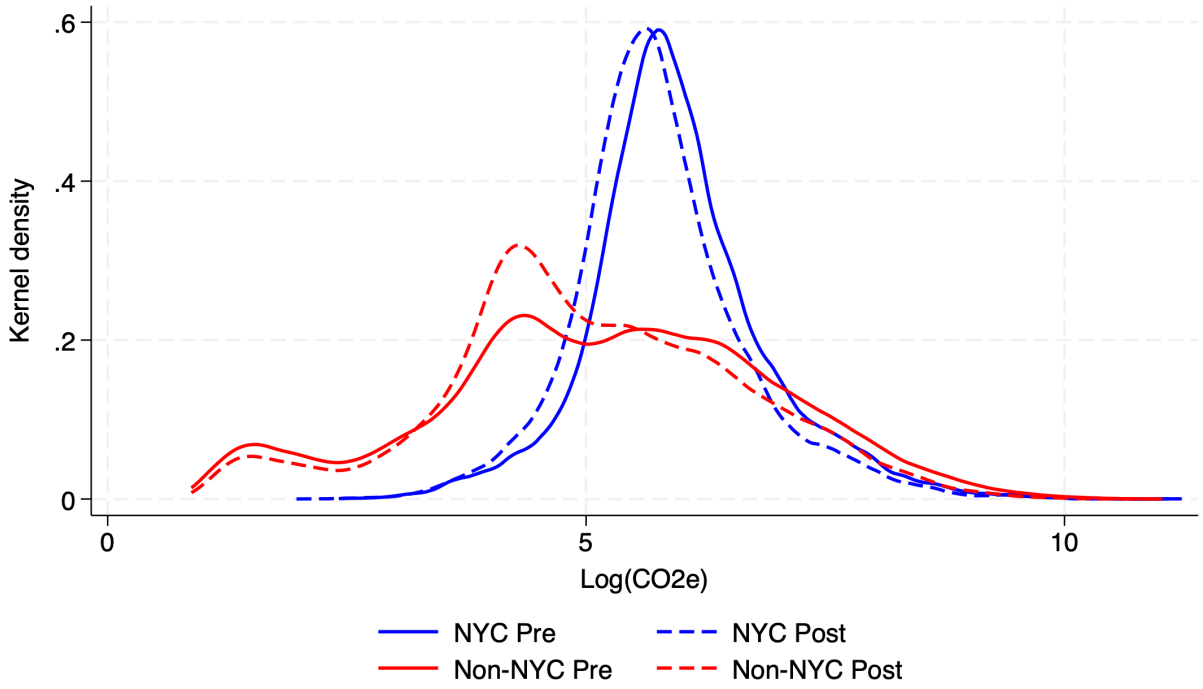


Figure 1: Distribution of CO_2e: NYC vs. Other Cities

Notes: This figure plots kernel density estimates of log CO_2e emissions at the building level. The treated group consists of buildings located in New York City, while the control group includes buildings from all other cities in the sample. Densities are shown separately for the pre-2019 and post-2019 periods.

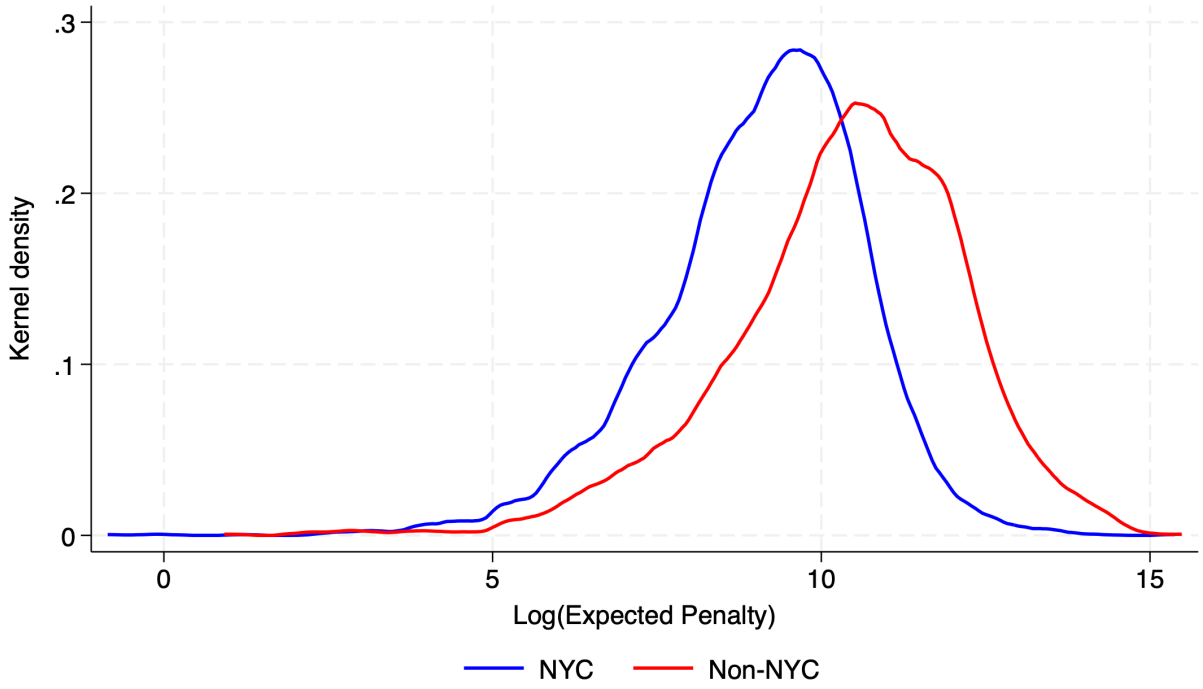


Figure 2: Distribution of Expected Penalties: NYC vs. Other Cities

Notes: Kernel density estimates of building-level expected penalties. The treated group is New York City buildings. The control group is all other cities. Control penalties are computed as shadow penalties by applying New York City (LL97) emissions factors and the penalty schedule to non-NYC buildings to ensure comparability.

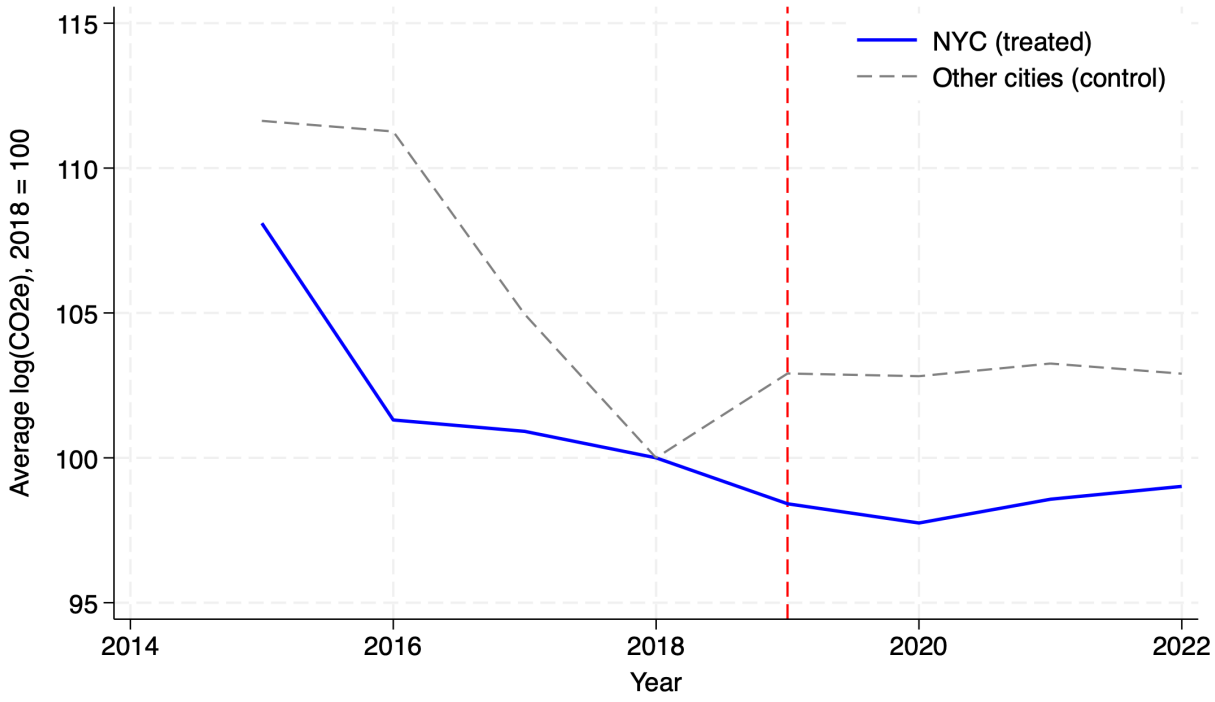


Figure 3: Parallel Trends: NYC vs Other Cities

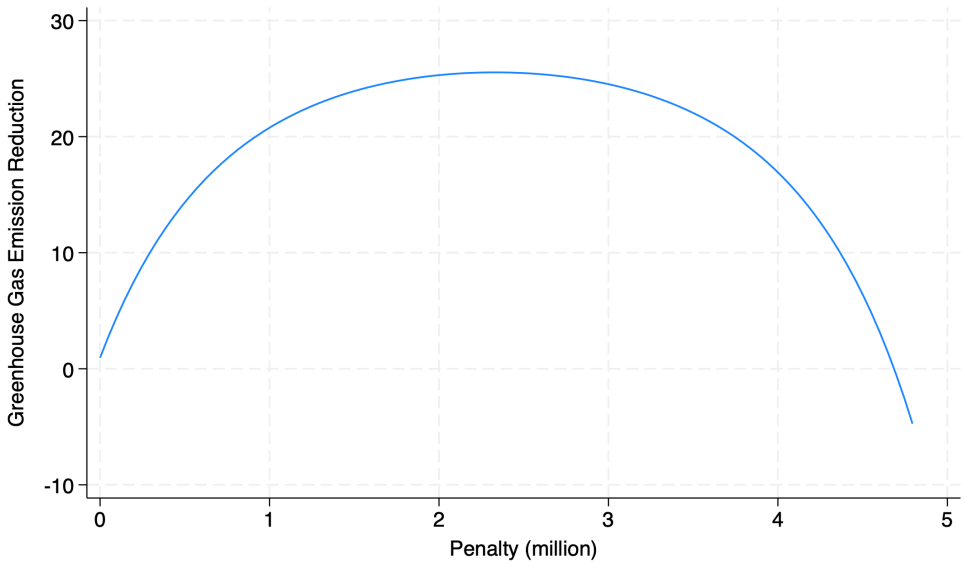


Figure 4: Greenhouse Gas Emission Reduction (tCO_2e)

Notes: The vertical axis measures average of predicted building-level greenhouse gas (GHG) emission reduction, calculated as the difference between post-2019 and pre-2019 emissions (tCO_2e). Positive values indicate reductions in emissions, while negative values indicate increases.

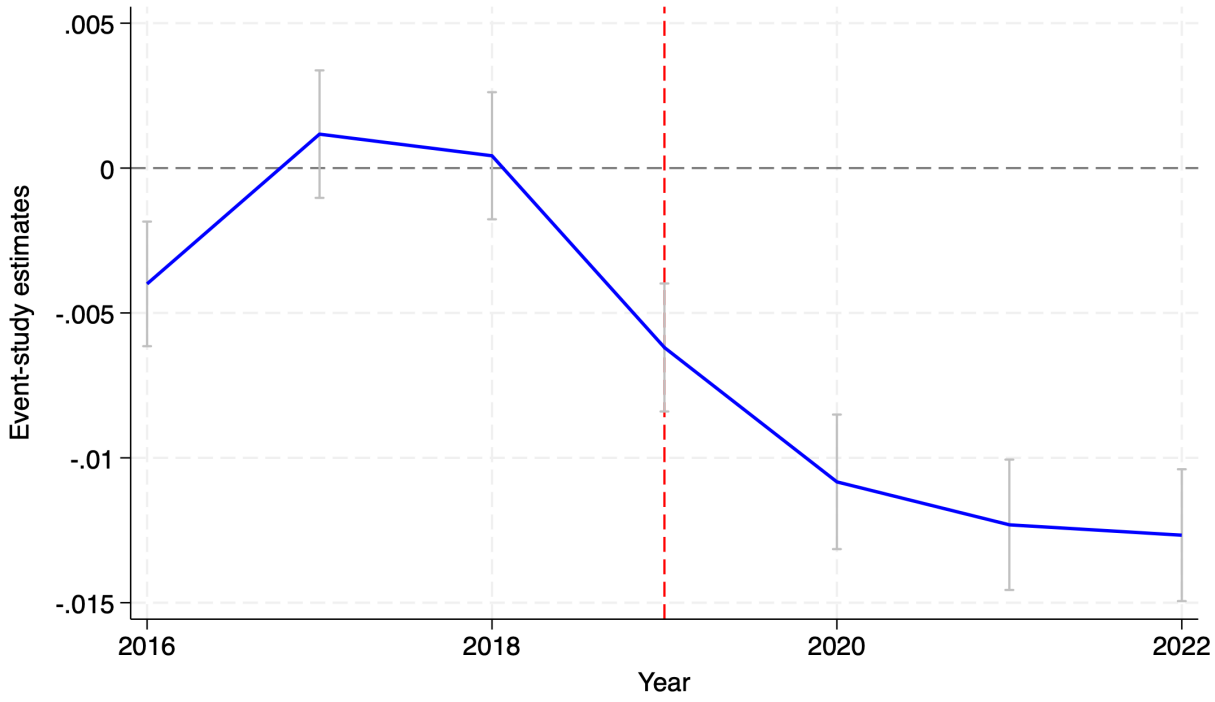


Figure 5: Event Study Estimates (Continuous Difference-in-Difference)