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The impact of mandatory energy audits on building energy use

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Cities are increasingly adopting energy policies that reduce information asymmetries and knowledge gaps through data transparency, including energy disclosure and mandatory audit requirements for existing buildings. Although such audits impose non-trivial costs on building owners, their energy use impacts have not been empirically evaluated. Here we examine the effect of a large-scale mandatory audit policy—New York City's Local Law 87—on building energy use, using detailed audit and energy data between 2011 and 2016 for approximately 4,000 buildings. This specific policy context, in which the compliance year is randomly assigned, provides a unique opportunity to explore the audit effect without the self-selection bias found in studies of voluntary audit policies. We find energy use reductions of approximately −2.5% for multifamily residential buildings and −4.9% for office buildings. The results suggest that mandatory audits, by themselves, create an insufficient incentive to invest in energy efficiency at the scale needed to meet citywide carbon-reduction goals.

Energy use in buildings accounts for a significant proportion of urban greenhouse gas (GHG) emissions, particularly in high-density cities[1]. For example, New York City's (NYC's) most recent carbon inventory estimates that building energy use is responsible for approximately 67% of citywide emissions[2]. Given the substantial contribution of the built environment to global GHG emissions, city policymakers have made increasing building energy efficiency a central component of long-term sustainability goals.

As new construction represents a small fraction of the building stock of a given city in any year, city energy policies are increasingly focused on ways to improve the efficiency of existing buildings[3]. Informational energy regulations, which are premised on the idea that an absence of data and transparency causes suboptimal investment in energy efficiency[4], have become popular policy instruments to encourage market-based interventions for energy use reductions. More than 20 cities in the United States, including Austin, Chicago and San Francisco, have adopted energy informational policies in recent years, and the pace of adoption continues to increase[5].

NYC has been a leader in this regard, and has implemented two informational regulations in its efforts to reduce building energy use and cut GHG emissions. The first, set forth in Local Law 84 of 2009 (LL84), requires property owners of large buildings to release annual energy consumption data used to benchmark building energy performance. The second, known as Local Law 87 (LL87), introduced a mandatory energy audit requirement for buildings larger than 50,000 ft^2. Each covered property must conduct an audit, also referred to as an Energy Efficiency Report, once every 10 years and report its findings, which include detailed energy end-use information and recommended energy conservation measures (ECMs). Roughly 10% of regulated buildings have been required to conduct an audit each year since 2013, and annual deadlines are randomly assigned based on the last digit of the property's Borough-Block-Lot (BBL) tax parcel identifier. LL87 also requires owners to implement certain retrocommissioning measures to 'tune-up' existing systems at the time of audit, such as to ensure that light fixtures are clean and water pumps are operating as designed[6].

Early studies indicate that energy disclosure is correlated with meaningful reductions in building energy use[7–9], although recent evidence suggests that there are differential impacts of the policy[10]. Yet few, if any, studies have examined the effect of a mandatory audit policy on energy use in commercial and multifamily residential buildings. This is an important omission: if information gained from the required energy audits leads property owners to invest in energy efficiency improvements that they would not otherwise implement, policymakers may be justified in expanding audit requirements to a broader range of properties and other cities may consider these requirements in their carbon-reduction-policy toolkit. A positive effect of mandatory audits on energy efficiency may also provide support for requiring more rigorous audits, including the consideration of 'deep energy retrofits', which will be necessary to achieve citywide 80%, and greater, carbon emissions reduction targets. However, if mandatory audits—which can be quite costly and time-consuming for property owners, especially of smaller buildings[11]—do not meaningfully influence behaviour or investment decisions, policymakers may do well to simply adopt an energy performance standard and allow the market to determine the optimal way to meet the requirement. Notably, in April 2019 NYC passed a law that caps the amount of fossil-fuel based energy that large buildings can consume without paying a fine[12]. This law, which effectively established performance standards for the buildings it covers, may obviate the need for additional mandates.

This study seeks to inform urban energy policy decisions by comparing energy use in properties that have performed a mandatory energy audit with those that have not. Specifically, we analysed energy benchmarking data collected by NYC annually under LL84 from 2011 to 2016 to investigate whether properties that conducted an audit exhibited greater average reductions in energy use than similar, non-audited properties. We collected detailed audit report data from mandatory LL87 audits conducted in 2013 and 2014 through a randomly assigned allocation process, which resulted in an integrated sample of 3,981 buildings. The analysis examines two primary building types (office and multifamily

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housing), while it controls for multiple time-invariant and time-varying attributes to evaluate whether energy audits have differential impacts across market segments. We also attempt to contextualize the audit effect by disaggregating the potential impacts of retrocommissioning activities from those attributable to ECMs. Our results indicate postaudit energy use reductions of 2.5% for multifamily and 4.9% for office buildings compared to non-audited properties. The magnitude of savings is found to be consistent with what could be achieved through low-cost and no-cost energy efficiency improvements.

Energy retrofits and the energy efficiency gap

Numerous studies have demonstrated that energy efficiency retrofits can substantially reduce building energy use[13,14]. In fact, building science research indicates that 'deep' retrofits can reduce building energy use by 50% or more[15,16]. Given that commercial and residential buildings are responsible for approximately 40% of the total energy consumption in the United States[17], to implement even a fraction of these measures would make a material contribution to governments' GHG reduction goals. As a case in point, one study reports that, by 2050, more than 11% of US energy use could be saved through building retrofits alone[18].

Many of the available energy efficiency retrofit measures, whether technological or behavioural, are shown to have relatively short payback periods, after which they are expected to confer net cost savings[19]. For larger commercial or multifamily buildings, several common ECMs, such as upgrading building controls and replacing lighting, are estimated to have payback periods of five years or less and, in many cases, less than one year[20,21]. Despite the apparent economic case for retrofits, adoption has been slow[22,23]. This disconnect between the availability of cost-effective energy efficient technologies and their diffusion and use in the marketplace is often referred to as the 'energy efficiency gap'[4].

Scholars have long theorized that the energy efficiency gap is due, at least in part, to information deficits[11,24–26]. Three distinct types of deficits are believed to be at play. First, building owners may lack information about the energy performance of their buildings, which includes information about strategies to reduce consumption, and thus may not be knowledgeable about energy efficiency investment opportunities. Second, even where building owners are so informed, they may withhold relevant information from their tenants. Landlords may have an incentive to withhold such information where tenants pay their own utility bills because, in such instances, landlords will bear the cost of energy efficiency upgrades, whereas their tenants receive the benefits through lower utility payments[27]. This misalignment of incentives between landlords and tenants is typically referred to as the 'split incentive' problem[25]. Finally, the absence of energy use information in the marketplace creates barriers to accounting for building energy efficiency in investment or tenant and homebuyer locational decisions. Labelling and rating systems, such as the US Environmental Protection Agency's ENERGY STAR programme and the US Green Building Council's Leadership in Energy and Environmental Design rating system, are designed to overcome this knowledge gap, similar to nutrition labelling or vehicle fuel efficiency ratings[28,29]. However, these programmes, and others, are constrained by the self-selection of participants and non-trivial flaws in data quality and the statistical methods used to calculate scores[30,31].

The literature contains substantial evidence to support the existence of persistent information deficits[32,33]. Even more concerning is how information asymmetries might impact lower-income households, for whom a lack of knowledge about efficiency opportunities or mismatched utility subsidies and payment programmes may hinder measures for energy cost reduction[34–36]. Recent studies of energy efficiency in subsidized housing found these properties to be far less efficient than similar market-rate housing, which suggests that significant opportunities exist to improve the quality of the low-income housing stock[37,38].

Effects of energy disclosure and audit policies

Policies that require energy audits, such as LL87, and the disclosure of energy performance information, like LL84, are designed to help overcome information gaps[39]. Yet the two types of policies employ different tactics to do so. In particular, although audit requirements aim to improve building owners' awareness of cost-effective retrofit opportunities, disclosure policies seek to reduce information asymmetries between building owners and prospective investors or renters so that this information can factor into decision-making processes[40].

A growing body of evidence suggests that disclosure policies can generate efficiency improvements. For instance, a recent study by Meng et al. revealed that LL84 produced a 6% reduction in energy use intensity (EUI) in the first three years after the policy took effect, and a 14% reduction over the first four years[8]. Papadopoulos et al. also found energy use reductions over time in the buildings covered by LL84, but identified distinct clusters of buildings that actually increased their consumption during the same time period[10]. A number of other studies also demonstrate that energy information disclosure impacts real-estate prices, which is assumed to reflect rental premiums, higher occupancy rates or lower operating expenses in more efficient buildings[41,42].

In contrast, relatively few scholars have examined the impact of energy audits on energy use, and most of those who have done so focused on voluntary audits in the industrial sector, rather than on mandatory audits of buildings[43,44]. With respect to the building sector, a study of municipalities in northern Italy found that municipal authorities were significantly more likely to make energy efficiency improvements to public buildings after having conducted an energy audit[45]. Conversely, Murphy[46] found that voluntary energy audits in private homes in the Netherlands had little, if any, impact.

The paucity of scholarship that evaluates the impact of mandatory building energy audits is surprising given the increasing prevalence of such policies across the United States. As of 2017, at least eight American jurisdictions require building owners to conduct energy audits in some form[40]. Some of these cities have released compliance data and early results from their audit programmes, but this information has not been formally studied. The lack of analysis is striking given the costs associated with energy audits. In NYC, for example, the audits required by LL87 have been estimated to cost approximately \$0.15 ft^{-2} (ref. [11]). Applying this cost estimate to our dataset of properties that were audited in 2013 or 2014 indicates that an average size multifamily building (126,368 ft^2) and office building (412,430 ft^2) would pay \$17,691 and \$57,740, respectively, for their audits. Although these are relatively small figures when compared to the value or net operating income of buildings of this size, the time, cost and regulatory oversight create the possibility of undue burdens for some building owners.

The question, then, is whether mandatory energy audits lead to energy use reductions over time. If so, does the magnitude of the effect justify the cost and time associated with conducting and reporting the results of the audit? We use a two-way mixed design analysis of variance (ANOVA) and Bayesian regression to evaluate the impact of building audits on energy consumption pre- and postaudit compared with a control group not subject to the audit requirement. The analysis is based on energy use and audit compliance data for 3,981 large multifamily and office buildings in NYC from 2011 to 2016.

Evidence of postaudit energy use reductions

From Fig. 1, we observe a clear decrease in EUI for audited (treatment) multifamily buildings in the post-audit period, when compared to non-audited buildings. For office buildings, there is a reduction in EUI for audited properties between the pre-audit and

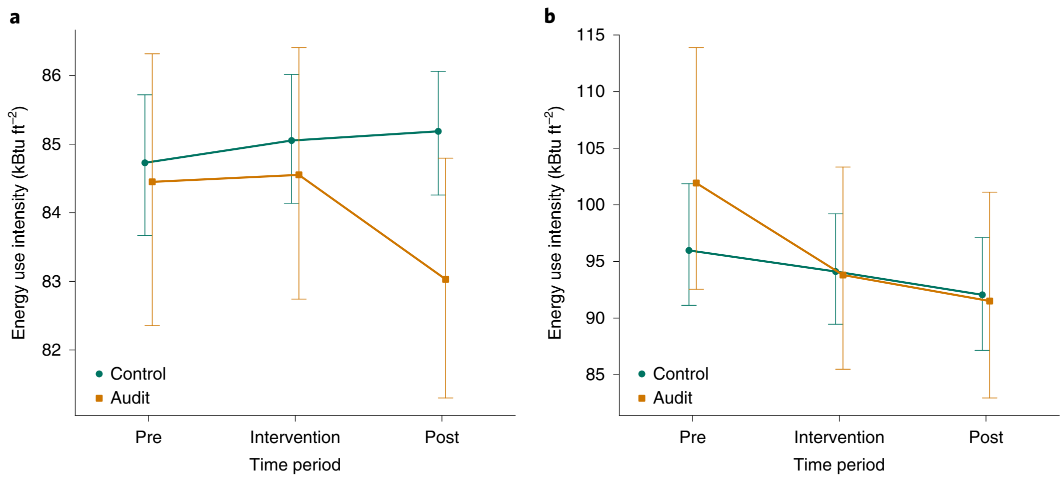

Fig. 1 | EUI distribution pre-, during and postaudit period. a,**b**, Multifamily housing (**a**) and office buildings (**b**). The error bars correspond to the 95% confidence intervals. Although there is an observable difference in control and audited office buildings during the pre-audit period, the overlapping confidence intervals make this difference not statistically significant. The *t*-test results in Table 3 further validate the above argument. Btu, British thermal units.

Table 1 | Mixed design ANOVA results—statistical significance

	Multifamily housing	Office
Treatment (*P* value)	0.352	0.749
Time (*P* value)	0.706	0
Interaction (treatment × time) (*P* value)	0.085	0.047

intervention periods, after which EUI values between the control and treatment groups converge, with audited properties exhibiting greater uncertainty. Given higher initial average EUI, office buildings experience larger absolute decreases, on average, in energy use over time when compared to multifamily residential buildings. The ANOVA results, as shown in Table 1, demonstrate statistically significant coefficients for the interaction term (time period and intervention) for both office and multifamily buildings at the 95 and 90% confidence levels, respectively. Although these results suggest that audits do have an impact on energy use over time, they represent a relatively coarse quantification of the audit policy's impact because they do not account for other factors that could influence building energy use in the postaudit period. The Bayesian regression results discussed below account for both the effect of energy audits and the dynamic control variables that affect building energy use over time.

In Table 2, we show that Bayesian regression model coefficient means and the 95% highest posterior density (HPD) intervals for NYC's office and multifamily housing building stock. We note that in both cases, when controlling for factors that might affect changes in energy consumption over time, the average value of the coefficient related to audits (that is, audited property) is negative. Specifically, audited office buildings tend to reduce their EUI by 4.86% compared to non-audited properties, and multifamily properties are found to have a 2.47% reduction. From the intercept of the two models, however, we notice diverging results. Although office buildings, on average, reduced their energy consumption, multifamily properties, on average, increased their energy consumption during the study period. Therefore, in the multifamily housing case, audits result in a smaller increase in energy use than would otherwise be expected.

Table 2 | Bayesian regression results demonstrate the effect of audits on energy use

	Multifamily housing		Office	
	Mean coefficient	95% HPD interval	Mean coefficient	95% HPD interval
Intercept	4.27	(2.32, 6.22)	-7.81	(-19.46, 4.99)
Audited property	-2.47	(-4.45, -0.44)	-4.86	(-10.49, 0.83)
Number of floors	-0.01	(-0.12, 0.10)	0.01	(-0.28, 0.26)
Building age	-0.02	(-0.05, 0.01)	0.07	(0, 0.15)
Gross floor area	0	(0, 0)	0	(0, 0)
Electricity as primary fuel source	8.28	(5.83, 10.84)	-3.58	(-9.26, 1.86)
Mean pre-audit EUI	-0.36	(-0.39, -0.33)	-0.14	(-0.19, -0.09)
Property market value	0	(-0.01, 0.01)	-0.01	(-0.04, 0.02)
Worker density difference	-	-	0.04	(-0.10, 0.17)
Computer density difference	-	-	0.04	(-0.09, 0.18)
Operating hours difference	-	-	-0.04	(-0.14, 0.06)

Focusing on the coefficient of interest for the effect of energy audits on change in energy consumption over time, we show the coefficient posterior distributions for multifamily and office buildings, respectively, in Figs. 2 and 3. The three Markov Chains converged well and are stationary, which means that there are no drifts and discrepancies in the mean and standard deviation of the distributions. To answer the question of 'how certain are we that audits have a negative impact on energy consumption over time?', we calculate the density of the posterior distribution that

Table 3 | Mean values and *t*-test results

	Multifamily housing			Office		
Variable (mean value)	**Control**	**Treatment**	**Matched**	**Control**	**Treatment**	**Matched**
Building age	65	66	66	75	77	77
Number of floors	11	11	11	21	24	22
Gross floor area (ft^2)	133,801	146,207	132,196	410,318	470,741	371,380
Electricity as primary fuel source	0.11	0.1	0.1	0.72	0.8	0.8
Property market value ($\$\,ft^{-2}$)	64	60.6	61.5	139.7[a]	165.4	144.4
Mean pre-audit EUI ($kBtu\,ft^{-2}$)	84.7	84.5	84.1	96	101.9	90.3

[a]Difference significant at 95% confidence level (*P* value<0.05)

falls below the threshold of zero, which for multifamily housing is $P(\beta_{\text{audited}} < 0) = 0.990$ and for office is $P(\beta_{\text{audited}} < 0) = 0.958$, where β is the coefficient for the effect of energy audits on energy use.

In an attempt to associate the observed savings with potential retrofit actions, we estimate from the audit report data the average expected EUI improvement possible through recommended low-cost ECMs (those with payback periods of less than two years) and retrocommissioning. The expected savings from low-cost ECMs are found to be 4.56% for multifamily and 1.87% for office buildings, with retrocommissioning activities associated with approximately 2% savings in both building types. Based on the magnitude of the audit-impact coefficients, these figures suggest office buildings exhibit, on average, energy savings that are consistent with those expected from recommended low-cost measures. For residential buildings, however, as the audit coefficient is lower than that expected from low-cost ECM adoption, the impact of the mandatory audit is negligible in relation to identified savings opportunities.

Finally, we link the savings associated with energy audits to a financial consideration that is often overlooked in the retrofit decision: the cost burden of the audit itself. According to the US Department of Energy, the cost of a building energy audit ranges between \$0.12 and 0.50 ft^{-2} (ref. [47]), whereas NYC market-specific estimates set the cost at \$0.15 ft^{-2} (refs [11,48]). Given the average energy savings attributed to audits from the Bayesian model discussed above, combined with building fuel mix and energy cost estimates from the US Environmental Protection Agency[49], we find that the average annual energy cost savings due to auditing for the NYC building stock are \$0.121 ft^{-2} for office and \$0.038 ft^{-2} for residential buildings. Therefore, especially for residential properties, the relatively high payback period of the energy audit (four years or more, on average) is an important consideration in the cost-benefit analysis of mandatory audit policies.

Discussion and policy implications

Our analysis finds that buildings that conduct a mandatory audit reduce their energy use over time more than non-audited buildings. However, it is important to note that the magnitude of the audit effect is consistent with, or less than, the expected savings from low-cost ECMs and retrocommissioning. This effect is particularly limited for multifamily buildings, which exhibited percentage decreases in EUI postaudit of approximately half those of office buildings. We consider two explanations for the relatively modest effect of mandatory audits.

First, it is possible that LL87 audits are, in fact, influencing property owners' plans for energy efficiency improvements, but capital cycles for investment in the relevant measures are too long to be captured by the temporal period of our analysis. Stated otherwise, it may be that after reviewing a required LL87 audit, a property owner decides to eventually invest in some relatively costly recommended improvement, such as new heating, ventilation and air conditioning equipment, but plans to do so (or did do so) after 2016, which is the last year for which we have EUI data in this analysis.

Notably, however, we did not find a greater difference between energy consumption in audited and non-audited properties when we included only those buildings that conducted audits in 2013, rather than the original 2013 and 2014 combined treatment group. This finding suggests that the investment cycle hypothesis may not be a significant factor, as these buildings had an additional year to implement audit recommendations. Of course, capital cycles may still be too long for certain capital-intensive ECMs to be captured during this time period. However, many ECMs with non-trivial energy savings have relatively low first costs and/or have short payback periods.

The second possible explanation is that energy audits do not motivate property owners to invest in ECMs that they would not otherwise pursue. There are at least three reasons why this might be the case.

Poor audit quality. The most straightforward explanation as to why LL87 audits may not be encouraging meaningful energy savings is that the audit process and reports are not of sufficient quality to reduce the uncertainty that buildings owners have regarding the cost and energy savings of particular ECMs[50]. A case study of 30 commercial and residential audits conducted in buildings across the United States revealed widespread shortcomings, which included missed ECMs and overestimated savings[51]. It is possible that the audits being produced in compliance with LL87 are similarly lacking.

Insufficient economic incentives for investment. Assuming mandatory audits are effective in identifying substantial cost-effective ECMs, other capital improvements, such as renovating a lobby or adding new amenities, may generate larger risk-adjusted returns on investment. This may be driven, in part, by the perceived uncertainty around energy retrofit investments, and thus inflate the required rate of return (or hurdle rate) for energy investments when compared with more traditional building improvements. Building owners, then, may lack sufficient economic incentive, in the absence of strong energy pricing signals, public incentives or regulatory mandates, to implement energy improvements over other capital improvements[33].

It is important for local policymakers to understand whether this is, indeed, a barrier to the implementation of recommended ECMs. If so, cities will need to strengthen the incentives for efficiency improvements before audit mandates can have a significant impact. For instance, to require property owners to assess more ambitious ECMs in their audits, as has been proposed (for example, NYC's One City Built to Last sustainability plan[52]), will not lead to actual energy savings if property owners do not have an incentive, and the access to capital, to invest in energy efficiency in the first place.

Motivation of property owners. A final reason as to why LL87 audits may not generate substantial energy savings relates to the mandatory nature of the programme. Clearly, not all property owners are equally interested in energy efficiency and those who are

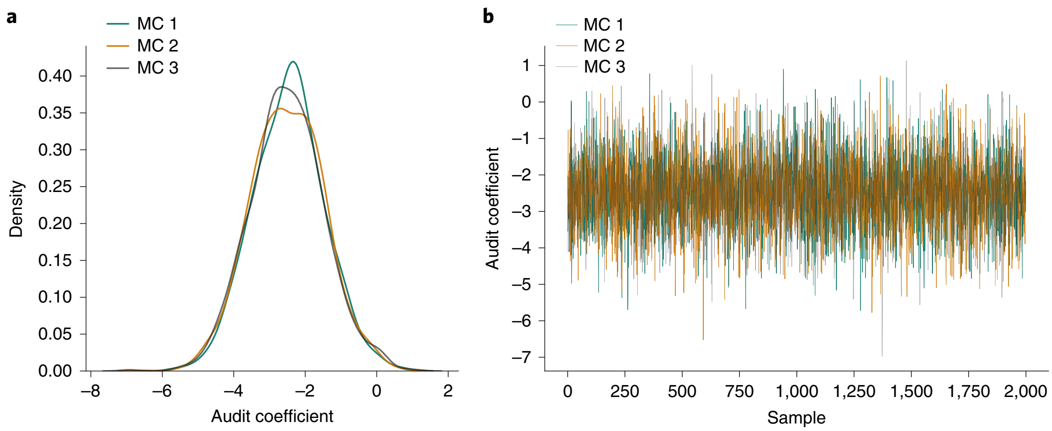

Fig. 2 | Audit coefficient distribution (multifamily housing). a,**b**, Multifamily housing audit coefficient distribution (**a**) and sampled values (**b**) for the three Markov Chains (MC) used to train the regression model.

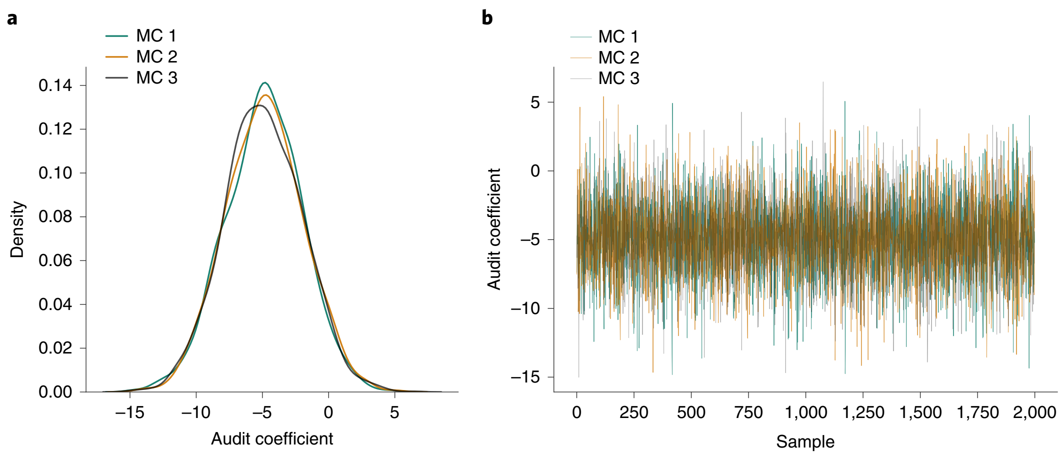

Fig. 3 | Audit coefficient distribution (office). a,**b**, Office audit coefficient distribution (**a**) and sampled values (**b**) for the three Markov Chains used to train the regression model.

most motivated will probably begin exploring energy saving opportunities voluntarily, without waiting for the obligation to conduct an audit[26,53]. It can be argued that much of the reduction in energy use over time observed in cities with energy disclosure laws can be attributed to this self-selection by owners more sensitive to environmental concerns or, conversely, the public perception of a lack of interest in environmental responsibility. If this assumption holds, then the information produced by mandatory audits should be most useful for those owners who are not otherwise motivated to reduce their energy consumption. Requiring property owners to devote time and money to conduct an audit may provide little value in shifting behaviour. Indeed, it may further discourage energy investments out of contempt for the mandatory nature of the process and create an incentive to simply do the minimum reporting necessary to comply with the law. These attitudinal factors could potentially explain the discrepancy between the findings in our study, which investigates the impact of mandatory energy audits on energy consumption, and previous studies that have examined responses to voluntary, subsidized audit programmes and found a robust adoption of the recommended measures[43,54].

Independent of the exact cause, if mandatory audits do not encourage investment in ECMs proportionate to the time and cost of conducting the audit, policymakers should consider whether a mandatory policy is the most efficient strategy to encourage energy efficiency in buildings. Although mandatory audits do produce substantial amounts of data about building systems and energy reduction potentials, which can have a significant value for policymaking, it may be possible to collect these data through less costly means, and complete coverage of a city's building stock may not be necessary to make reasonable inferences about where savings opportunities exist. For example, a recent study demonstrates how machine learning can be used to predict ECM recommendations and cost-savings opportunities with a high degree of certainty based on simple surveys of building systems[55]. Such 'automated' audits could significantly reduce the time and cost associated with building assessments.

Conclusions and future work

Climate action is becoming an increasingly pressing priority for city leaders. Given the substantial contribution building energy use has on GHG emissions in urban areas, cities are focusing their efforts on increasing the efficiency of the building sector through a range of data-driven policy and regulatory tools. Although energy reporting is a relatively low-cost mandate, required audits impose non-trivial costs in terms of capital and time for building owners. The question we explore here is whether this requirement actually advances the goal of reducing energy consumption in buildings.

We find that, for the time period studied between 2011 and 2016, mandatory energy audits had a modest negative impact on energy consumption in office and residential buildings in NYC, at a magnitude consistent with the savings potential of low-cost ECMs and retrocommissioning activities. The result reinforces the hypothesis that audits, by themselves, provide only limited incentive to invest in energy efficiency upgrades. Ultimately, building owners remain constrained by factors that audit information alone may not overcome, such as limited access to capital, uncertainty in savings projections, opportunity costs and weak pricing signals in energy markets.

To begin to address these economic and behavioural barriers, cities need to develop a comprehensive strategy to support energy efficiency in the building sector that starts with a foundation of data transparency and rigorous analytics. Energy disclosure mandates are an important first step: once the data are available, buildings can be evaluated on their energy performance and compared with their peers, which creates a 'grading' scheme that can help to shift individual and collective decision-making[56]. Following this, cities can consider performance targets and provide financial and regulatory incentives to motivate building owners to improve their energy efficiency and also ensure that regulations are in place to require poorly performing buildings to improve when owners do not respond to incentives. Audit requirements, then, could be used to target deep retrofits, focusing on ECM opportunities that could achieve 30% or greater savings, and automated or virtual audits could replace the existing need for traditional audit mandates. Similarly, because audit policies produce significant data on building systems and operating characteristics—information that is useful for a range of city agencies, but often difficult to collect–mandatory requirements could be replaced by incentives for voluntarily reporting audit data.

Our analysis here is an initial attempt to empirically investigate the impact of a citywide mandatory energy audit law. As we continue our research, future work will extend this analysis as additional years of data become available. A detailed survey of building owners and managers would help to understand the motivations for and barriers to implementing energy efficiency upgrades and provide the needed context to develop a comprehensive city energy strategy. A systematic evaluation of audit quality should also be conducted to ensure the accuracy of audit reports, which would help to provide owners with greater certainty on the validity of the proposed recommendations. Finally, machine learning and artificial intelligence applications should be explored more fully to understand if data-driven modelling can enhance, complement or even replace more manual processes for collecting relevant building data and developing ECM recommendations. Together, these steps could be used to develop evidenced-based and data-driven policies for city climate action.

Methods

Data description. Our energy performance data (total energy use and EUI) and audit data were collected by the NYC Department of Finance and the Department of Buildings pursuant to LL84 and LL87. Data were provided by the NYC Mayor's Office of Sustainability subsequent to a data sharing request. The LL84 dataset includes all covered buildings, which are defined as buildings with greater than 50,000 ft^2 of gross floor area, that submitted energy use data in calendar years 2011 through 2016. EUI is defined as the total annual energy consumption divided by the gross floor area of the building, and we utilized weather-normalized site EUI to capture the direct consumption reported through utility bills adjusted for the total number of heating degree days and cooling degree days in a given year[57]. In addition to the total energy use and EUI values, the dataset contains building-specific features, which include physical (age, gross floor area and so on) and operational (occupancy density, weekly operating hours, conditioned spaces and so on) characteristics.

We performed preprocessing of the LL84 dataset prior to our analysis. First, as EUI data are self-reported, we identified and removed misreported and erroneous entries. Specifically, we applied a logarithmic transformation to the EUI data and filtered outlier values that fell outside the threshold of two standard deviations from the mean[58]. Second, using the unique Borough Block Lot property identifier, we merged energy and building attribute data with tax lot and zoning information provided by the NYC's Primary Land Use Tax Lot Output database to identify additional building characteristics, such as assessed value. Finally, we integrated the merged dataset with information from individual audit reports submitted to the Department of Buildings as per LL87 requirements to identify properties that conducted an energy audit in calendar years 2013 or 2014, and to analyse building-specific ECM recommendations and savings potentials.

After our data processing steps, we analysed whether the audited properties in our sample demonstrated larger percentage reductions in site EUI between the pre- and postaudit period than those of similar buildings that did not perform an audit during the study period. We defined the EUI percentage change for each building as the difference between the mean EUI during the two years prior to the audit (2011 and 2012) and the two years after the audit (2015 and 2016). We used the two-year average to account for anomalous variations in building energy consumption that could occur in a given year (for example, Hurricane Sandy had a non-trivial impact on energy use in buildings in the impacted areas in 2012). We focused on multifamily and office buildings, as the two types account for more than 90% of the total LL84 covered properties by quantity and aggregate energy consumption. The merged dataset contains 3,981 properties, which include 3,563 multifamily buildings and 418 office buildings.

Methodology. To assess the impact of energy audits on building EUI over time, we split the data into three time periods: pre-audit (average EUI in years 2011 and 2012), intervention (average EUI in years 2013 and 2014) and postaudit (average EUI in years 2015 and 2016). As a first step to test the significance of the audit effect, we used a two-way mixed design ANOVA in which the dependent variable is EUI, the within-group variable is time (with three levels as mentioned above) and the between-group variable is the intervention (with two levels, which indicate audited and non-audited buildings).

One significant limitation of this approach is that it does not account for additional variables, besides time and intervention, that might be associated with changes in EUI, such as changes in occupancy characteristics.

Bayesian regression. To more comprehensively examine the impact of the audit policy, we used a Bayesian regression model to quantify the impact of energy audits on energy reduction over time while controlling for additional time-varying (dynamic) covariates that can influence changes in energy consumption. Bayesian statistics and probabilistic programming allow us not only to assess the effect of audits on energy use, but also to quantify the uncertainty of the estimated parameters[59,60]. Bayesian regression is a useful alternative to frequentist methods for policy analysis, as it provides a more intuitive, probabilistic output rather than relying on fixed *P*-value thresholds. We formulate our problem as follows:

$$y \approx N(\beta^T X, \sigma_y^2) \quad (1)$$

The output *y*, which is the percentage difference in EUI between the pre- and postaudit period, is generated from a normal distribution (*N*) with a mean equal to the transpose (*T*) of the coefficients' (β) matrix multiplied by the independent variables' (*X*) matrix and variance σ_y^2.

The frequentist approach to this problem estimates the model parameters using the maximum likelihood estimation method as static values: $\hat{\beta} = (X^T X)^{-1} X^T y$. This constitutes the fundamental difference between Bayesian and frequentist statistics; Bayesian makes a statement of probability about a parameter value given a fixed credible region ($P(\theta|$ credibleregion)), whereas frequentist makes a statement of probability about the confidence interval given a fixed parameter value ($P($ confidenceinterval $|\theta))$[61,62]. Therefore, in the context of our policy evaluation research problem, Bayesian statistics allow us to ask and answer the question 'how certain are we that the effect of energy audits on energy consumption over time is negative?'.

The independent variables we use in our model cover a range of building characteristics, changes in occupancy and the audit treatment effect. We control for non-varying characteristics, which include building age, size and EUI levels prior to the audit, as well as time-varying occupancy factors, which include worker density and operating hours, that might cause changes in the EUI over time. Note that occupancy variables are not available for multifamily buildings, and hence they are omitted from the residential model.

We used the No-U-Turn Sampler developed by Hoffman and Gelman[63], an efficient Markov Chain Monte Carlo algorithm, to draw 2,000 posterior samples for the office and multifamily housing stock models. Monte Carlo is a general approach of drawing random samples, whereas Markov Chain revolves around the concept that the next sample to be drawn is independent of the past, based solely on the present sample (the Markov process). We repeated the process for three chains to assess the robustness of our estimated model parameters. Another advantage of Bayesian regression is the ability to include prior knowledge regarding the model parameters' distribution. In this work, as NYC is among the first large cities to enact a mandatory energy audit law, we do not provide any prior information in the algorithm (an uninformative prior).

To measure the uncertainty in the model estimates, we calculated the HPD intervals, which is the range of values that cover the maximum distribution density under a predefined probability. Let *f*(*x*) be the density function of the random variable *X*; then the 95% highest density region is the subset $R(f_{95}) = \{x : f(x) \geq f_{95}\}$, where $P(X \in R(f_{95})) \geq 0.95$ (ref. [64]).

Prior to fitting the Bayesian model, we examined the treatment and control groups to verify that the inherent variability between audited and non-audited building characteristics is random and not attributable to some unobserved selection bias. As the year a building must comply with LL87 and submit its audit data is determined based on the last digit of its tax lot number, the selection and reporting process is essentially random. However, the concern is that the treatment (audited) group is not a randomized sample of the population and therefore fundamentally different than the control (non-audited) group. To account for this, Table 3 shows the mean values of the model covariates that do not change over time for audited (treatment), non-audited (control) and a set of matched non-audited properties using propensity scores with 1:1 nearest-neighbour matching[65,66]. We ran *t*-tests to examine the difference in means between the control and matched sample with that of the treatment group. With the exception of the assessed value per square foot for office buildings, we found no statistically significant differences in the treatment and control groups, either with or without matching. Therefore, we are confident in the random assignment of buildings to the treatment and control samples.

Data availability

All data, except LL87 data, are available through the NYC Open Data Portal at https://opendata.cityofnewyork.us/. LL87 data are available upon reasonable request, and with permission, from the NYC Mayor's Office of Sustainability. The data that support the plots within this Article and other findings of this study can be obtained from the NYC Mayor's Office of Sustainability or the authors, upon permission from the NYC Mayor's Office of Sustainability who own the data.

Code availability

Any applicable code relevant to the findings is available from the authors upon reasonable request.

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Competing interests

The authors declare no competing interests.

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