Baltic Journal of Economics

ISSN: (Print) (Online) Journal homepage: www.tandfonline.com/journals/rbec20

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To cite this article: Andrius Kažukauskas & Xiaoying Li (2025) The energy performance gap and its determinants in Soviet-era multi-apartment buildings, Baltic Journal of Economics, 25:1, 21-38, DOI: 10.1080/1406099X.2025.2455821

To link to this article: https://doi.org/10.1080/1406099X.2025.2455821

Published online: 11 Feb 2025.

BALTIC JOURNAL OF ECONOMICS
2025, VOL. 25, NO. 1, 21–38
https://doi.org/10.1080/1406099X.2025.2455821

The energy performance gap and its determinants in Soviet-era multi-apartment buildings

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ABSTRACT

Deep renovation, is seen as crucial in dealing with energy security and meeting climate targets, especially in post-Soviet countries with notoriously energy-inefficient residential housing stock. One critical question is whether these retrofits can achieve the energy savings promised by the engineering model. This paper assesses the energy performance gap–the discrepancy between realized energy savings and the predictions of engineers at the building level. In contrast to previous studies, we find that, on average, the predicted savings are fully realized for a retrofit programme of multi-apartment buildings in Lithuania. Among other factors, we consider how the differences in the energy performance gap for each building can be explained by energy efficiency measures, targeted energy class, and the type of multi-apartment building management. Interestingly, we find that multi-apartment buildings managed by outsourced specialized housing management companies tend to realize higher energy savings than buildings managed by communities of apartment owners.

ARTICLE HISTORY
Received 28 May 2024
Accepted 14 January 2025

KEYWORDS
Energy performance gap; multi-apartment buildings; retrofit; space heating; housing management

JEL CLASSIFICATION
D12; D82; Q47; Q48

1. Introduction

The building sector accounts for approximately 40% of total final energy consumption in the European Union (EU), and 36% of greenhouse gas emissions from energy. Energy efficiency improvement in buildings is widely viewed as a cost-effective way of reducing greenhouse gas emissions and has become a crucial element of achieving worldwide climate goals (IEA, 2019). In late 2021, the European Commission proposed a revision of the Energy Performance of Buildings Directive (EPBD) that aims to increase the retrofit rate of the worst-performing buildings in the EU (European Commission, 2021). This will require the scaling up of retrofit programmes in the member states, especially in post-communist countries with notoriously energy-inefficient building stock, built during a time of grossly underpriced and abundant energy provided by the Soviet Union (Kumar & Osband, 1991). However, studies analyzing energy efficiency

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programmes in Western countries often find that retrofits achieve lower actual energy savings than the engineering predictions suggest (e.g. Filippidou et al., 2019; Levinson, 2016). This paper aims to determine whether these (deep) retrofit programmes of Soviet-era multi-apartment buildings can deliver the energy savings that are predicted by the engineering models.

This paper has two main objectives. First, this paper intends to evaluate the 'performance gap'—the discrepancy between actual energy savings and engineer-predicted savings—in the retrofit programme of old Soviet-era multi-apartment buildings in Lithuania. This programme aims to achieve deep energy savings (greater than 50%) and is seen as a guiding model for retrofit programmes in the rest of the EU (Capps, 2022). Our sample consists of multi-apartment buildings retrofitted in Lithuania between 2014 and 2019. By using month-level data for actual and predicted energy savings, we calculate the energy performance gap for each retrofitted multi-apartment building in our sample. The second objective of this paper is to explore what factors explain differences in the energy performance gap across the retrofitted buildings.

In contrast to previous studies mainly from the United States, we find that, on average, the predicted energy savings from the engineering model are fully realized by the actual savings in the retrofit programme of Soviet-era multi-apartment buildings in Lithuania. We find that energy efficiency measures (such as glazing windows and insulating floors) do not explain differences in the energy performance gap among the retrofitted buildings. However, our results indicate that retrofitted multi-apartment buildings under 'outsourced' specialized housing management tend to have a smaller performance gap than retrofitted buildings under an 'in-house' administrator who usually resides in the building and is appointed by other apartment owners. In addition, the targeted energy class after retrofitting is a significant determinant in explaining the performance gap. Compared with retrofitted buildings that achieve the minimum required energy class of C, the performance gap tends to be larger for those buildings that target a higher energy class of A or B.

To our knowledge, our study is the first to measure the significance and factors of the energy performance gap for the retrofitted Soviet-era multi-apartment buildings connected to district heating systems. This study provides valuable policy implications for the former Soviet countries, where 170 million people still live in mostly non-retrofitted and highly energy-inefficient buildings (Meuser & Zadorin, 2015).

The remainder of this paper is organized as follows. Section 2 reviews recent studies related to the energy performance gap and its determinants in building retrofit programmes. Section 3 provides background information on the retrofit programme in Lithuania. Section 4 describes the data and empirical model. Section 5 reports the results, and Section 6 concludes the paper with a discussion of our findings and their policy implications.

2. Literature review

Table 1 summarizes recent studies on building retrofit programmes that measure the energy performance gap. Column 2 shows that all these empirical studies originate from North America (the United States and Mexico) and Western Europe (the Netherlands and Ireland). They examine energy use for electricity and natural gas in various residential

Table 1. Summary of selected studies that measure the energy performance gap in building retrofit programmes.

Study	Location	Housing type	Outcome variable	Realized energy savings	The performance gap
Zivin and Novan (2016)	California, U.S.	Single-family houses	Electricity	7%	21%
Allcott and Greenstone (2017)	Madison and Milwaukee, U.S.	Single-family houses	Natural gas and electricity	$89/household/year	42%
Fowlie et al. (2018)	Michigan, U.S.	Dwellings	Gas and electricity	10%–20%	Approximately 70%
Liang et al. (2018)*	Phoenix, U.S.	Residential buildings	Electricity	8%	28.3%
Filippidou et al. (2019)	Netherlands	Non-profit housing	Gas	0.033-0.089 kWh/m^2/year	23%–79%
Davis et al. (2020)	Northeast, Mexico	One-story and two-story housings	Electricity	No detectable impact	26%
Coyne and Denny (2021)	Ireland	Non-social housing	Whole-home energy	1091 kWh/year	18%
Christensen et al. (2021)	Illinois, U.S.	Single-family houses	Gas and electricity	14.83%	49%

*Liang et al. (2018) also analyze the effects of retrofitting on commercial buildings in their study. However, we only summarize the effects on residential buildings in Table 1.

buildings (columns 3 and 4). However, none of these studies consider the energy performance gap for residential buildings with district heating systems or residential buildings in the post-Soviet countries.

In terms of the retrofit effects on realized energy savings (column 5), most studies report positive effects, with the exception of the study in Mexico (Davis et al., 2020). However, all studies reveal a deviation between realized energy savings and engineering estimates (column 6). The performance gap varies from 21% to 28.3% when measuring energy use for electricity (Davis et al., 2020; Liang et al., 2018; Zivin & Novan, 2016). When considering energy use for natural gas, the performance gap tends to be even wider, ranging between 23% and 79% (Allcott & Greenstone, 2017; Christensen et al., 2021; Filippidou et al., 2019; Fowlie et al., 2018).

Several empirical studies also investigate the determinants of the energy performance gap. Some of these studies find that the rebound effect[1] can explain a portion of the performance gap (Allcott & Greenstone, 2017; Christensen et al., 2021; Liang et al., 2018). Filippidou et al. (2019) assess the impact of energy efficiency measures (EEMs) on actual and predicted energy consumption savings. Their findings suggest that the gap between actual and predicted savings tends to increase with the implementation of more EEMs. Christensen et al. (2021) identify poor construction quality resulting from poor workmanship, heterogeneity, and modelling errors in engineering models as critical factors contributing to the performance gap. Majcen et al. (2013) find that housing ownership type significantly affects actual energy consumption. Their study also indicates that energy-efficient buildings (labelled A or B) are more likely to consume more energy than predicted.

Furthermore, energy-related stakeholders have a great impact on the energy performance gap. The energy management team, as one of the stakeholders, plays a critical role in mitigating the performance gap through their knowledge and collaboration (Xu et al., 2021; Xu et al., 2022). However, if the building management staff lack knowledge and experience, they may provide imperfect information to households. This type of market failure is one critical barrier to achieving optimal levels of energy efficiency (Ramos et al., 2015).

Our study addresses a gap in the literature on retrofits by measuring the energy performance gap and investigating potential determinants of this gap in Soviet-era multi-apartment buildings that are connected to centralized district heating systems.

3. Background on the retrofit programme in Lithuania

Lithuania has a large share of buildings below the energy performance class of D, which is the median energy performance certificate (EPC) label for EU building stock. This indicates substantial potential for energy efficiency improvement through the renovation of older buildings (Housing Europe, 2021). In Lithuania, residential multi-apartment buildings constructed during the Soviet era account for 72% of the total residential multi-apartment building stock in terms of square metres and 55% of the total number of residences in 2019 (Government of Lithuania, 2021). These multi-apartment structures are frequently associated with very poor energy efficiency (NAOL, 2020).

The multi-apartment building retrofit programme in Lithuania is a government-led initiative aimed at improving the energy efficiency of residential buildings in the country. The programme, launched in 2014, focuses on multi-apartment buildings that were built before 1993 and is funded by the Lithuanian government and the EU. The goal of the programme is to encourage apartment owners to implement energy-efficient measures such as insulation, replacement of windows and doors, and modernization of heating systems. Between 2014 and 2019, the main incentives offered by the government to owners were 30% subsidies for energy efficiency measures and loans with annual interest rates of approximately 3%.

As in other Eastern and Central European post-communist countries, almost all dwellings (approximately 90%) in Lithuania are owner-occupied, including multi-apartment buildings. Apartment owners in multi-apartment buildings set rules, take care of shared spaces, and make retrofit decisions through democratic votes. Retrofit projects are initiated by the apartment owners, but decisions are facilitated and delivered through their elected representative, or through an outsourced housing administrator, which is usually a specialized housing administration and maintenance company.

To participate in the programme, each multi-apartment building must first undergo an energy audit to determine the most effective energy-efficient measures for the building. The audit is carried out by certified energy auditors, who provide a report with recommendations for improving the energy efficiency of the building. Once the audit is completed, apartment owners can apply for funding collectively. Government funding is provided if a simple majority of apartment owners approve the retrofit. Hence, the retrofit decision is a collective and binding decision for all owners within the apartment building. In addition, loans that finance retrofit projects are linked to the apartments, not their owners. Thus, if a particular apartment is sold, the obligation to pay back the loan is passed on to the new apartment owner.

The multi-apartment building retrofit programme in Lithuania provides funding for a wide range of EEMs aimed at reducing energy consumption and improving the thermal comfort of the buildings. Some of the typical EEMs funded by the programme include the following:

- The installation of wall, roof, and floor insulation materials such as mineral wool, expanded polystyrene, and polyurethane foam.
- The replacement of old windows and doors with new energy-efficient ones that feature double or triple glazing and low-emissivity coatings.
- The modernization of heating systems, such as the installation of new energy-efficient boilers, heat pumps, and other heating technologies.

To qualify for the multi-apartment building retrofit programme in Lithuania, buildings must meet certain energy performance requirements. Specifically, buildings must achieve a minimum energy performance class of C, as defined by the Lithuanian energy performance certification system.[2]

4. Data and empirical model

4.1. Predictive and actual energy consumption data

In estimating the energy performance gap within the retrofit programme, a crucial variable in our study is the predicted energy savings derived from the engineering model. The predicted savings data are provided by the Housing Energy Efficiency Agency, the organization responsible for administering the residential multi-apartment building retrofit programme in Lithuania. Our study includes Soviet-era multi-apartment buildings that underwent retrofitting between 2014 and 2019 and achieved an energy efficiency class of C or higher. The datasets were merged using the address of the building as the unique identifier, combining them with data on actual energy usage in the residential multi-apartment buildings, which was obtained from district heating utility companies in major cities in Lithuania.

The sample includes monthly space heating consumption data at the building level from January to April, and from October to December, for the years 2011–2019.[3] Retrofits (construction work) take approximately 8–9 months in most cases. Since the data only contain information on the completion date of each retrofit project, we assume a one-year duration for the retrofit work and exclude observations during this period. For each year, we only include retrofitted buildings with a full heating season (7 months) of energy consumption data, which results in a monthly balanced sample. Furthermore, buildings with energy consumption data for only the pre-retrofit or post-retrofit period were removed from the balanced sample.

After these adjustments, 139 retrofitted buildings remain in the final sample. Buildings retrofitted in 2014, 2018, or 2019 were dropped from the sample, as these buildings were less likely to have energy consumption data for a full heating season in either the pre-retrofit or post-retrofit period. However, given the strong seasonal pattern of heating energy consumption, maintaining accurate monthly balanced data is crucial for the transparency and credibility of the sample. As summarized in Table 2, all remaining buildings were retrofitted between 2015 and 2017, with most completed during 2016–2017. Among the three cities of Siauliai, Vilnius, and Klaipeda, the majority of the retrofitted buildings in our sample are located in the latter two.

Table 2. Distribution of retrofitted multi-apartment buildings in the final sample.

	Retrofitted year			
	2015	2016	2017	Total
Vilnius	2	42	29	73
Klaipeda	0	21	26	47
Siauliai	5	11	3	19
Total	7	74	58	**139**

Predicted savings for each month are calculated as a product of the expected savings rate and the monthly energy consumption from the reference years.[4] Next, actual energy savings for space heating are calculated on a monthly basis. For each specific month, the average energy consumption during the pre-retrofit reference years serves as the baseline. The actual savings resulting from the retrofit project are calculated as the difference between the current monthly energy use and the pre-retrofit average for that particular month from the reference years.

Table 3 reports the descriptive statistics for the predicted and actual savings for each month. In all months, the actual savings are slightly larger than the predicted ones. Both predicted and actual savings show a seasonal pattern, with savings amounts exceeding 20 MWh/month during the colder winter months (December, January, and February). In total, there are 1750 observations across 139 retrofitted buildings in our sample, the average predicted savings per month are 16.69 MWh. The actual savings, calculated based on pre- and post-retrofit data, amount to 19.61 MWh per month. This suggests that, on average, the predicted savings are fully realized.

The key variable of interest in this paper is the energy performance gap—the discrepancy between engineer-predicted savings and actual energy savings. We define the

Table 3. Descriptive Statistics of monthly predicted and actual savings (MWh/month).

	N	Mean	Std. Dev.	Min	Max
January					
predicted savings	256	24.94	15.236	2.718	94.245
actual savings	256	29.861	19.54	1.38	122.173
February					
predicted savings	253	22.535	13.687	2.27	79.234
actual savings	253	26.531	17.615	1.561	104.427
March					
predicted savings	245	16.586	9.693	1.877	61.037
actual savings	245	17.558	12.232	.554	69.941
April					
predicted savings	254	9.605	7.62	.893	52.189
actual savings	254	13.968	11.437	.026	86.484
October					
predicted savings	235	5.756	3.875	.758	24.093
actual savings	235	6.031	5.102	.013	33.178
November					
predicted savings	253	15.089	9.838	1.406	56.46
actual savings	253	17.078	12.553	.432	67.509
December					
predicted savings	254	21.461	12.964	2.468	70.659
actual savings	254	25.121	16.121	1.445	86.197
Total					
predicted savings	1750	16.692	12.824	.758	94.245
actual savings	1750	19.614	16.174	.013	122.173

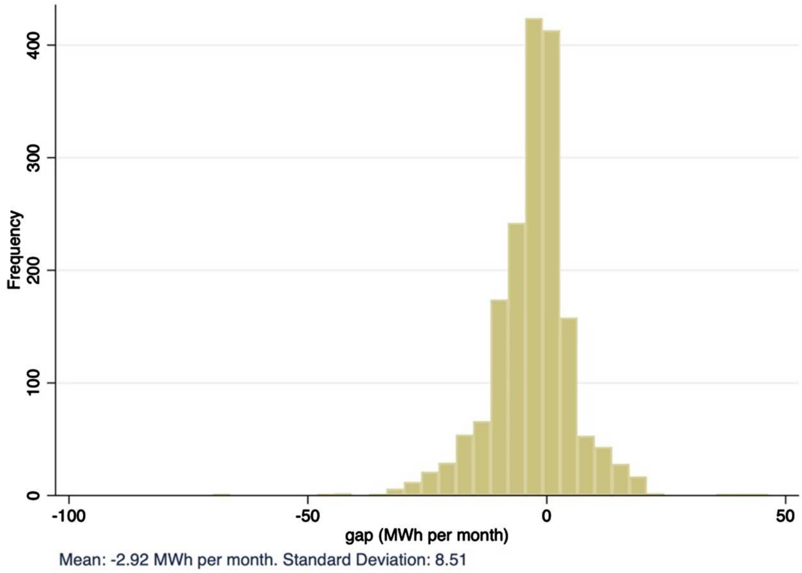

Figure 1. The distribution of the energy performance gap.

performance gap as the difference between predicted and actual savings for multi-apartment building *i* in the post-retrofit period *t*:

$$gap_{it} = \ predicted\ savings_{it} - actual\ savings_{it}$$

Figure 1 displays the distribution of the energy performance gap. The average monthly performance gap is −2.92 MWh, and the high standard deviation of 8.51 indicates significant variability around the mean value. The distribution reveals that the energy performance gap spans both negative (actual savings larger than predicted) and positive (actual savings lower than predicted) values, with the majority of observations clustering around the mean.

4.2. Retrofit programme administrative and other supplementary data

The sample also includes several time-invariant retrofit administrative variables, such as implemented EEMs, average retrofit project investment costs, energy class pre- and post-retrofit, and the building's type of housing management. Furthermore, the dataset includes information on monthly weather conditions, income, and heating prices at the city level. Retrofit investment costs, income, and energy prices are adjusted to their real values using Lithuania's consumer price index (CPI).

Table 4 presents the descriptive statistics, with Panel A summarizing the building and retrofit information. The statistics reveal that the mean value of average real retrofit investment costs is 198.71 EUR/m^2, with a range between 37.19 EUR/m^{2}and 486.98 EUR/m^2, depending on the implemented EEMs. Regarding building characteristics, the average heating space of retrofitted buildings in our sample is 2195 m^2, and the mean year of construction is 1972.

The housing management variable refers to the type of agent responsible for facilitating retrofit investments, building maintenance, and management services. In this study,

Table 4. Descriptive statistics.

	Mean	Standard Deviation	Min	Max
Panel A: Building and other retrofit information				
Average real investment cost (EUR/m^2)	198.71	62.33	37.19	486.98
Heating space (m^2)	2195.06	1364.20	173.48	8349.84
Construction year	1972	11.05	1953	1992
Housing administrator – Outsourced (%)	53.34			
EPC at level D before the retrofit (%)	61.71			
EPC at level A or B after the retrofit (%)	26.17			
Panel B: Implemented Energy Efficiency Measures (EEMs)				
BLK – replacement of windows in apartments and other premises (%)	92.23			
LLK – replacement of staircase windows and doors (%)	88.63			
BST – balcony glazing (%)	79.20			
RPA – basement floor insulation (%)	27.54			
Panel C: Other control variables				
Real income (EUR/month)	700.51	69.21	526.22	772.96
Real heating prices (ct/kWh)	4.90	0.49	3.53	6.48
Outside temperature (°C)	2.49	4.86	−7.55	10.31
Normalized temperature (°C)	0.36	2.83	−7.18	6.79
Number of observations	1750			

Notes: In panel B, the other category of housing administrator is owner-elected administrator; the other category of energy class before the retrofit is E, and the other category of energy class after retrofitting is C.

the types of management are categorized into two groups: owner-elected in-house representatives and outsourced specialized housing management companies. The statistics reveal that approximately half of the buildings are managed by outsourced housing management companies and the other half by owner-elected representatives. In terms of EPCs, before retrofitting, approximately 62% of the buildings in the sample are at class D (with 38% at class E). After retrofitting, around 26% of the buildings are classified as class A or B, which indicates that the large majority of retrofitted buildings fall into energy class C.

Panel B in Table 4 summarizes the implemented EEMs. The summary statistics indicate that common EEMs implemented in retrofits are the replacement of windows in apartments (BLK), the replacement of staircase windows and doors (LLK), and balcony glazing (BST), with implementation rates of 88.56%, 82.59%, and 78.61%, respectively. However, only 27.54% of buildings in the sample received basement floor insulation (RPA). In addition to the selected EEMs, all buildings in our sample were retrofitted with external wall insulation, roof insulation, and new heating systems.

Panel C reports summary statistics on time-varying control variables at the city level. The statistics indicate that, on average, real monthly income is 700.51 EUR per month, and the average real heating price is 4.90 ct per kWh. Regarding weather conditions, the average outdoor temperature is 2.49 °C. Additionally, a normalized temperature is calculated as the change in the outdoor temperature relative to the pre-retrofit (reference years) average for that month. The statistics show that the mean value of the normalized temperature is 0.36 °C, suggesting that outdoor temperatures are higher than in the pre-retrofit years. We use the normalized temperature instead of the nominal outdoor temperature in our analysis, as it is better suited to account for the effects of changes in temperatures on the energy performance gap.[5]

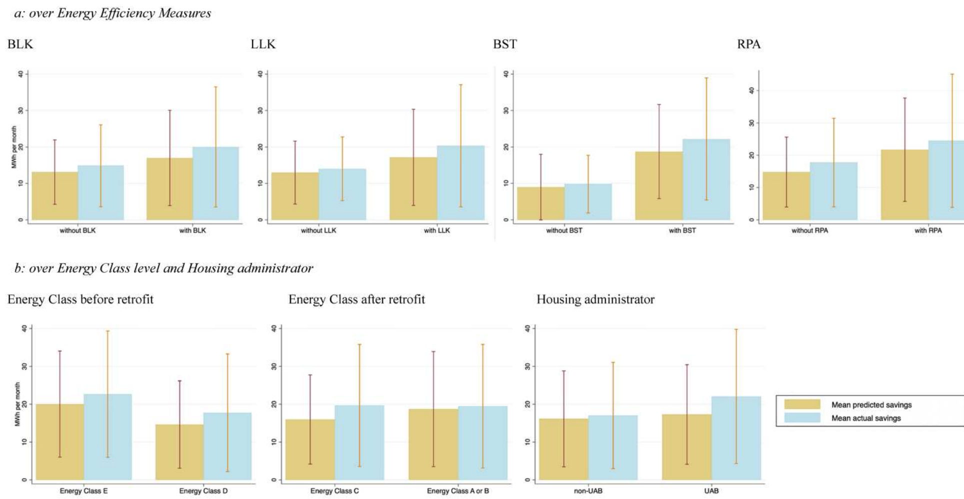

Figure 2. Predicted and actual energy savings for space heating (MWh/month) over various retrofit/building characteristics. *2a: over Energy Efficiency Measures. 2b: over Energy Class level and Housing administrator.*

Figure 2 shows both the predicted and actual energy savings for space heating, along with standard deviations. Figure 2a shows how monthly average savings relate to various EEMs. For all four EEMs, both the predicted and actual savings increase when the EEMs are implemented compared to when they are not, and the average actual monthly savings are slightly greater than predicted. The largest increase in energy savings occurs when balconies are glazed (BST). While actual energy savings for buildings without balcony glazing are approximately 10 MWh per month, buildings with this EEM achieve savings of more than 20 MWh per month on average.

Figure 2b illustrates the monthly energy savings based on different energy classes and housing administrator categories. First, the plot indicates that relatively inefficient buildings (energy class E before retrofitting) save more energy on average than buildings with an energy class of D, which aligns with expectations. Second, after retrofitting, predicted savings are greater on average for buildings in energy class A or B than those in energy class C. However, this difference is not as evident in actual savings, as the average energy savings for both categories are approximately 20 MWh per month. There is no difference in average predicted savings between buildings under the management of owner-elected representatives (*non-UAB*) and outsourced specialized housing management companies (*UAB*). However, the actual energy savings for buildings with outsourced management administrators (*UAB*) tend to be much greater than those for buildings under the management of owner-elected representatives (*non-UAB*).

4.3. Empirical model

To investigate the statistical significance of the main determinants of the energy performance gap, we conduct a simple econometric analysis. In our analysis, we consider several potential predictors of the energy performance gap which include EEMs, targeted energy class, and the type of housing administrator for each multi-apartment building. Moreover,

Table 5. Model descriptions.

Model	Explanatory variables in the model
1	*EEMs + controls*
2	*EEMs + EPC after retrofit + controls*
3	*EEMs + EPC after retrofit + relative time + controls*
4	*EEMs + EPC after retrofit + relative time + housing admin + controls*

given that the performance gap may change in the years after retrofitting, we include post-retrofit periods in the model. The main ordinary least squares (OLS) regression model is estimated as follows:

$$\text{gap}_{it} = \alpha_0 + \sum_{k=1}^{K} \beta_k 1\{EEM = k\}_i + \gamma_1 EPC_i + \gamma_2 relative\_time_{it} + \gamma_3 Housing\_admin_i + \delta Z_{it} + \varepsilon_{it}$$

where gap_{it} is the energy performance gap for retrofitted building *i* in period *t*. $1\{\text{EEM} = \text{k}\}_{\text{i}}$ is the EEM indicator for building *i*, which equals 1 if measure *k* has been implemented during the retrofit. Measure *k* includes the replacement of windows in apartments (BLK), the replacement of staircase windows and doors (LLK), balcony glazing (BST), and basement floor insulation (RPA). EPC_i is the categorical variable for the energy class of building *i* after the retrofit. $relative\_time_{it}$ is the relative year after retrofitting for each building *i*. $Housing\_admin_i$ is the categorical variable for building *i*'s type of housing administrator. Z_{it} are control variables, including energy class before retrofitting, construction year of the building, heating space in the building, real retrofit investment costs per square metre, normalized outdoor temperature, real district heating prices, average real income, and month dummies to control for seasonality. Given the clustered nature of the data, to account for potential autocorrelation issues and unobserved building-specific characteristics, we apply clustered standard errors at the multi-apartment building level in the OLS estimation.

The coefficient of interest, β_k, indicates the marginal change in the gap associated with implementing each measure *k*. The coefficient γ_1 measures the marginal effect on the gap if the building achieves an energy efficiency label of A or B relative to the mandatory level of C (*EPC*). γ_2 measures the additional effect on the gap if the post-retrofit time is longer by one year. γ_3 captures the additional effect on the gap if the building is managed by an outsourced specialized company rather than an owner-elected administrator. To see marginal changes and sensitivity caused by adding each variable of interest, we run four model specifications. The models are described in Table 5.

5. Results

5.1. Determinants of the energy performance gap

Table 6 presents the regression results for each model. First, we analyze the effect of EEMs on the performance gap. The coefficients in Models 1–3 suggest a negative association between the installation of replacement windows (BLK) and the performance gap; in contrast, Model 4 shows a positive association. However, none of these coefficients are statistically significant. The positive coefficients on the replacement of staircase windows and doors (LLK) across all models indicate a positive association, but as with replacement windows, these are not statistically significant. The coefficient on the balcony glazing (BST) shows a consistent negative association across all models, indicating that balcony glazing tends to have a negative impact on the dependent variable. However, statistical significance is not indicated. Finally, the coefficient on basement floor insulation (RPA) shows a positive but insignificant association in all models.

When energy class after the retrofit is considered, the result indicates that depending on the model specification, the energy performance gap is between 2.4 and 3 MWh per month higher for multi-apartment buildings with a targeted energy class of A or B than those with a targeted energy class of C. This suggests that the performance gap tends to become larger for more energy-efficient buildings, which is in line with the findings of Majcen et al. (2013) and Filippidou et al. (2019).

In Model 3 we add an indicator for relative time after retrofit implementation. We find no significant changes in the effect in the years after retrofit completion. This result suggests that the retrofit energy savings remain similar over time, and quality does not deteriorate in the first few years after retrofitting.

Table 6. Estimation of determinants of the energy performance gap.

	Model (1)	Model (2)	Model (3)	Model (4)
Variables of interest				
Replacement of windows in apartments/other premises (BLK)	−1.396	−.452	−.583	.978
	(1.623)	(1.703)	(1.747)	(2.052)
Replacement of staircase windows and doors (LLK)	.868	.747	.798	.598
	(1.352)	(1.402)	(1.378)	(1.415)
Balcony glazing (BST)	−1.503	−1.9	−1.932	−2.295
	(1.529)	(1.556)	(1.545)	(1.685)
Basement floor insulation (RPA)	.935	.151	.124	1.339
	(1.456)	(1.376)	(1.384)	(1.132)
Targeted EPC at A or B level		2.996**	3.006**	2.434**
		(1.255)	(1.256)	(1.132)
Relative time (year) after the retrofit			−.381	−.798
			(.542)	(.532)
Outsourced housing administrator				−7.363***
				(1.243)
Control variables				
EPC at D before retrofit (ref: EPC at E)	−.765	−1.02	−1.116	−2.948**
	(1.357)	(1.344)	(1.342)	(1.187)
Construction year	−.026	−.024	−.025	−.084
	(.054)	(.054)	(.054)	(.052)
Heating space	−.002***	−.002***	−.002***	−.002***
	(.001)	(.001)	(.001)	(.001)
Real retrofit costs per sqm	−.032***	−.031***	−.031***	−.022*
	(.01)	(.01)	(.01)	(.011)
Normalized temperature	−.912***	−.906***	−.877***	−.949***
	(.076)	(.077)	(.069)	(.072)
Real heating prices	−1.014	−.945	−1.195	−.137
	(.699)	(.698)	(.849)	(.807)
Real income	.023***	.022***	.023***	.041***
	(.006)	(.006)	(.007)	(.008)
constant	50.541	46.285	48.887	149.172
	(106.314)	(107.558)	(107.776)	(103.236)
Month dummy	Yes	Yes	Yes	Yes
Observations	1750	1750	1750	1708
R−squared	.208	.229	.23	.349

Notes: ***, **, and * denote the significance at the 1%, 5%, and 10% levels, respectively. Clustered standard errors at the building level are in parentheses. Model 4 is estimated with fewer observations due to some buildings missing values for the type of housing administrator.

Finally, in Model 4, we include an indicator for the type of housing administrator. The findings indicate that multi-apartment buildings managed by outsourced specialized management companies, as opposed to managers elected by the apartment owners themselves, tend to realize greater energy savings—approximately 7.4 MWh per month. This effect suggests that specialized housing management companies may possess more extensive knowledge, skills, and experience in managing complex retrofitting processes, which can raise household awareness of potential energy savings and result in smaller performance gaps. These results align with the findings of Xu et al. (2021) and Xu et al. (2022), which highlight the importance of communication and networking among building stakeholders, particularly emphasizing the potential for collaboration in building energy management.

Regarding the control variables, the energy class prior to retrofitting does not demonstrate a statistically significant influence on the performance gap in most models, except in Model 4. Heating space exhibits a negative association with the performance gap, indicating that larger buildings can achieve better performance.

Interestingly, the coefficient of average income shows a statistically significant positive impact on the performance gap. This finding suggests that an increase in income results in a reduction in actual energy savings and may be viewed as an indication of the rebound effect.

To control for retrofit quality, we use retrofit costs per square metre for each building. We find that the average retrofit investment cost is negatively associated with the performance gap, indicating that the performance gap tends to decrease with an increase in retrofit quality.

Finally, a key control variable for accurately estimating the effects of our variables of interest is normalized monthly outside temperature. As expected, a higher outdoor temperature significantly affects the performance gap.

5.2. Heterogeneous effects

Given that the energy performance gap is unevenly spread across the buildings, for the variables of interest, we also explore whether these effects vary based on the levels of the performance gap. We apply quantile regression to assess the heterogeneous effects of these determinants at different percentiles of the performance gap. Figure 3 presents the estimated coefficients of quantile regression for our main regression model specification (Model 4) with 95% confidence intervals. Furthermore, we use a zero gap as the threshold (where predicted savings are equal to actual savings) and separately estimate the regression model for both negative and positive energy performance gaps. The results are presented in the Appendix.

Figure 3a shows the association of various EEMs with the performance gap. The results suggest that the effects of replacing windows (BLK) and replacing staircase windows and doors (LLK) are moderately positive below approximately the 70th quantile but become negative at higher quantile levels for the performance gap. The coefficient on balcony glazing (BST) starts positive at lower quantiles but shows a consistent negative association at higher quantile levels. The coefficient on basement floor insulation (RPA) remains positive across all quantiles of the performance gap. However, all associations are statistically insignificant. These results indicate that the effects of EEMs do not vary significantly across levels of the performance gap. These findings are largely supported by separate

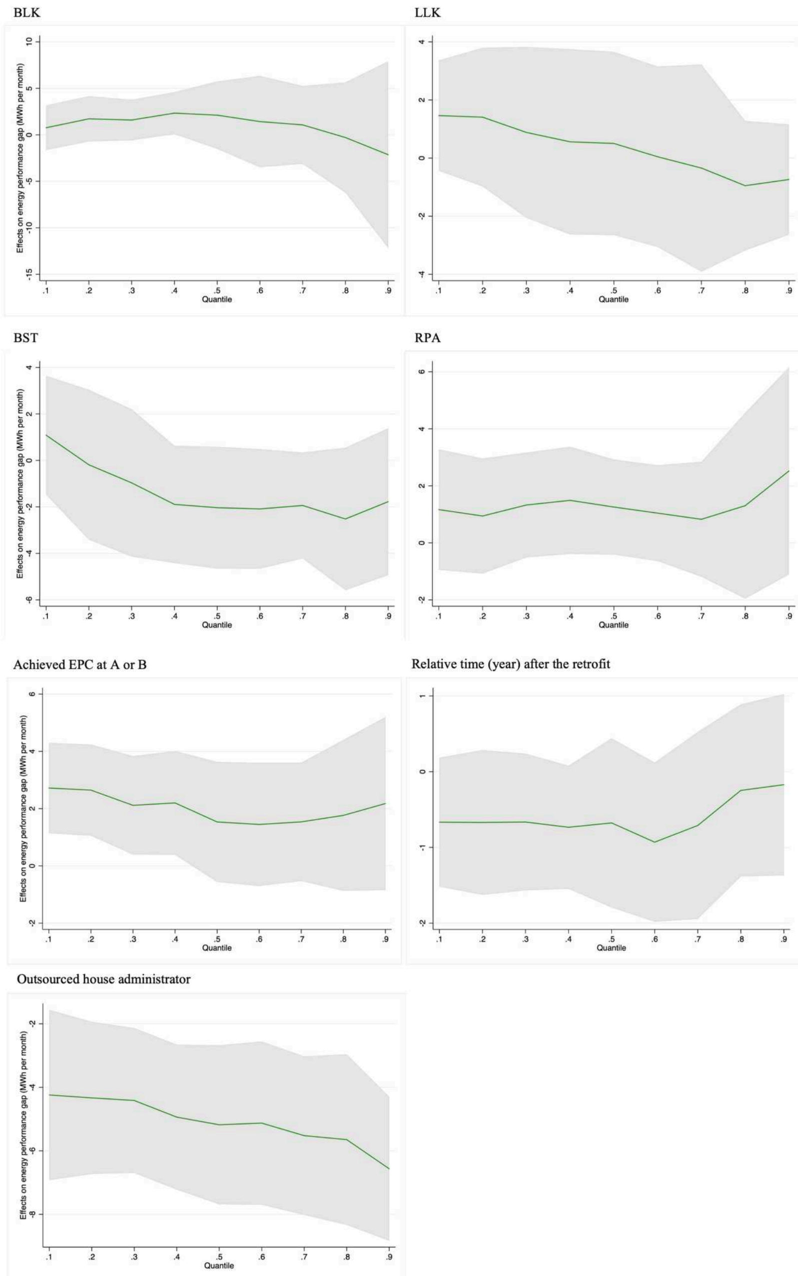

Figure 3. Estimated coefficients of quantile regression (Model 4) with 95% confidence intervals. 3a. Various EEMs. 3b. Other factors.

Notes: The quantile regression is based on the approach suggested by Parente and Santos Silva (2016). The estimation includes 1708 observations. Clustered standard errors at the building level are used.

regressions. As presented in the Appendix, the coefficients for various EEMs are statistically insignificant for both negative and positive performance gaps, with the exception that the negative effect of replacing windows is significant at the 10% level when the gap is positive.

Figure 3b shows the effects of three other variables of interest. Regarding the effect of the targeted energy class (EPC) on the performance gap, in comparison to multi-apartment buildings targeting energy efficiency class C, the marginal effect of targeting energy efficiency class A or B on the energy performance gap is relatively stable at approximately 2 MWh per month across the quantile distributions. However, the 95% confidence interval indicates that the effect on the energy performance gap is statistically significant at quantile levels below the median, mainly in cases of negative performance gap (where predicted savings are lower than actual savings); this is consistent with the results reported in the Appendix. The effect of the relative years after the retrofit is statistically insignificant across different quantiles. Regarding the impact of the type of housing administrator on the energy performance gap, the results suggest that the magnitude of the negative effect on the performance gap tends to increase with the quantile level, and this effect is statistically significant across the entire quantile distribution.

Table A1 in the Appendix also shows whether the effects of control variables differ between negative and positive performance gaps. First, the energy class prior to retrofitting has a statistically significant influence on the negative performance gap but not on the positive one. Second, the construction year shows a negative association with the positive performance gap, indicating that newer buildings can achieve better performance in actual energy savings. Furthermore, the negative effect of the average retrofit investment cost is statistically significant only on the positive performance gap, suggesting that the retrofit quality is an important factor in reducing the gap when the predicted savings are not fully realized as actual savings.

5.3. Robustness check

As a robustness test to determine whether actual savings match predicted savings, we calculate alternative actual savings based on our estimated actual savings rate, taking counterfactuals into consideration. To achieve this, we utilize the cohort and year-specific effects on energy savings from an event study model, as described by Kažukauskas and Li (2024). Due to concerns about self-selection bias, we use later-completed retrofits as the control (counterfactual). We select multi-apartment buildings that were retrofitted after 2018 as our control group and compare the energy consumption of buildings retrofitted earlier by controlling for building characteristics, incomes, and weather conditions. We apply the approach proposed by Sun and Abraham (2021), which is robust to heterogeneous retrofit effects across multi-apartment buildings. The fundamental idea of the method is to categorize renovated buildings into cohorts based on the retrofit completion date. Buildings whose retrofits were completed in the same year are included in the same cohort. However, this approach requires us to drop always-retrofitted buildings.

Table 7 presents the mean values of monthly energy savings based on the engineering model predictions and actual energy savings for space heating using the before-after method and event study method. The actual energy savings for space heating estimated based on the event study approach ('with counterfactual,' column 4) amount to 16.54 MWh per month, just slightly less than the predicted savings. Moreover, the difference between the two estimates of actual savings is statistically significant (column 5). This can be explained by the fact that the event study method takes into account warmer winters in the post-retrofit periods.

Table 7. Sample Mean Statistics on monthly energy savings for space heating.

	Predicted savings	Actual savings (before - after)	Actual savings **CSBARLINE** (with counterfactual)	Diff. on two actual savings
Retrofit effects	16.69 MWh	19.61 MWh	16.54 MWh	3.07 MWh ***
Number of buildings	139			
Number of observations	1750			

Notes: Among 1750 observations, 83, 630, 733, 269, and 35 observations are in the current, first, second, third, and fourth years after the retrofit. *** denotes significance at the 1% level.

6. Conclusion and policy implications

This study measures the energy performance gap—the discrepancy between actual energy savings and engineer-predicted savings—for multi-apartment buildings in Lithuania. Using monthly data from 139 retrofitted buildings, we observe that the performance gap varies between negative and positive values. On average, the predicted savings from the engineering model are fully realized by the actual savings.

In our case, the performance gap of buildings under the retrofit programme in Lithuania is fully realized, and it is considerably different from the estimated gaps for buildings under other retrofit/weatherization programmes that mainly focus on conservation of natural gas and electricity (e.g. Allcott & Greenstone, 2017; Christensen et al., 2021; Fowlie et al., 2018). Our findings present a different picture of the energy performance gap in retrofit programmes for multi-apartment buildings with district heating systems.

Our findings indicate that multi-apartment buildings managed by outsourced specialized management companies have a smaller performance gap than those with owner-elected housing administrators. Moreover, we provide evidence that the performance gap is larger for those targeting energy class A or B. This finding is consistent with a case study in the Netherlands (van den Brom et al., 2019) that observed that more extensive retrofits often lead to lower actual savings than expected when compared to simpler retrofits.

From a policy perspective, policymakers are particularly concerned with understanding the factors relating to a positive performance gap—where the predicted savings are not fully realized as actual savings. Our study generates several policy implications for retrofitting Soviet-era multi-apartment buildings. Our findings suggest that outsourced specialized management could play a crucial role in ensuring that retrofitting delivers the expected results for apartment owners. Retrofits are likely to be more professionally managed by housing companies, who have staff specializing in building management and energy efficiency. A specialized and skillful management team can achieve better energy performance of the buildings by managing the risks and uncertainty of project administration and implementation. Moreover, Chen et al. (2023) show that managing the risks of retrofit projects not only reduces the cost of these projects but is also critical to the adoption of more energy efficiency measures. Notably, in this study, we only observe a statistically and economically significant association between better energy performance of the buildings and their management type. Future research should further explore what actions or characteristics of management lead to this higher energy performance of the retrofit programme.

In addition, our findings also suggest that the potential rebound effect resulting from changes in income levels may help explain the performance gap. The statistically significant positive impact of average income on the performance gap indicates that some of the predicted savings may not be realized due to the increase in average income.

One limitation of our study is the lack of household-specific characteristics, such as age group, gender distribution, and employment status, which could influence the energy performance gap by impacting actual energy consumption. For a more accurate assessment of the performance gap, future research should consider the inclusion of these household characteristics. Furthermore, in addition to EEM indicators, future studies could collect more detailed data for the prediction model—including energy audit data related to the construction and retrofit processes—to identify other specific explanations for the performance gap.

Notes

1. In building retrofit programs, energy efficiency improvements decrease the cost of energy services. The reduction in costs may cause households to increase their utilization of energy services. This rebound effect occurs when households consume a part of the savings delivered by the retrofits.
2. Since 2023, buildings must achieve a minimum energy performance class of B to be eligible for subsidies.
3. Since district heating is centralized and is not used all year round, the sample contains heat energy consumption data from January to April and from October to December each year.
4. According to regulations, the reference years for calculating the predicted savings rate are the three years prior to retrofit.
5. Using the normalized temperature instead of the nominal outdoor temperature does not significantly affect the main results.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

This work was supported by Research Council of Lithuania [grant number: P-MIP-23-121]; Östersjöstiftelsen.

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Appendix

Table A1. Estimation of Model (4) for the positive performance gap versus the negative performance gap.

	Negative Performance Gap	Positive Performance Gap
Variables of interest		
Replacement of windows in apartments/other premises (BLK)	1.615	−3.222*
	(1.116)	(1.804)
Replacement of staircase windows and doors (LLK)	.232	.063
	(1.071)	(1.016)
Glazing of balconies (BST)	−.884	−1.063
	(1.2)	(1.59)
Basement floor insulation (RPA)	1.222	−.289
	(.925)	(.744)
Targeted EPC at A or B level	2.073***	−.499
	(.759)	(.818)
Relative time (year) after the retrofit	−.26	−.278
	(.427)	(.433)
Outsourced housing administrator	−3.025***	−2.757***
	(1.089)	(.826)
Control variables		
EPC at D before retrofit (ref: EPC at E)	−2.395**	−.667
	(1)	(.946)
Construction year	−.003	−.072**
	(.049)	(.032)
Heating space	−.003***	.001**
	(.001)	(.0005)
Real retrofit costs per sqm	−.001	−.021***
	(.007)	(.007)
Normalized temperature	−.569***	−.274***
	(.084)	(.078)
Real heating prices	−.097	.134
	(.65)	(.64)
Real income	.022***	.012**
	(.006)	(.006)
constant	−7.879	146.992**
	(96.067)	(65.062)
Month dummy	Yes	Yes
Observations	1124	584
R-squared	.515	.404

Notes: ***, **, and * denote the significance at 1%, 5%, and 10% levels, respectively. Clustered standard errors at the building level are in parentheses.