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Lithuania's Educational Building Stock: Energy Performance, Data Gaps and Renovation Screening

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Abstract

National building registers can provide complete stock coverage, but missing energy performance data constrain renovation prioritisation. This study assessed all 4736 building objects officially registered for educational purposes across all 60 Lithuanian municipalities (8.77 million m^2), using registry data, policy documents and exploratory responses from five municipalities. Overall, 91.8% of buildings were completed before 1991, and 96.2% were at least 20 years old. Official energy performance certificates were available for 2075 buildings (43.8%), and positive calculated heating demand values for 36.5%. Analytical proxy categories for uncertified buildings increased screening coverage to 100%. Validation against EPCs yielded 49.8% exact agreement, 82.8% agreement within one harmonised category and a linearly weighted Cohen's κ of 0.243. The proxy classified 99.2% of buildings with official classes D–G as ≤D, but its specificity for retaining C-or-better buildings was 18.3%, demonstrating a trade-off between coverage and certainty. The broad D-or-lower screening group contained 3534 buildings; restricting it to those with registry-based physical depreciation of at least 40% and no recorded intervention completion identified 536 candidates for further assessment. Registry proxies can support transparent national screening and identify certification needs but cannot replace official EPCs or establish individual rankings under the Energy Performance of Buildings Directive.

Keywords: EPBD; educational buildings; building stock; energy performance; data quality; renovation

1. Introduction

Renovation of existing buildings plays an important role in the European Union's (EU) transition towards climate neutrality. The European Climate Law requires climate neutrality to be achieved by 2050 [1]. The European Commission's Renovation Wave (2020) identified building renovation as a practical way to reduce energy demand and greenhouse gas emissions while improving the built environment [2]. The Renovation Wave is reinforced by the recast Energy Performance of Buildings Directive (EPBD) [3] and the revised Energy Efficiency Directive (EED) [4]. Together, these EU directives require Member States to move from broad renovation ambitions towards measurable targets, structured renovation plans and better information on individual buildings.

The recast EPBD sets specific targets for non-residential buildings. Member States must establish maximum energy performance thresholds corresponding to the worst-performing 16% and 26% of their national non-residential building stock. Buildings must

Academic Editor: Aliakbar Kamari

Received: 28 September 2026
Revised: 23 October 2026
Accepted: 28 October 2026
Published: 30 October 2026

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meet these thresholds by 2030 and 2033, respectively [3,5,6]. The thresholds can be set for the non-residential stock as a whole or separately by building type or category [6]. The Directive also replaces long-term renovation strategies with National Building Renovation Plans (NBRPs), which must describe the national stock, renovation rates, barriers, financing needs and the pathway towards a zero-emission building stock by 2050 [3,7]. Article 22 further strengthens national databases by requiring information on the energy performance of individual buildings and the overall building stock [3,8]. The revised EED also requires annual renovation of at least 3% of the floor area of eligible heated or cooled buildings owned by public bodies; the calculation covers buildings with more than 250 m^2 of total useful floor area [4]. These requirements highlight the need for reliable building-level data to guide renovation prioritisation.

The scale of renovation required in Lithuania presents a considerable challenge. The Ministry of Environment (2026) reports that the national building stock comprises more than 2.5 million buildings [9]. A separate review by the National Audit Office (2025) reports that approximately 661,000 energy-using buildings have assigned energy performance classes and a combined area of 201.7 million m^2. The same review calculated that buildings account for approximately 25 TWh, or about 40%, of Lithuania's annual final energy use [10]. These figures highlight the scale of the renovation challenge and the need to establish clear priorities for building renovation. This article contributes to addressing that challenge.

Lithuania is also adapting its policy framework to the recast EPBD. The Lithuanian Long-Term Renovation Strategy was approved in 2021 and aims to achieve a highly energy-efficient and decarbonised building stock by 2050 [11]. A more detailed plan outlining how to achieve these targets was developed in 2022 [12]. Renovation and energy efficiency are also addressed in the updated National Energy and Climate Action Plan 2021–2030 [13] and the 2024 National Energy Independence Strategy [14]. Lithuania submitted its draft NBRP on 6 January 2026, and the European Commission published its feedback on 14 July 2026 [7,15,16]. Maduta et al. (2026) examined 16 draft NBRPs, including Lithuania's, and found that the new plans generally provide more structured and comparable information than the previous long-term renovation strategies. Further development is still needed for the implementation of minimum energy performance standards for non-residential buildings [17].

Lithuanian regulations identify educational buildings as a distinct registered-use category within the public-purpose group [18]. This category includes schools, vocational and higher education institutions, kindergartens, nurseries, research institutes, observatories, meteorological stations and non-industrial laboratories. Energy performance design and certification are governed by the construction technical regulation (STR) STR 2.01.02:2016 [19], while hygiene norms establish requirements for general education schools and pre-school environments [20,21]. Public renovation projects are also subject to green public procurement requirements [22]. Within this broad registered category, the condition of schools and kindergartens has particular implications for occupants' health, comfort and cognitive performance [23–28].

School studies have identified ventilation problems and associations between indoor conditions, health and learning [23,24,29–31]. Classroom carbon dioxide (CO_2) can indicate ventilation conditions during occupancy, although it does not describe indoor air quality as a whole [27,32]. Lithuanian studies have examined classroom conditions alongside the energy and carbon outcomes of renovation [33–38]. Other research has considered energy performance together with indoor environmental quality and occupant outcomes [39–44]. Broader assessment approaches include environmental-comfort indicators, school sustainability frameworks, indoor-environmental-quality tools and digital twins [42,45–49]. These studies establish the relevance of occupied conditions to renovation assessment, but the registry analysed here contains no indoor environmental measurements.

At stock level, Lithuanian residential building studies have used energy performance certificate (EPC) databases to examine performance across construction and regulatory periods [50,51]. Building performance also has increasing relevance within the European sustainability framework [52]. Broader research has demonstrated the potential of EPC data for urban energy and retrofit analysis [53,54], while identifying errors, uneven data quality and differences between national assessment methods [53,55,56]. EPC-based analyses describe the certified subset, whose characteristics may differ from those of uncertified buildings. Linking certificates with registry information on building use, age, area, physical depreciation and intervention history can therefore clarify both stock characteristics and remaining information gaps.

Related Baltic research provides useful regional context. Kundzina et al. (2022) examined Latvia's non-residential building stock using statistical information and EPC records [57]. Using Estonian EPC data, including educational buildings, Ferrantelli and Kurnitski (2022) examined how alternative classification methods affected estimated renovation requirements [58]. The present study complements this regional work by examining the relationship between registry coverage, incomplete certification and preliminary educational building screening.

Evidence remains limited on combining a registry-defined educational building population with official EPCs, registry-based physical depreciation and recorded intervention history. A rule-based hierarchy was selected to make its assumptions traceable to regulatory requirements and national stock-modelling sources [11,19]. Simple baselines were used to assess its additional classification value. This choice supports transparent screening under incomplete certification; it does not establish superiority over statistical imputation, machine learning or building typology methods.

This study characterises the registry-defined population of 4736 educational-purpose building objects across all 60 Lithuanian municipalities. Its primary contribution is to identify stock characteristics, data-completeness patterns and the uncertainty introduced when analytical proxy categories extend screening beyond buildings with official EPCs. It also examines whether physical depreciation and recorded intervention history can narrow a preliminary screening group. Policy documents support regulatory interpretation, while responses from five municipalities provide exploratory contextual evidence.

The aim of this study is to determine how effectively national registry and energy performance data can describe Lithuania's officially registered educational-purpose building stock and support transparent preliminary renovation screening. The following research questions were addressed:

RQ1. What are the main characteristics and data completeness patterns of Lithuania's registry-defined educational-purpose building stock?

RQ2. To what extent do analytical energy performance proxy categories agree with official EPC groupings among buildings with known certificates, and how much additional coverage of the national stock do they provide?

RQ3. To what extent can EPC information, analytical proxy categories, registry-based physical depreciation and recorded intervention history be combined to narrow a preliminary renovation screening group, and which data limitations prevent a defensible ranking of individual buildings?

2. Materials and Methods

2.1. Research Design

Three data sources were used in this study:

1. An extract from Lithuania's national building register covering officially registered educational buildings.
2. Written questionnaire responses from Lithuanian municipalities.
3. European and Lithuanian policy documents on building renovation, energy performance and public-sector responsibilities.

The study was a quantitatively led assessment of Lithuania's registry-defined educational building stock. Registry analysis formed the primary empirical component and addressed stock characteristics and data completeness (RQ1), proxy coverage and agreement (RQ2), and preliminary renovation-screening scenarios (RQ3). Policy documents provided the regulatory context for interpreting the available variables. Written responses from five municipalities provided exploratory evidence on practices, barriers and information needs. The three evidence streams were analysed separately and integrated during interpretation. The municipal responses were not treated as nationally representative evidence or as independent tests of the research questions.

2.2. Definition and Scope of the Educational Building Stock

The analysis focused on individual building objects officially registered for educational or scientific purposes.

Buildings were selected for this study based on their officially registered purpose. All selected buildings were classified as having an educational or scientific purpose within the public-purpose group. They met the definition of the educational building category set out in the Lithuanian construction regulation on the classification of structures and premises [18]. The unit of analysis was therefore an individual registered building object rather than an educational institution or organisation.

The scope included all building objects meeting this registered-purpose criterion. Separately registered premises were not included, and educational institutions operating within buildings registered for residential, administrative or another purpose fell outside the registry-defined population. Accordingly, the term "Lithuanian educational building stock" in this study refers specifically to the registry-defined population of building objects officially registered for educational or scientific purposes, rather than every location in which educational activities may occur.

2.3. Building-Stock Data Source and Collection

Building-level data were obtained from the Lithuanian Centre of Registers (Registrų centras). A preliminary manual review of selected registry records was used only to identify the relevant variables and define the requested data structure. It was not used to select the final study population. The authors requested that all building objects meet the registered-purpose criterion described in Section 2.2. The request specified the required variables, spreadsheet structure and an extraction unit of one officially registered building object per row. The Centre of Registers then prepared a custom national extract specifically for this study rather than supplying a pre-existing publicly available educational building database. Data collection took place between 15 January and 12 May 2026. The supplied registry information contained update dates between 1 January and 8 April 2026 and was therefore treated as a time-specific registry snapshot.

The resulting extract contained 4736 building-object records across all 60 Lithuanian municipalities and approximately 80 source variables. No records were excluded after receipt, and all 4736 building objects were retained in the national analysis. Data quality

checks covered the record count, municipal coverage, exact duplicate rows, missing values, variable formats, year ranges and consistency between information on the start and completion of construction. No exact duplicate records were detected. Original registry values were preserved, while cleaned and derived analytical variables were stored separately. Missing or invalid values were handled separately for each indicator and did not lead to exclusion of the corresponding building. Because the formal request covered all registry objects meeting the specified purpose criterion, the dataset was treated as the registry-defined population of building objects officially registered for educational or scientific purposes at the registry reference date.

2.4. Variables Included in the Analysis

Table 1 summarises the main groups of registry and derived variables available in the dataset. Selected variables were used in the analyses described below (not all available fields were analysed).

Table 1. Main groups of building stock variables.

Variable Group	Main Variables	Analytical Purpose
Stock classification	Municipality, object name, object type, registered-purpose group and registered purpose.	Definition of the national stock and municipality-level aggregation
Construction characteristics	Construction-start and completion years, building age, construction period, number of floors, walls, roof covering and building category.	Description of the historical and structural composition of the stock
Area and valuation	Total, useful, principal, residential, basement and built-up areas, volume, replacement value, market value and valuation date.	Description of building size and registry valuation information
Registry-based physical depreciation	Registry-based physical depreciation percentage.	Description of a registry-based property-valuation indication (not an engineering assessment of technical condition)
Energy information	Official EPC class, calculated thermal energy demand for heating, heating system and combined official/proxy energy performance category.	Assessment of official-data availability, proxy coverage and energy performance patterns
Intervention history	Registered start and completion years of reconstruction, capital repair, simple repair and modernisation.	Description of recorded administrative intervention history.

Note: EPC = energy performance certificate.

Calculated thermal energy demand for heating a building or part of a building was recorded in kWh/(m²·year) for 2075 buildings with official EPC information (43.8%) [19]. Of these entries, 1727 were positive, and 348 were recorded as zero. Because the meaning of the zero entries could not be verified from the registry extract, the main heating-demand summaries and group comparisons used strictly positive values only (n = 1727, 36.5% of the registry-defined population). The 348 buildings with zero entries remained in all other applicable analyses.

A sensitivity analysis retained all 2075 registered heating-demand values, including zeros, and compared the mean, median, interquartile range, age correlation and construction-period differences with the positive-only analysis. Zero-value and positive-value records were also compared by official EPC class and recorded intervention completion. No zero values were imputed or recoded as missing in the source data.

The registry contained a physical depreciation percentage for 4226 buildings. In Lithuanian real estate valuation practice, this variable contributes to the determination of property value [59]. The source extract did not specify whether each value was derived from an age-based calculation, an inspection or another valuation procedure.

Accordingly, this study treats the variable as a registry-based physical depreciation indicator. It is not interpreted as an engineering assessment of structural defects, safety or technical condition.

2.5. Data Preparation and Derived Variables

To improve data accuracy, the dataset was screened for duplicate rows, incompatible formats, missing values and other errors. All string and categorical variables were converted to numerical formats and coded.

Some variables were not included in the extract and therefore had to be calculated from the available data. Building age was one such variable and was calculated from the registered construction-completion year as follows:

$$\text{Building age} = \text{reference year (2026)} - \text{construction completion year.}$$

Building age and the indicator for buildings aged at least 20 years were calculated from the registered year in which construction was completed. In the 2026 reference year, an age of at least 20 years corresponds to completion in 2006 or earlier. A separate year variable was used for descriptive construction-period assignment: the registered year in which construction started when present and valid ($n = 3177$), with the registered completion year used as a fallback for 1559 records (32.9%) with no recorded start year. The original start-year field was not overwritten. A separate year-source flag identified whether the period assignment for each record was based on the construction-start year or the completion-year fallback. Building age and completion-based stock totals were based solely on the registered completion year and were not inferred from the descriptive construction-period assignment. The following inclusive year bands were used for descriptive construction-period grouping:

- Before 1940: Interwar modernism and natural materials;
- 1940–1990: The Soviet era and mass construction based on standardised designs;
- 1991–2005: The beginning of independence and the period before EPCs;
- 2006–2013: The first energy standards, under which buildings must meet energy classes C/B;
- 2014–2016: Transition to energy class A;
- 2017–2020: Strict energy efficiency (A+/A++);
- 2021 or later: Green transformation and sustainability (A++ and sustainable construction).

These periods were selected to reflect stages in Lithuanian history and to examine whether those stages influenced changes in the building stock and transitions in Lithuanian energy performance requirements. However, the construction period was used as a descriptive grouping variable and was not interpreted as a direct measure of energy performance or physical condition. Energy-class proxy rules are described separately in Section 2.5.1.

2.5.1. Analytical Energy Performance Proxy Assignment

The officially registered energy performance certificate (EPC) class was retained as the primary observed energy performance variable and was not overwritten. An official EPC class was available for 2075 buildings (43.8%). For the remaining 2661 buildings, a separate analytical proxy category was assigned for stock-level screening. The assignment hierarchy and the source flag retained for each building are presented in Table 2.

Table 2. Hierarchy and source flags used for the combined official/proxy energy performance variable.

Priority	Source	Assignment Rule	Buildings, n
1	Official EPC class	Original registered EPC class retained without modification	2075
2	New-building regulatory proxy	Construction-start year used first; completion year used only when start year was missing: 2006–2013 = C; 2014–2016 = B; 2017 = A; 2018–2020 = A+; 2021 or later = A++	25
3	Modernisation regulatory proxy	Modernisation start year used as an annual proxy: before 2014 = D; 2014–2023 = C; 2024 or later = conditional B proxy for qualifying renovation/modernisation financed from Lithuanian and/or European Union public funds (funding of modernisation could not be verified)	20
4	Long-Term Renovation Strategy construction-period proxy	Start-year-first variable: 2005 or earlier = ≤D; 2006–2013 = C; 2014–2018 = B; 2019 = A	2616
	Total		4736

Note: EPC = energy performance certificate. Counts describe the source used for the combined variable after retaining official EPCs. Proxy categories were assigned only when an official EPC was unavailable. No buildings remained unclassified. The same proxy rules were subsequently applied without using the official EPC value for the internal validation analysis. ≤D is a broad analytical proxy category that does not distinguish between official EPC classes D, E, F and G.

When constructing the combined official/proxy variable, the proxy hierarchy was applied only when an official EPC class was unavailable. First, a new-building regulatory proxy was assigned using the registered construction-start year, with the construction-completion year used only when the start year was missing. Second, where the new-building rule did not apply, a modernisation regulatory proxy was assigned using the registered modernisation-start year. Third, the remaining buildings were assigned a construction-period proxy using the construction-year-based energy-performance classification described in Subsection 1.1.6 of the Lithuanian Long-Term Renovation Strategy [11]. This final step used the same start-year-first variable, with a completion-year fallback, defined in Section 2.5. A separate source variable identified whether each final value came from an official EPC, the new-building proxy, the modernisation proxy or the construction-period proxy.

The new-building and modernisation categories represent annual approximations of the minimum requirements specified in the Lithuanian energy performance regulation [19]. These categories are analytical regulatory proxies and are not official or legally verified EPC classes. In particular, the registry did not establish whether every recorded modernisation met the applicable intervention-scope or cost-to-value conditions. The construction-period categories from the Long-Term Renovation Strategy represent national stock-modelling assumptions based on certified buildings from the corresponding periods [11]. The broad ≤D category indicates that the available information did not support assigning a building to a higher category, but it does not distinguish between official classes D, E, F and G.

The proxy used the registered year in which modernisation started but did not use the years of reconstruction, capital repair or simple repair to assign an energy category. The registry records did not establish whether these interventions included energy

performance improvements, affected the whole building or met the regulatory conditions required for a specific minimum energy class. Consequently, the analytical proxy represents a screening baseline based on construction and modernisation rather than an estimate of current certified energy performance.

Throughout this study, values generated by the regulatory and strategy-based rules are termed analytical proxy categories. They are not official EPC classes, do not constitute energy certification and are not used to demonstrate legal compliance or to identify individual buildings exceeding future EPBD thresholds. The variable that retains the official EPC class where available and otherwise applies an analytical proxy category is termed the combined official/proxy energy performance category.

2.5.2. Internal Validation of the Analytical Proxy Categories

Internal validation was conducted using all 2075 buildings with an official EPC class recorded in the registry. For this analysis, the official EPC value was excluded from the assignment hierarchy, and the same new-building, modernisation and construction-period proxy rules were applied independently using the remaining registry variables. The original official EPC field remained unchanged.

Because the construction-period method generated a broad ≤D category, official EPC classes D, E, F and G were harmonised into a single ≤D group for validation. The D category generated by the modernisation proxy was harmonised in the same way. The resulting ordered comparison scale was A++, A+, A, B, C and ≤D. Agreement within one category refers to this harmonised scale. Because ≤D combines four official EPC classes, this measure should not be interpreted as agreement within one original EPC class at the lower end of the scale.

Agreement between the harmonised category labels was described using a six-category confusion matrix, exact agreement, agreement within one category, the direction of disagreement and linearly weighted Cohen's kappa. The proxy was classified as higher when it assigned a better category than the official EPC and as lower when it assigned a poorer category. For binary screening, official D–G and proxy D/≤D were treated as positive, and C-or-better as negative. Sensitivity, specificity, positive predictive value (PPV) and negative predictive value (NPV) were calculated. Agreement was examined by construction period, proxy source and whether at least one intervention completion was recorded.

The hierarchy was compared with two six-category baselines: assigning every building to ≤D, and using construction year alone. The construction-year-only comparator applied the same new-building date bands as the hierarchy and assigned ≤D before 2006, without using modernisation information. A separate binary comparator flagged buildings with a start-first/completion-fallback construction year before 1990. All comparisons used the same certified subset. These comparators did not change the study's proxy assignment rules.

The new-building and modernisation regulatory proxies were evaluated primarily as minimum performance bounds rather than predictions of the exact final EPC class. Using the original, unharmonised official EPC scale, a record was classified as compatible when its official class was equal to or better than the applicable proxy minimum. Exact agreement and kappa for these sources were retained as descriptive comparisons of the labels entering the combined screening variable, rather than measures of whether a minimum bound was satisfied. Minimum-threshold compatibility was not interpreted as legal compliance because the extract did not contain relevant permit or application dates or establish the modernisation scope, cost-to-value ratio or financing source. The timing of the official EPC relative to the intervention was also unavailable.

Ninety-five per cent percentile bootstrap intervals were calculated from 10,000 paired building-level resamples. Paired differences in exact agreement were calculated using the same resampled buildings for the hierarchy and each baseline. Construction-period

analyses were resampled within each period. Metrics with zero denominators were reported as undefined. These intervals describe empirical stability under building-level resampling within the certified subset. They do not represent sampling uncertainty for the registry-defined population, correct non-random certification, or establish performance among uncertified buildings.

To examine potential selection associated with EPC availability, certified and uncertified buildings were compared descriptively by completion-based age, construction period, positive registered total floor area, registry-based physical depreciation and intervention status. The intervention indicator included reconstruction, capital repair, simple repair and modernisation and required at least one recorded completion year. A prevalence sensitivity analysis recalculated PPV and NPV at assumed official D–G prevalences of 30%, 40%, 50%, 60%, 70% and 80%, holding sensitivity and specificity at their observed certified-subset values. The observed certified prevalence was included as a reference. These scenarios did not estimate the true prevalence or proxy accuracy among uncertified buildings.

2.5.3. Intervention History

Separate binary indicators were created for reconstruction, capital repair, simple repair and modernisation, based on whether a completion year was recorded for each category. The combined completed-intervention indicator was positive when at least one of these completion years was present. Where several completion years were recorded, the latest was used to calculate the number of years since the last intervention. The separate major-intervention indicator included reconstruction, capital repair and modernisation and excluded simple repair.

Under STR 2.01.02:2016, reconstruction, renovation or modernisation and repair may be subject to minimum energy performance requirements when the work restores or improves the building envelope and/or engineering systems and its cost exceeds 25% of the building value, excluding land [19]. However, the registry extract did not provide sufficient information to determine whether these conditions applied to each recorded intervention or whether the resulting energy class had been formally verified. Intervention records were therefore retained as contextual screening information, while only the registered modernisation-start year was used to construct the conditional regulatory proxy described in Section 2.5.1.

2.5.4. Preliminary Renovation-Screening Scenarios

Two exploratory screening scenarios were constructed to address RQ3. The official-EPC scenario was limited to the 2075 buildings with an official EPC class recorded in the registry. Buildings were ordered from class G to class A++, and proportions of 16% and 26% were applied to this certified subset to identify the EPC classes containing the corresponding illustrative boundaries. Because multiple buildings shared the same EPC class, these calculations identified class-level boundaries rather than a unique ranking of individual buildings.

The complete-stock scenario used the combined official/proxy energy performance category for all 4736 buildings. Proportions of 16% and 26% were applied only to illustrate the possible scale of complete-stock screening groups. They were not treated as Lithuania's formal EPBD thresholds or used to identify individual worst-performing buildings. A broad D-or-lower screening group was defined as buildings with an official D, E, F or G class or an analytical D/≤D proxy category.

To examine whether the broad D-or-lower group could be narrowed transparently, two registry indicators were applied: a recorded physical depreciation value of at least 40% and no recorded completion year for reconstruction, capital repair, simple repair or modernisation. The 40% value was retained as the main illustrative threshold because it

was close to the upper quartile of the observed physical depreciation distribution (75th percentile: 38%). Alternative thresholds of 30% and 50% were examined to assess sensitivity to this choice. The thresholds were treated as exploratory screening choices rather than engineering condition limits or an empirically established optimal cut-off. Counts, percentages and associated registered floor areas were calculated, with missing depreciation values reported separately.

The energy performance relevance of the registry indicators was assessed among all 1908 certified buildings with recorded physical depreciation. The depreciation and intervention filters were applied before considering the official EPC class. Buildings meeting the 40% threshold and completion-based intervention criterion were compared with the remaining buildings in this certified subset using official EPC class distributions and strictly positive calculated heating demand. This provided an internal comparison of the indicators without restricting the validation population to official D–G buildings. No composite score or individual ranking was produced.

2.6. Quantitative Statistical Analysis

Categorical variables were summarised using frequencies and percentages. Continuous variables were described using means and standard deviations and, for skewed distributions, medians and interquartile ranges. Minimum and maximum values were also examined.

Pearson's chi-square test and Cramér's V were used for categorical comparisons. Kruskal–Wallis tests compared physical depreciation and positive calculated heating demand across construction-period groups defined using construction-start year first and construction-completion year as a fallback. Building age used in Spearman correlation analyses was calculated from the registered construction-completion year.

Because building age, physical depreciation, floor area and calculated heating demand were not normally distributed, non-parametric methods were used. The Kruskal–Wallis test was used to compare three or more independent groups. The effect size was calculated as follows:

$$\varepsilon^2 = \frac{H - k + 1}{n - k}$$

where (H) is the Kruskal–Wallis statistic, (k) is the number of groups and (n) is the valid sample size. Spearman's rank correlation was used to analyse relationships between building age, physical depreciation and positive calculated heating demand.

The analysis covered the registry-defined educational-purpose building population. Stock-level comparisons were interpreted primarily through absolute differences, effect sizes, data completeness and practical relevance. Statistical tests and p-values were retained as secondary descriptive summaries rather than as a basis for generalising from a sample to that population. Certification was not randomly distributed, so registry-wide coverage did not remove uncertainty when interpreting certified-building validation results for uncertified buildings. Bootstrap intervals described the empirical stability of validation estimates within the certified subset; they did not correct for certification selection or establish predictive performance in the uncertified buildings. Data preparation and construction of derived variables were performed in Microsoft Excel for Microsoft 365. Descriptive and inferential statistical analyses were conducted in IBM SPSS Statistics, version 32.0.0.0 (IBM Corp., Armonk, NY, USA).

The additional benchmark comparisons, sensitivity analyses, predictive-value calculations and bootstrap analyses were performed in Python 3.12. ChatGPT (GPT-5.6 Sol and GPT-6.1 Sol. OpenAI, San Francisco, CA, USA) assisted with script preparation and checking.

2.7. Municipality Questionnaire Design

To better understand the Lithuanian building stock at the municipal level, a questionnaire was developed and sent to each Lithuanian municipality. The questionnaire aimed to examine how sustainability considerations are addressed in educational building renovation and public procurement processes. The study's researchers developed the questionnaire, which contained 20 open-ended questions. The collected educational building-stock data did not influence the questionnaire's design.

The same questionnaire was sent to all 60 municipalities. No questions or questionnaire versions were tailored to individual municipalities or their political party majorities. The questions focused on renovation, energy performance, indoor environmental quality and green procurement, reflecting topics addressed in European and Lithuanian policies [3,4,19,22]. The topics and their distribution across the 20 open-ended questions are shown in Table 3.

Table 3. Municipality questionnaire domains.

Domain	Questions	Main Topics
Green public procurement	Q1–Q3	Procurement requirements, education-specific criteria and sustainability
Energy efficiency and renewable energy	Q4–Q6	Minimum energy requirements, renewable systems, programmes and financing
Indoor environmental quality	Q7–Q9	Microclimate monitoring, indoor air quality and sustainability indicators
Implementation barriers and support	Q10–Q12	Financial and administrative barriers, circularity, training and institutional support
Wellbeing and financial decision-making	Q13–Q19	Comfort, health, budget constraints, long-term benefits and life-cycle considerations
Assessment systems	Q20	Indicators and formal evaluation systems used in decision-making

2.8. Municipality Recruitment and Questionnaire Administration

The municipal questionnaire component of the study was conducted between 26 March and 1 September 2025. All 60 Lithuanian municipalities were invited to participate.

Municipalities were contacted by email between 21 May and 12 June 2025. Because municipal organisational structures differed, the study's researchers identified potential respondents separately for each municipality using publicly available contact information on municipal websites. Initial messages were sent to municipal administration directors, construction or architecture personnel, procurement specialists or other employees with the relevant expertise to answer the questionnaire.

If the original recipient was not responsible for the relevant subject, the study's researchers asked municipal staff to forward the questionnaire to the appropriate personnel. The questionnaire was sent as a Microsoft Word document, and the questions were also included directly in the email when this was more convenient for municipal staff.

Twenty-two municipalities responded to the initial emails and engaged in communication, giving a contact-response rate of 36.7%. However, only five municipalities submitted usable, completed questionnaire responses, corresponding to a questionnaire-completion rate of 8.3%. Because the response group was small and self-selected, the questionnaire findings were treated as qualitative evidence rather than as a nationally representative account of sustainability in educational building renovation or public procurement processes.

2.9. Qualitative Analysis of Municipality Responses

Voyant was used for text analysis and visualisation. One researcher analysed the questionnaire responses manually in Lithuanian, following qualitative content-analysis practice informed by Hsieh and Shannon (2005) [60].

Before analysis, the responses were read several times and organised according to the main questionnaire topics: green procurement, energy performance, renewable energy, indoor environmental quality, sustainability, renovation planning, financial constraints, administrative and technical capacity, user wellbeing and assessment needs. Responses were compared to identify recurring views and differences between municipalities. The findings from this stage were used to explain and contextualise the registry and policy findings.

2.10. Policy-Document Analysis

To better understand how Lithuania's educational building stock relates to European and Lithuanian renovation objectives, a policy-document review was conducted. Document analysis was based on the principles described by Bowen (2009) [61].

The reviewed documents included:

- Directive (EU) 2024/1275 on the energy performance of buildings [3];
- Directive (EU) 2023/1791 on energy efficiency [4];
- European Commission EPBD implementation guidance [5,6,8];
- Documents concerning National Building Renovation Plans [7,15,16];
- The Lithuanian Long-Term Renovation Strategy and its implementation plan [11,12];
- The updated National Energy and Climate Plan [13];
- The National Energy Independence Strategy [14];
- Lithuanian regulations concerning building classification and energy performance certification [18,19];
- Lithuanian green public-procurement requirements [22].

No formal policy-extraction matrix or document-scoring system was developed or used for this stage of the study. Relevant European and Lithuanian policy documents were reviewed and summarised under common topics relevant to the study, including educational buildings, target dates, renovation and energy performance requirements.

The European and Lithuanian policy review aimed to compare the collected educational building-stock information and the practices described by municipalities with policy objectives and requirements, and to identify areas of alignment or discrepancy.

2.11. Ethical Considerations

The municipality questionnaire was approved by the Kaunas University of Technology Research Ethics Commission on 26 March 2025 (protocol No. M4-2025-06).

Participation was voluntary. Potential participants received information about the purpose of the research, the intended use of their responses, confidentiality, withdrawal and data processing.

The analysis did not use municipal staff members' names, positions or other directly identifying personal information. All municipalities were assigned non-identifying codes, such as M1–M60, but only five were included in the analysis because only five of the 60 municipalities submitted final responses. Original responses were stored in restricted-access locations on the researcher's computer and in the OneDrive/SharePoint environment of the institution employing the study's researchers, with a retention period of 5 years.

3. Results

The registry results are presented according to their role in addressing the research questions. Sections 3.1, 3.2, 3.3.1, 3.4.1 and 3.5 describe stock characteristics and data-completeness patterns relevant to RQ1. Sections 3.3.2 and 3.3.3 assess proxy coverage and agreement with official EPC information for RQ2. Sections 3.4.2 and 3.4.3 present the preliminary screening scenarios used to address RQ3. Section 3.6 provides exploratory municipality questionnaire findings, while Section 3.7 compares the registry findings with the national strategy baseline (RQ1 and RQ2).

3.1. Coverage and Construction Profile of the Educational Building Stock (RQ1)

As of 12 May 2026, there were 4736 officially registered educational buildings across all 60 Lithuanian municipalities. Of these, 4374 (92.4%) were registered as non-residential buildings and 362 (7.6%) as mixed buildings. The number of educational buildings per municipality ranged from 6 to 542, with a median of 66.5 buildings.

A total of 2234 building records (47.2%) were assigned to the school subcategory. The remaining records represented various educational and related subcategories, including kindergartens, teaching blocks, laboratories, workshops, universities and scientific institutes. Because all these subcategories fell within the educational building category, they were analysed together rather than separately.

The combined registered floor area in the 4736-record extract was 8,769,617.24 m² (approximately 8.77 million m²). Although most buildings had total floor-area information available, two had a recorded value of 0 m². Among the 4734 buildings with positive values, the median total floor area was 1021.2 m² (interquartile range: 427.1–2383.2 m²), and the mean was 1852.5 m² (standard deviation: 2290.4 m²). The largest recorded building had a total floor area of 31,643.9 m². The mean age of the educational buildings was 58.4 years (standard deviation: 27.2 years), while the median was 54 years (interquartile range: 43–65 years). A high proportion of educational buildings, 96.2% (4556), were at least 20 years old. The general characteristics of Lithuania's educational building stock are shown in Table 4.

Table 4. General characteristics of Lithuania's officially registered educational-purpose building stock.

Indicator	Result
Number of building objects	4736
Municipalities represented	60
Non-residential building objects	4374 (92.4%)
Mixed building objects	362 (7.6%)
Combined registered total floor area	8.77 million m²
Median total floor area	1021.2 m²
Mean building age	58.4 years
Median building age	54 years
Buildings completed before 1991	4347 (91.8%)
Buildings aged ≥20 years	4556 (96.2%)
Recorded physical depreciation available	4226 (89.2%)
Official EPC class available	2075 (43.8%)
Positive calculated heating demand available	1727 (36.5%)
At least one intervention completion recorded	2203 (46.5%)

Note: EPC = energy performance certificate.

The construction-start year was blank for 1559 records (32.9%), all of which had a valid construction-completion year. Grouping based on construction-start year, with construction-completion year as a fallback, assigned 645 records (13.6%) to the period before 1940, 3786 (79.9%) to 1940–1990, 163 (3.4%) to 1991–2005 and 142 (3.0%) to 2006 or later. In

total, 4431 records (93.6%) were assigned a year before 1991 (Figure 1 and Table 5). This differs from the 4347 buildings (91.8%) recorded as completed before 1991 (Table 4). Using the completion year alone changed the construction-period assignment for 187 records (3.9%). Among records with both dates, 138 had intervals of at least 20 years between the registered construction-start and construction-completion years, including 22 with intervals of at least 50 years.



Figure 1. Distribution of Lithuanian educational-purpose buildings by construction period. Construction periods use the registered construction-start year, with the completion year as a fallback (authors' own work).

Table 5. Educational building characteristics by construction period.

Construction Period	Buildings, n (%)	Median Recorded Physical Depreciation, %	Buildings with Official EPC Class, n (%)	Median Positive Calculated Heating Demand, kWh/(m²·year)
Before 1940	645 (13.6%)	53.0	211 (32.7%)	188.7
1940–1990	3786 (79.9%)	26.0	1677 (44.3%)	122.2
1991–2005	163 (3.4%)	10.0	70 (42.9%)	88.2
2006–2013	66 (1.4%)	0.0	53 (80.3%)	47.0
2014–2016	22 (0.5%)	0.0	20 (90.9%)	49.4
2017–2020	35 (0.7%)	0.0	27 (77.1%)	17.1
2021 or later	19 (0.4%)	0.0	17 (89.5%)	9.3
Total	4736 (100.0%)	26.0	2075 (43.8%)	116.3

Note: EPC = energy performance certificate. EPC percentages use all records within each period; medians use valid depreciation or strictly positive heating demand. Valid n by period: depreciation 578/3386/123/64/22/34/19. Heating 187/1373/60/43/20/27/17. Rounded period shares sum to 99.9%. Construction periods use the registered construction-start year, with the completion year as a fallback.

3.2. Registry-Based Physical Depreciation and Recorded Intervention History (RQ1 and RQ3 Inputs)

Registry-based physical depreciation values were available for 4226 educational buildings (89.2%). The mean value was 29.4% (standard deviation: 17.5%), and the median was 26% (interquartile range: 17–38%). Values ranged from 0% to 85%.

Registry-based physical depreciation differed across construction-period groups defined using construction-start year first and completion year as a fallback (Kruskal–Wallis $H(6) = 1132.89$, $n = 4226$, $p < 0.001$, $\varepsilon^2 = 0.267$). The within-period median was 53.0% before 1940, 26.0% in 1940–1990 and 10.0% in 1991–2005. It was 0.0% in each later period group. Building age, calculated separately from construction-completion year, was positively associated with the registry-based depreciation indicator (Spearman's $r_s = 0.676$, $n = 4226$, $p < 0.001$). These comparisons do not establish a measured technical condition for individual buildings.

Figure 2 shows the distribution of the registry-based physical depreciation indicator by construction period.

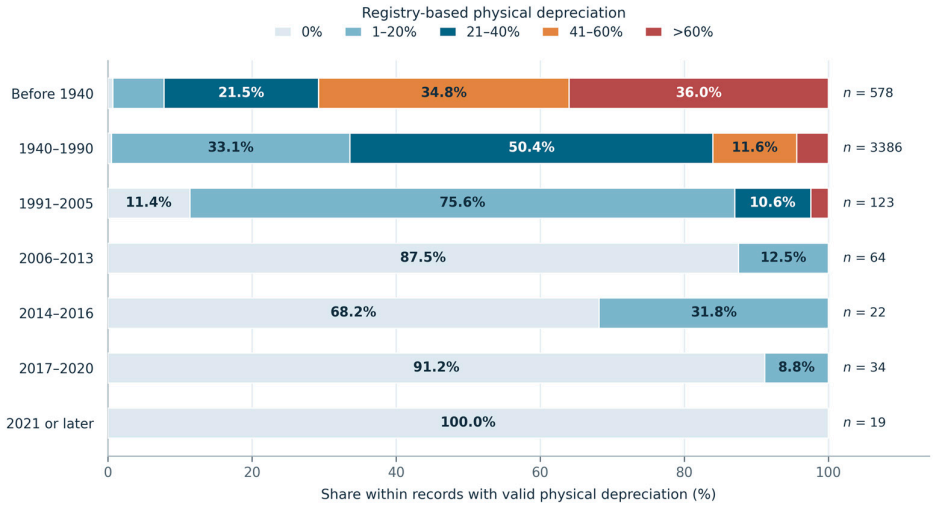


Figure 2. Distribution of the registry-based physical depreciation indicator by construction period (authors' own work). Note: Each percentage is calculated among buildings with a valid registry-based depreciation value in that period. Denominators are shown alongside the bars. Construction periods use the registered construction-start year, with completion year as a fallback.

At least one completion year for reconstruction, capital repair, simple repair or modernisation was recorded for 2203 educational buildings (46.5%). The remaining 2533 educational buildings (53.5%) had no intervention completion recorded.

A reconstruction completion year was recorded for 1172 educational buildings (24.7%), simple repair completion for 1060 (22.4%), capital repair completion for 351 (7.4%) and modernisation completion for 233 (4.9%). Because a building could have completion years recorded for more than one intervention category, these categories were not mutually exclusive.

Among educational buildings with at least one intervention completion recorded, the median time since the latest intervention was 11 years (interquartile range: 6–16 years), and the mean was 12.5 years. The distribution of buildings by time since the latest recorded intervention completion is shown in Table 6.

Table 6. Time since the latest recorded intervention completion.

Time Since Latest Recorded Intervention Completion	Buildings, n	% of Complete Stock	% of Buildings with an Intervention Completion Recorded
0–5 years	498	10.5%	22.6%
6–10 years	507	10.7%	23.0%
11–20 years	981	20.7%	44.5%
More than 20 years	217	4.6%	9.8%
No intervention completion recorded	2533	53.5%	-
Total	4736	100.0%	-

For period-based analyses, a recorded major intervention was defined as at least one completed reconstruction, capital repair or modernisation. Simple repair was not included in this combined indicator. Each building was counted once, even when it had more than one qualifying intervention. The reported area is the building's registered total floor area, not a verified renovated area or a measure of energy savings.

The 1940–1990 group, defined using construction-start year first and completion year as a fallback, contained the largest number of buildings with a recorded major intervention (n = 1247). Their combined registered total floor area was 3,339,644.25 m². Across all periods, 1566 buildings (33.1%) had such a record, and their combined registered floor area was 4,029,114.16 m². Table 7 and Figure 3 show the distribution of these records across construction periods. They do not measure the area renovated.

Table 7. Number of interventions and total area of educational buildings by construction period.

Construction Period	Buildings with at Least One Recorded Major Intervention, n (%)	Combined Registered Total Floor Area of Those Buildings, m²
Before 1940	264 (40.9%)	464,428.64
1940–1990	1247 (32.9%)	3,339,644.25
1991–2005	47 (28.8%)	183,960.77
2006–2013	5 (7.6%)	39,212.17
2014–2016	2 (9.1%)	772.81
2017–2020	0 (0.0%)	0.00
2021 or later	1 (5.3%)	1095.52
Total	1566 (33.1%)	4,029,114.16

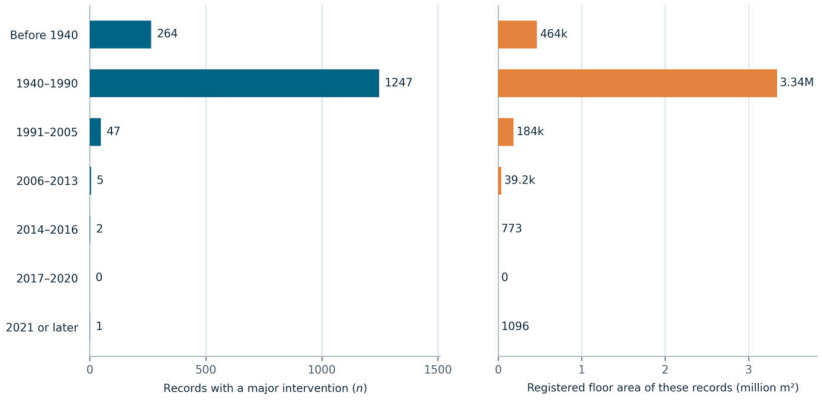


Figure 3. Educational buildings with at least one recorded major intervention by construction period. Construction periods use the registered construction-start year, with the completion year as a fallback (authors' own work).

3.3. Energy Performance Information (RQ1 and RQ2)

3.3.1. Official EPC Availability and Calculated Heating Demand (RQ1)

An official EPC class was available for 2075 buildings (43.8%), and the official EPC field was missing for the remaining 2661 buildings (56.2%). These missing official values were neither filled nor overwritten. Separate analytical proxy categories were generated for stock-level screening and are reported in Sections 3.3.2 and 3.3.3.

Among the 2075 buildings with an official EPC class, 484 (23.3%) were in class B or higher, 683 (32.9%) in class C and 908 (43.8%) in classes D–G.

Official EPC availability varied across construction-period groups defined using construction-start year first and completion year as a fallback. An official EPC class was recorded for 211 of 645 records assigned to the pre-1940 period (32.7%) and for 20 of 22 records assigned to 2014–2016 (90.9%). The association between construction period and EPC availability yielded $\chi^2(6, n = 4736) = 120.09$, $p < 0.001$, with Cramér's V = 0.159. Construction-period assignment does not itself identify an official EPC class or indicate when a certificate was issued. The official EPC class distribution is shown in Figure 4.

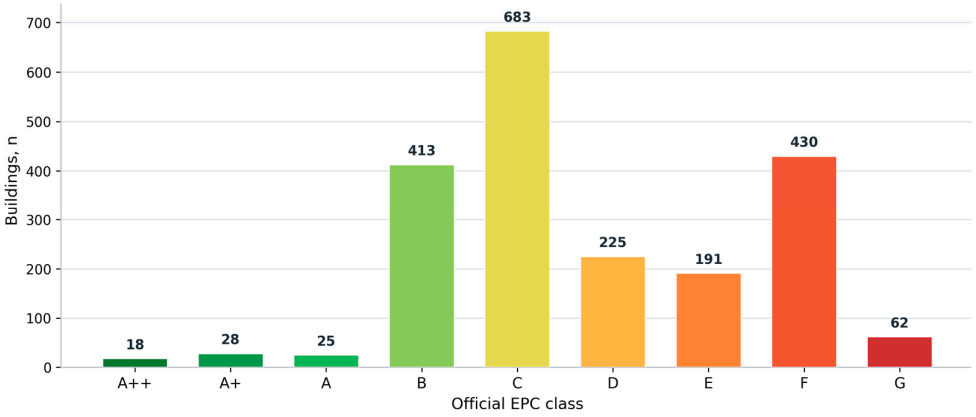


Figure 4. Distribution of official EPC ratings among educational buildings (*n* = 2075) (authors' own work). Note: EPC = energy performance certificate.

Certified and uncertified buildings differed in their registry characteristics. Median completion-based age was 51 years among certified buildings and 56 years among uncertified buildings. The median positive registered floor area was 1759.7 m² and 636.8 m², respectively, while median registry-based physical depreciation was 24% and 29%. The proportions completed before 1991 were 88.7% and 94.2%. At least one intervention completion was recorded for 1273 of 2075 certified buildings (61.3%) and 930 of 2661 uncertified buildings (34.9%), a difference of 26.4 percentage points. Classes B and C together accounted for 1096 official certificates (52.8%). Detailed comparisons and valid denominators are provided in Table 8.

Table 8. Registry characteristics of educational-purpose buildings by official EPC availability.

Characteristic	Official EPC Available (*n* = 2075)	Official EPC Unavailable (*n* = 2661)
Completion-based age, years	51 (41–62); *n* = 2075	56 (45–67); *n* = 2661
Positive registered total floor area, m²	1759.7 (786.0–3517.9); *n* = 2075	636.8 (330.2–1529.0); *n* = 2659
Registry-based physical depreciation, %	24 (15–34); *n* = 1908	29 (19–43); *n* = 2318
Completed before 1991	1840/2075 (88.7%)	2507/2661 (94.2%)
Age at least 20 years	1931/2075 (93.1%)	2625/2661 (98.6%)
At least one recorded intervention completion	1273/2075 (61.3%)	930/2661 (34.9%)

Note: EPC = energy performance certificate. Continuous variables are presented as median (interquartile range), followed by the valid number of records. Categorical variables are presented as count/denominator (%). Building age was calculated as 2026 minus the registered construction-completion year. Two uncertified buildings with zero registered total floor area were excluded from the positive-area summary only. Physical depreciation is a registry-based property-valuation indicator, not an engineering assessment. The intervention indicator required at least one recorded completion year for reconstruction, capital repair, simple repair or modernisation; each building was counted once.

Calculated heating demand was recorded for all 2075 buildings with an official EPC class. Of these values, 348 (16.8%) were zero. Official classes B or C accounted for 306 zero-value records (87.9%), compared with 790 of the 1727 positive-value records (45.7%). At least one intervention completion was recorded for 263 zero-value records (75.6%) and 1010 positive-value records (58.5%). The zero entries were therefore unevenly distributed across the observed EPC and intervention groups.

The main heating-demand analysis retained 1727 strictly positive records, representing 36.5% of the 4736-record extract. The median calculated heating demand was 116.3 kWh/(m²·year) (interquartile range: 68.4–277.7 kWh/(m²·year)), and the mean was 208.2

kWh/(m²·year). Results with the zero entries included are presented alongside the main analysis in Table 9.

Table 9. Sensitivity of calculated heating-demand results to inclusion of unverified zero entries.

Measure	Main Analysis: Strictly Positive Values	Sensitivity Analysis: Zeros Included
Buildings, n	1727	2075
Calculated heating demand, median (IQR), kWh/(m²·year)	116.3 (68.4–277.7)	90.5 (40.8–232.8)
Calculated heating demand, mean, kWh/(m²·year)	208.2	173.3
Spearman's r_s: building age and calculated heating demand	0.278	0.206
Kruskal–Wallis H (6): construction-period groups	213.00	112.85
Construction-period effect size, ε^2	0.120	0.052

Note: IQR = interquartile range. Building age was calculated from completion year. Construction-period groups used construction-start year, with the completion year as a fallback. The sensitivity analysis included all 348 recorded zeros without assuming that they represented verified zero demand. The main analysis remained restricted to strictly positive values. These are calculated EPC-related values, not metred energy use.

Among the 1727 records with strictly positive calculated heating demand, demand varied across construction-period groups based on construction-start year, with completion year as a fallback (Kruskal–Wallis H(6) = 213.00, $p < 0.001$, $\varepsilon^2 = 0.120$). The period-specific median was 188.7 kWh/(m²·year) for the pre-1940 group and 9.3 kWh/(m²·year) for 2021 or later. Building age, based on the registered construction-completion year, had a weak positive correlation with calculated heating demand (Spearman's $r_s = 0.278$, $n = 1727$, $p < 0.001$). These values represent calculated EPC-related heating demand, not measured building energy use.

3.3.2. Combined Official/Proxy Energy Performance Categories and Coverage Gain (RQ2)

An official EPC class was available for 2075 buildings (43.8%), while 2661 buildings (56.2%) had no official class. For buildings without an official EPC, the hierarchy described in Section 2.5.1 assigned new-building regulatory proxies to 25 buildings, modernisation regulatory proxies to 20 and Long-Term Renovation Strategy construction-period proxies to 2616. All 4736 buildings therefore had either an official EPC class or an analytical proxy category.

All 2616 buildings assigned through the Long-Term Renovation Strategy fallback were placed in the broad ≤D category. Under the start-year-first hierarchy, buildings assigned a construction year of 2006 or later had already been evaluated using the higher-priority new-building rule. The strategy fallback therefore comprised buildings with assigned construction years of 2005 or earlier, using the construction-start year when available and the construction-completion year otherwise.

The strategy fallback accounted for 2616 of the 2661 uncertified buildings (98.3%), so most proxy assignments depended solely on construction year. The validation subset contained 117 new-building and 213 modernisation proxy records, whereas these rules were applied to 25 and 20 uncertified buildings, respectively. Their validation results therefore describe the certified records and do not directly establish performance in the smaller uncertified groups. Relative to the construction-year-only comparator, modernisation information changed the harmonised category of ten uncertified buildings (0.4%), from ≤D to C. Table 10 presents the official EPC classes and the combined official/proxy energy-performance categories.

Table 10. Official EPC classes and combined official/proxy energy performance categories.

Energy Performance Category	Official EPC, n (% of 2075)	Combined Official/Proxy Category, n (% of 4736)
A++	18 (0.9%)	20 (0.4%)
A+	28 (1.3%)	33 (0.7%)
A	25 (1.2%)	28 (0.6%)
B	413 (19.9%)	415 (8.8%)
C	683 (32.9%)	706 (14.9%)
D	225 (10.8%)	235 (5.0%)
≤D proxy	-	2616 (55.2%)
E	191 (9.2%)	191 (4.0%)
F	430 (20.7%)	430 (9.1%)
G	62 (3.0%)	62 (1.3%)
Total	2075 (100.0%)	4736 (100.0%)

Note: EPC = energy performance certificate. The combined variable retained the official EPC wherever available. The ≤D proxy is a broad analytical screening category and is not an official EPC class.

The combined official/proxy variable contained 20 buildings in category A++, 33 in A+, 28 in A, 415 in B, 706 in C, 235 in D, 2616 in the broad ≤D proxy category, 191 in E, 430 in F and 62 in G. In total, 3534 buildings (74.6%) had either an official EPC class from D to G or an analytical D/≤D proxy category. The combined distribution is a stock-level screening estimate and does not represent Lithuania's official EPC distribution for educational buildings. In particular, the 2616 buildings in the ≤D proxy category could not be separated into official D, E, F or G classes. Figure 5 compares the official EPC distribution with the combined official/proxy categories.

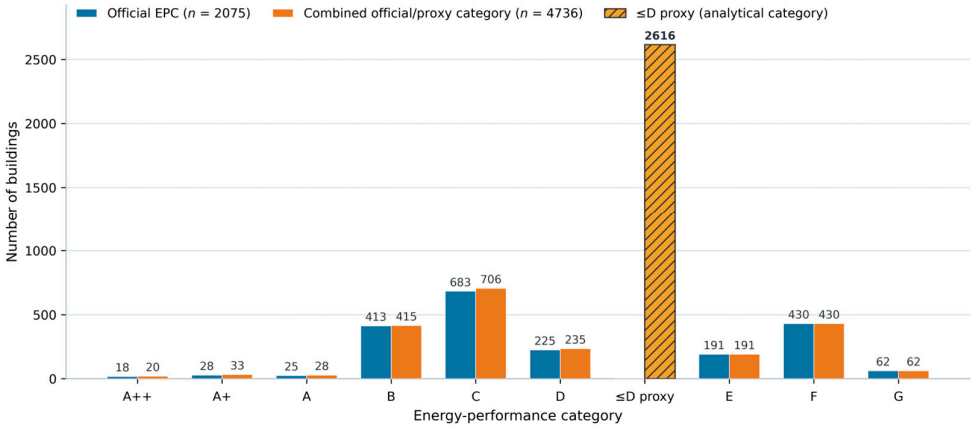


Figure 5. Distribution of official EPC classes and combined official/proxy energy performance categories. The ≤D proxy is a broad analytical screening category and not an official EPC class (authors' own work). Note: EPC = energy performance certificate.

3.3.3. Internal Validation of Analytical Proxy Categories (RQ2).

To evaluate agreement between the analytical proxy and observed energy performance information, the proxy assignment procedure was applied separately to the 2075 buildings with known official EPC classes, without using the official EPC class as an input. Official classes D, E, F and G and the corresponding D/≤D proxy outputs were harmonised into a single ≤D category, resulting in six ordered categories: A++, A+, A, B, C and ≤D. The resulting cross-classification is presented in Table 11.

Table 11. Confusion matrix comparing harmonised official EPC classes with analytical proxy categories.

Harmonised Official EPC	A++	A+	A	B	C	≤D	Total
A++	13	4	0	0	0	1	18
A+	4	16	0	1	2	5	28
A	0	3	4	0	1	17	25
B	0	0	0	19	65	329	413
C	0	0	0	0	81	602	683
≤D	0	0	0	1	6	901	908
Total	17	23	4	21	155	1855	2075

Note: EPC = energy performance certificate. Rows show harmonised official EPC categories, and columns show analytical proxy categories. Official D, E, F and G classes and the D/≤D proxy outputs were harmonised into ≤D. Diagonal cells indicate exact agreement.

Exact agreement between the analytical proxy and the harmonised official EPC category was observed for 1034 of the 2075 validated buildings (49.8%, 95% bootstrap interval: 47.7–52.0%). Agreement within one harmonised category was 82.8% (81.2–84.4%), and linearly weighted Cohen's κ was 0.243 (0.205–0.280). Assigning every building to ≤D produced 43.8% exact agreement and κ = 0.000; the construction-year-only comparator produced 46.8% exact agreement and κ = 0.197. The hierarchy's paired gain in exact agreement was 6.1 percentage points over the constant baseline (95% bootstrap interval: 5.0–7.2) and 3.0 points over construction year alone (2.2–3.8). Detailed benchmark results are presented in Table 12.

Table 12. Internal comparison of the analytical proxy hierarchy and simple category-assignment baselines (n = 2075).

Metric	Full Proxy Hierarchy	Construction-Year-Only Comparator	Always ≤D Baseline
Exact agreement, %	49.8 (47.7–52.0)	46.8 (44.8–49.0)	43.8 (41.6–45.9)
Within one harmonised category, %	82.8 (81.2–84.4)	81.3 (79.6–82.9)	76.7 (74.9–78.5)
Linearly weighted Cohen's κ	0.243 (0.205–0.280)	0.197 (0.158–0.235)	0.000 (0.000–0.000)
Sensitivity, %	99.2 (98.6–99.8)	99.7 (99.2–100.0)	100.0 (100.0–100.0)
Specificity, %	18.3 (16.1–20.5)	9.8 (8.1–11.5)	0.0 (0.0–0.0)
Positive predictive value (PPV), %	48.6 (46.3–50.9)	46.2 (44.1–48.4)	43.8 (41.6–45.9)
Negative predictive value (NPV), %	96.8 (94.3–99.0)	97.4 (94.3–100.0)	—

Note: Parentheses contain 95% percentile bootstrap intervals from 10,000 building-level resamples. The ordered categories are A++, A+, A, B, C and ≤D. Binary metrics treat official D–G and proxy D/≤D as positive. The construction-year-only comparator uses the same new-building date bands and assigns ≤D before 2006, without modernisation information. Regulatory labels represent minimum-performance assumptions; exact agreement compares output labels rather than satisfaction of a minimum bound. — = undefined because the method produces no negative results. These intervals describe stability within the certified subset and do not correct certification selection or establish accuracy in uncertified buildings.

Agreement by intervention completion status and proxy source is presented in Table 13.

Table 13. Agreement between official EPC and proxy categories by intervention completion status and proxy source.

Validation Group	n	Exact Agreement, n (%)	Within-One-Category Agreement, n (%)	Linearly Weighted κ
All validated buildings	2075	1034 (49.8%)	1718 (82.8%)	0.243
No intervention completion recorded	802	569 (70.9%)	735 (91.6%)	0.550
At least one intervention completion recorded	1273	465 (36.5%)	983 (77.2%)	0.080
New-building proxy	117	67 (57.3%)	114 (97.4%)	0.722
Modernisation proxy	213	82 (38.5%)	176 (82.6%)	0.070
Strategy construction-period proxy	1745	885 (50.7%)	1428 (81.8%)	0.000

Note: κ = linearly weighted Cohen's kappa. Official D–G and proxy D/≤D categories were harmonised into ≤D. Exact agreement, within-one-category agreement and κ compare the labels entering the screening variable. For new-building and modernisation sources, minimum-threshold compatibility is the primary interpretation; label agreement does not assess satisfaction of a minimum bound. The strategy proxy has a constant ≤D output, resulting in κ = 0.000 on the fixed six-category scale.

For the regulatory sources, the primary comparison assessed compatibility with a minimum performance bound. On the original official EPC scale, the official class was equal to or better than the proxy minimum for 107 of 117 new-building records (91.5%; 95% bootstrap interval: 86.3–95.7%) and 203 of 213 modernisation records (95.3%; 92.5–98.1%). These results describe compatibility with the assumed minimum, not exact-class prediction or regulatory compliance because the applicability and timing conditions could not be verified for individual buildings.

The proxy assigned a lower energy performance category than the official EPC to 1027 buildings (49.5%) and a higher category to 14 buildings (0.7%). The remaining 1034 buildings received the same category. The direction of disagreement therefore showed that the proxy was predominantly conservative rather than optimistic.

For binary screening, the proxy identified 901 of the 908 buildings with official D–G classes, giving a sensitivity of 99.2% (95% bootstrap interval: 98.6–99.8%). Of the 1167 buildings officially rated C or better, 213 remained C-or-better under the proxy, giving a specificity of 18.3% (16.1–20.5%). PPV was 901/1855 = 48.6% (46.3–50.9%), and NPV was 213/220 = 96.8% (94.3–99.0%). Thus, fewer than half of the proxy-positive certified buildings were officially D–G, despite the high sensitivity. A simple pre-1990 screening flag gave sensitivity of 95.4% (94.0–96.7%), specificity of 14.7% (12.7–16.8%), PPV of 46.5% (44.3–48.8%) and NPV of 80.4% (74.9–85.6%) in the same certified subset.

Descriptive exact-label agreement was 57.3% for the new-building proxy (n = 117, κ = 0.722) and 38.5% for the modernisation proxy (n = 213, κ = 0.070). These measures describe the screening labels rather than minimum-bound compatibility. All 1745 validation records assigned through the strategy construction-period fallback received ≤D. Exact agreement in this group was 50.7%, and weighted κ was 0.000 because the constant output provided no agreement beyond that expected from the marginal category distribution.

Performance also varied by construction period (Table 14). Among the 70 certified buildings assigned to 1991–2005, 67 received ≤D and three received C through the modernisation rule. Specificity was 7.0%, and PPV was 40.3%. This group accounted for 40 of the 954 false positives (4.2%), whereas the 1940–1990 group accounted for 829 (86.9%). Low specificity therefore extended across the older construction-period groups rather than being confined to 1991–2005.

Table 14. Agreement between analytical proxy categories and harmonised official EPC categories by construction period.

Construction Period	Certified n	Exact Agreement, %	Within One Harmonised Category, %	Linearly Weighted κ
Before 1940	211	59.2 (52.6–65.9)	86.7 (82.0–91.0)	0.031 (−0.004–0.075)
1940–1990	1677	48.4 (46.0–50.8)	81.4 (79.5–83.2)	0.063 (0.050–0.078)
1991–2005	70	42.9 (31.4–54.3)	80.0 (70.0–88.6)	0.038 (0.000–0.094)
2006–2013	53	30.2 (18.9–43.4)	98.1 (94.3–100.0)	0.000 (0.000–0.000)
2014–2016	20	90.0 (75.0–100.0)	90.0 (75.0–100.0)	0.000 (0.000–0.000)
2017–2020	27	74.1 (55.6–88.9)	100.0 (100.0–100.0)	0.458 (0.140–0.738)
2021 or later	17	76.5 (52.9–94.1)	100.0 (100.0–100.0)	0.000 (0.000–0.000)

Note: κ = linearly weighted Cohen's kappa. Periods use the construction-start year, with the completion year as a fallback. Parentheses contain 95% percentile bootstrap intervals from 10,000 within-period resamples. Category order is A++, A+, A, B, C and ≤D. Intervals use only replicates with defined denominators; 8823 κ replicates were defined for 2014–2016 and 9922 for 2021 or later. Zero-width intervals observed at 0% or 100% and constant-output κ describe the empirical resampling distribution and do not establish perfect performance elsewhere. Small recent-period groups have limited information. These intervals do not correct certification selection or account for unmodelled municipal dependence.

Among certified buildings without a recorded intervention completion (n = 802), exact agreement was 70.9% (κ = 0.550), compared with 36.5% (κ = 0.080) among those with at least one completion recorded (n = 1273). PPV was 72.5% (95% bootstrap interval: 69.2–75.8%) and 34.0% (31.2–36.7%), respectively, while specificity was 33.4% and 13.2%. The proportions with official D–G classes also differed: 63.8% without a recorded intervention completion and 31.1% with one.

Of the 954 buildings officially rated C or better but assigned proxy ≤D, 761 (79.8%) had a recorded intervention completion. Among the 2661 uncertified buildings, 930 (34.9%) also had at least one completion recorded. These buildings retained their assigned proxy categories because the intervention records did not verify the resulting energy performance.

In hypothetical scenarios holding sensitivity and specificity constant, assumed official D–G prevalences of 30%, 50% and 70% produced PPVs of 34.2%, 54.8% and 73.9%, respectively. The corresponding NPVs were 98.2%, 95.9% and 91.0%. At the observed certified prevalence of 43.8%, the recalculated values reproduced the observed PPV of 48.6% and NPV of 96.8%. These results illustrate prevalence dependence under the stated assumptions rather than observed performance among uncertified buildings (Table 15).

Table 15. Predictive values under hypothetical prevalences of official EPC classes D–G.

Assumed official D–G Prevalence, %	PPV, %	NPV, %
30.0	34.2	98.2
40.0	44.7	97.3
43.8 (certified-subset reference)	48.6	96.8
50.0	54.8	95.9
60.0	64.5	94.0
70.0	73.9	91.0
80.0	82.9	85.5

Note: PPV = positive predictive value, NPV = negative predictive value. Official D–G classes represent the positive outcome, and analytical D/≤D categories represent a positive screening result. Sensitivity and specificity were held at their unrounded certified-subset values, 901/908 and 213/1167, respectively. The reference prevalence was calculated as 908/2075 before rounding. These conditional scenarios illustrate prevalence dependence; they do not estimate actual prevalence or proxy performance among uncertified buildings.

https://doi.org/10.3390/su182111076

3.4. Data Completeness and Registry-Based Screening

3.4.1. Availability of Building-Level Information (RQ1)

Data availability varied across the analysed variables. Registered construction-completion year was available for all 4736 buildings, and 4734 had a positive registered total floor area. By contrast, official EPC class, positive calculated heating demand, intervention completion years and useful floor area were unavailable or unrecorded for substantial parts of the stock. The availability of selected variables is shown in Table 16.

Table 16. Availability of selected building-level information.

Variable	Value, n (%)	No Usable Value, n (%)
Construction-completion year	4736 (100.0%)	0 (0.0%)
Positive total floor area	4734 (99.96%)	2 zero values (0.04%)
Recorded physical depreciation	4226 (89.2%)	510 (10.8%)
Official EPC class	2075 (43.8%)	2661 (56.2%)
Calculated heating-demand field populated	2075 (43.8%)	2661 (56.2%)
Positive calculated heating-demand value	1727 (36.5%)	3009 (63.5%)
At least one intervention completion recorded	2203 (46.5%)	2533 with no intervention completion recorded (53.5%)
Useful floor area	326 (6.9%)	4410 (93.1%)

Note: EPC = energy performance certificate.

Official EPC class and calculated heating demand had identical field availability: values were recorded for 2075 educational buildings and missing for 2661. After zero heating-demand values were excluded from the main heating-demand analyses, positive values remained available for 1727 educational buildings. Physical depreciation was unavailable for 510 educational buildings, and 2533 had no intervention completion recorded.

3.4.2. Official-EPC Exploratory Screening Scenario (RQ3)

The first illustrative screening scenario comprised the 2075 buildings with official EPC classes. When these records were ordered from class G to class A++, the 16% boundary corresponded to 332 buildings and fell within class F: it included all 62 class G records and 270 of the 430 class F records. The 26% boundary corresponded to 540 buildings and fell within class E: it included all 492 records in classes F and G and 48 of the 191 class E records.

These calculations identify class boundaries within the certified subset but cannot uniquely identify individual buildings within the boundary class. Positive calculated heating-demand values were available for 1727 buildings, so this variable could not provide complete within-class ordering. Moreover, the certified subset represents 43.8% of the registered population and should not be assumed to represent buildings without an EPC.

The 16% and 26% values are therefore illustrative screening boundaries. They do not constitute Lithuania's formal EPBD thresholds or identify individual buildings that legally exceed those thresholds.

3.4.3. Complete-Stock Exploratory Screening Scenario (RQ3)

The complete-stock scenario combined official EPC classes with analytical proxy categories for all 4736 buildings. Applying proportions of 16% and 26% to this stock corresponded to approximately 758 and 1231 buildings, respectively. These values illustrate the potential scale of the screening groups but do not identify individual worst-performing buildings under the EPBD.

Official EPC classes E, F and G accounted for 683 buildings. Both proportional boundaries therefore extended into the group containing buildings with an official D class or an

analytical D/≤D proxy category. The 2616 buildings in the broad ≤D proxy category could not be ranked against one another using the available energy performance information.

In total, 3534 buildings (74.6%) had either an official EPC class from D to G or an analytical D/≤D proxy category. Their combined registered floor area was approximately 5.051 million m², representing 57.6% of the registered floor area of educational buildings.

Within the D-or-lower group of 3534 buildings, 903 had a recorded physical depreciation value of at least 40%, 2218 had no intervention completion recorded, and 536 met both conditions. Physical depreciation information was unavailable for 455 buildings in this group. The combined criteria identified 809 buildings at a 30% depreciation threshold and 406 at 50%, compared with 536 at 40% (Table 17). The 536-building pool contained 105 buildings with official D–G classes and 431 with analytical D/≤D categories. The latter represented 80.4% of the pool.

The main 536-building scenario refers specifically to the absence of a recorded intervention completion, rather than the absence of all intervention information. Detailed counts, percentages and associated registered total floor areas are presented in Table 17.

Table 17. Registry screening characteristics and sensitivity to physical depreciation thresholds among buildings with official D-G or analytical D/≤D categories.

Characteristic	Buildings, n	% of D-or-Lower Group	% of Registry-Defined Stock	Associated Registered Total Floor Area
All buildings in official D-G or proxy D/≤D	3534	100.0%	74.6%	5.051 million m²
Recorded physical depreciation ≥ 40%	903	25.6%	19.1%	0.843 million m²
No intervention completion recorded	2218	62.8%	46.8%	2.484 million m²
Depreciation ≥ 30% and no intervention completion recorded	809	22.9%	17.1%	0.568 million m²
Depreciation ≥ 40% and no intervention completion recorded	536	15.2%	11.3%	0.271 million m²
Depreciation ≥ 50% and no intervention completion recorded	406	11.5%	8.6%	0.163 million m²
Physical depreciation information unavailable	455	12.9%	9.6%	—

Note: The D-or-lower group contains buildings with official EPC classes D–G or analytical D/≤D proxy categories. Percentages use 3534 buildings for the D-or-lower group and 4736 for the registry-defined stock. No intervention completion recorded means no completion year for reconstruction, capital repair, simple repair or modernisation. Rows overlap, and the three combined threshold groups are nested. Missing depreciation values were excluded from threshold-based groups. Associated registered total floor area is not the area renovated. Physical depreciation is a registry valuation indicator. — = not reported.

Among the 1908 certified buildings with recorded physical depreciation, 116 met the 40% threshold and had no intervention completion recorded. This comparison included all official EPC classes. Of the selected buildings, 105 (90.5%) had official D–G classes, compared with 691 of the remaining 1792 buildings (38.6%), a difference of 52.0 percentage points. Median positive calculated heating demand was 578.8 kWh/(m²·year) in the selected group and 102.1 kWh/(m²·year) in the remaining group (Table 18). The selected group contained 105 of the 796 official D–G buildings with recorded physical depreciation (13.2%), showing that the filters narrowed the pool substantially while leaving many officially lower-rated buildings outside it.

Including zero heating-demand entries in this comparison retained the same direction of difference: median demand was 551.0 kWh/(m²·year) in the selected group (n = 116) and 81.0 kWh/(m²·year) in the remaining group (n = 1792).

Table 18. Internal comparison of registry screening indicators with official EPC classes and calculated heating demand among certified buildings with recorded physical depreciation.

Group	Buildings, n	Official D–G, n (%)	Positive Heating-Demand Values, n	Calculated Heating Demand, Median (IQR), kWh/(m²·Year)
Depreciation ≥ 40% and no intervention completion recorded	116	105 (90.5%)	112	578.8 (264.0–758.7)
All remaining certified buildings with recorded depreciation	1792	691 (38.6%)	1463	102.1 (63.0–228.3)

Note: EPC = energy performance certificate, IQR = interquartile range. The comparison includes all 1908 certified buildings with recorded physical depreciation; 167 certified buildings with missing depreciation were excluded. The registry filters were applied without selecting buildings by EPC class. The intervention criterion covers reconstruction, capital repair, simple repair and modernisation and is based on completion years. Heating-demand summaries include strictly positive calculated values only. The groups are mutually exclusive and together contain all 1908 buildings. These are internal descriptive associations, not verified engineering conditions or measured operational energy use.

3.5. Municipality-Level Stock Variation (RQ1)

The size of the educational building stock varied across Lithuania's municipalities. Vilnius city, Lithuania's capital, had the largest number, with 542 educational buildings. Kaunas, Lithuania's second-largest city, had 414 educational buildings, and Klaipėda, the third-largest city, had 177. The Vilnius district had 173 educational buildings and Šiauliai city had 143. Figure 6 illustrates municipality-level variation in official EPC availability and the proportion of buildings with at least one intervention completion recorded.

Vilnius city also had the largest combined area of educational buildings, at 1.77 million m². Kaunas city had 1.02 million m², Klaipėda city 0.49 million m² and Šiauliai city 0.35 million m².

The median age of educational buildings ranged from 38 to 63 years across municipalities. The highest median ages were observed in Pagėgiai, the Ignalina district and the Prienai district, and the lowest in Birštonas and Visaginas. Variation between municipalities was small in effect-size terms ($H(59) = 181.20$, $N = 4736$, $p < 0.001$, $\varepsilon^2 = 0.026$).

Median registry-based physical depreciation ranged from 14% to 38% across municipalities. The highest median values were found in Pagėgiai, the Širvintos district, the Ignalina district and the Rokiškis district. Variation between municipalities was also small in effect-size terms ($H(59) = 202.08$, $N = 4226$, $p < 0.001$, $\varepsilon^2 = 0.034$).

The proportion of educational buildings with an official EPC ranged from 12.7% to 83.3% across municipalities. Birštonas had the highest proportion, based on five of its six buildings (83.3%). Relatively high availability was also observed in the Šiauliai district (47/65), Visaginas (12/19), Kazlų Rūda (15/24) and the Kaunas district (70/114). The lowest availability was found in the Pasvalys district (8/63), the Rokiškis district (11/70), Rietavas (3/17), the Širvintos district (11/52) and the Prienai district (18/73). The association between municipality and EPC availability had Cramér's $V = 0.240$ ($\chi^2(59, N = 4736) = 273.69$, $p < 0.001$). Numerators indicate buildings with an official EPC, and denominators indicate the municipality's registry-defined educational building stock.

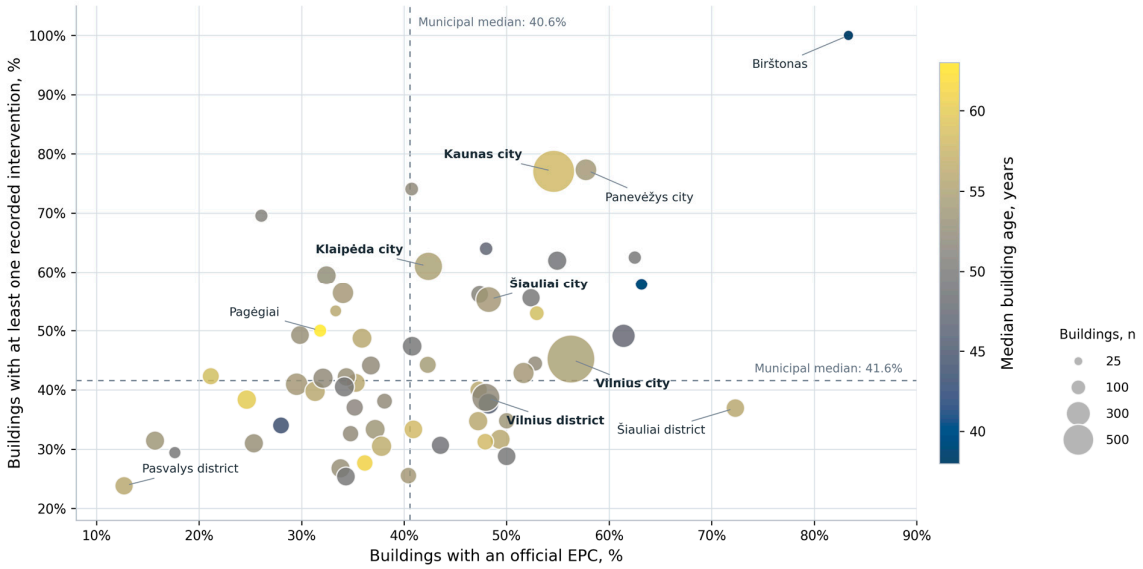


Figure 6. Municipality-level variation in official EPC availability and the proportion of buildings with at least one intervention completion recorded (authors' own work). Note: EPC = energy performance certificate. The vertical and horizontal dashed lines indicate the median municipality-level percentages of buildings with an official EPC (40.6%) and with at least one recorded intervention completion (41.6%), respectively.

The proportion of educational buildings with at least one intervention completion recorded ranged from 23.8% to 100% across municipalities. All six buildings in Birštonas had a completion recorded (6/6, 100%). Relatively high proportions were also observed in Panevėžys city (75/97), Kaunas city (319/414) and Druskininkai (20/27). The lowest proportions were found in the Pasvalys district (15/63), the Šalčininkai district (17/67) and the Zarasai district (12/47). The association between municipality and the presence of a completion record had Cramér's V = 0.293 ($\chi^2(59, N = 4736) = 406.73$, $p < 0.001$). Numerators indicate buildings with at least one intervention completion recorded, and denominators indicate the municipality's registry-defined educational building stock.

3.6. Contextual Municipality Questionnaire Findings

3.6.1. Municipality Participation

The study's researchers contacted all 60 Lithuanian municipalities. Twenty-two municipalities responded to the initial emails, giving a contact-response rate of 36.7%. Of these 22 municipalities, only five submitted questionnaire responses, representing a questionnaire-completion rate of 8.3% among all 60 municipalities contacted.

The five responses varied in length and completeness. Some municipal respondents addressed all 20 questions, while others left some individual questions unanswered. The findings from municipalities M1–M5 were treated as exploratory data for this study, rather than as representative estimates of the situation across Lithuania.

3.6.2. Procurement, Energy and Sustainability Practices

The responding municipalities reported that they followed general green public procurement requirements for construction work and public buildings. None of the five responding municipalities reported a separate procurement framework or system specifically designed for educational buildings.

One of the five municipalities reported that it considered quality as well as price when selecting contractors. That municipality's requirements covered building materials

and equipment, indoor air quality, acoustic and thermal comfort, and access to natural light. The municipalities also reported that minimum energy performance requirements for renovated buildings ranged from class C to class B, while new buildings were required to meet national energy performance standards.

Four of the five municipalities considered renewable energy an important factor in renovating educational buildings. Solar electricity was the most commonly mentioned technology, while one municipality also mentioned geothermal energy. The same municipality also described circular economy measures focused on sorting and recycling construction waste, using recycled materials and packaging, and limiting hazardous substances. The other four municipalities reported little practical experience with these measures or did not provide a detailed answer.

3.6.3. Indoor Environmental Quality

None of the five responding municipalities reported having a programme for monitoring CO_2, relative humidity or broader indoor environmental quality across their educational building stock. They stated that responsibility for meeting the relevant requirements for educational buildings lay with those responsible for managing them. When asked about microclimate monitoring, one municipality mentioned conducting energy audits, but these were not measurements of indoor environmental conditions. Overall, there was no reported practice of monitoring indoor environmental quality before and after renovation among these five municipalities.

3.6.4. Barriers, Support Needs and Prioritisation

All five municipalities reported financial challenges in renovating educational buildings. The main challenges were insufficient funding, increasing construction project costs, limited access to funding programmes and difficulties completing prepared projects without external financial support.

Other difficulties included the cost and duration of project preparation and the limited availability of qualified designers and technical specialists for educational buildings. The municipalities also reported challenges related to Lithuanian policies, including changing legal and technical requirements and short application periods for funding programmes that could help them renovate more buildings. They also reported a lack of experience with sustainable procurement practices and difficulties translating general sustainability criteria into technically applicable requirements.

Respondents also identified assistance that would help accelerate renovation projects. They reported that specialised training would help specialists work more efficiently. Practical examples of procurement procedures or documents would also help municipal staff save time when applying for additional funding. Because municipal staff involved in procurement and renovation differ in background and competence, clearer mandatory requirements are needed to avoid differing interpretations.

The five responding municipalities also had different priorities when selecting educational buildings for renovation. Prioritisation decisions were influenced by insufficient funding and the quality of project documentation. Overall, the responses did not show any use of a common or standardised framework for assessing and prioritising educational building renovations.

3.7. Comparison with the National Strategy Baseline (RQ1 and RQ2)

The Lithuanian Long-Term Renovation Strategy, approved in 2021, reported 2019 baseline figures of 4715 educational buildings and a total floor area of 8.503 million m^2 [11]. The dataset used in this study covered 4736 buildings with a total area of 8.770 million m^2. This represents a difference of 21 buildings and 0.267 million m^2. However, this

difference cannot be treated as direct growth in the educational building stock because some buildings may have been demolished or had their purpose changed from educational to other uses at different times during the intervening period.

The Lithuanian Long-Term Renovation Strategy reported that 1494 educational buildings had an EPC, representing 31.7% of the total educational building stock [11]. In this study, 2075 buildings had an official EPC class, representing 43.8%. The difference between the strategy figures and this study was 581 buildings, or 12.1 percentage points.

The Lithuanian Long-Term Renovation Strategy reported a distribution based on construction periods, with 79.4% in class D or lower, 13.4% in class C, 6.8% in class B and approximately 0.3% in class A or higher [11]. In the combined official/proxy variable used in this study, 74.6% of buildings had an official EPC class from D to G or an analytical D/≤D category, 14.9% were in category C, 8.8% were in category B, and 1.7% were in categories A–A++. This comparison is descriptive because the study combines official EPC observations with analytical proxy categories and therefore does not represent an official national EPC distribution. The differences between the Lithuanian Long-Term Renovation Strategy (LTRS) and this study are shown in Figure 7.



Figure 7. Comparison of the Lithuanian Long-Term Renovation Strategy's 2019 baseline with this study: (**A**) Differences between registered educational buildings, (**B**) registered total floor area, (**C**) official EPC availability, and (**D**) the strategy's construction-period-based distribution and this study's combined official/proxy categories. Panel D compares different classification bases and is descriptive (authors' own work). Note: EPC = energy performance certificate.

4. Discussion

4.1. General Findings

The central finding of this study is a coverage-certainty trade-off. National registry data permit characterisation of Lithuania's registry-defined educational-purpose building stock, but incomplete and heterogeneous energy performance and intervention information limits the certainty of building-level renovation screening. The discussion is therefore organised around the three research questions:

- Section 4.2 interprets registered-stock characteristics and data completeness (RQ1);
- Section 4.3 evaluates proxy coverage and agreement with official EPCs (RQ2);
- Section 4.4 assesses how the available indicators narrow a preliminary screening pool and why they cannot support a formal ranking (RQ3).

Sections 4.5 and 4.6 integrate the contextual municipal and policy findings and consider their implications for renovation planning.

4.2. Registered-Stock Characteristics and Data Completeness (RQ1)

The predominance of older completed buildings highlights the importance of adapting the existing stock. Construction-period grouping describes its historical composition, whereas completion year provides the basis for building age. Registry coverage and basic construction and area information were strong, but variables relevant to renovation assessment were less complete. The particularly limited availability of useful floor area, official EPCs and positive calculated heating demand restricts the assessments that the register can support.

Official EPC availability was higher than in the strategy baseline, but substantial certification gaps remained. Previous Lithuanian residential-stock studies [50,51] and related Latvian and Estonian analyses [57,58] demonstrate the value of EPC data for stock assessment. Including uncertified buildings here reveals information gaps that certificate-only analyses cannot describe. These findings also reflect broader concerns about EPC data quality and comparability [53–56].

The zero-inclusive sensitivity analysis reduced median calculated heating demand from 116.3 to 90.5 kWh/(m^2·year) and weakened the observed age and construction-period associations (Table 9). Zero entries were concentrated in classes B and C and more often had an intervention completion recorded, so their exclusion changed the analytical subset. Possible explanations include input or default-value errors, data-transfer or calculation artefacts, or genuine zero demand; none was verified. An explanation based on unheated buildings or parts could not be established. The main heating-demand summaries therefore describe records with strictly positive values and should not be treated as unbiased estimates for the certified or registry-defined stock.

4.3. Analytical Proxy Coverage and Agreement with Official EPCs (RQ2)

Analytical proxy categories extend screening coverage to all 4736 registered buildings, but their additional classification value is modest. Exact agreement was 49.8%, compared with 43.8% for assigning every building to ≤D and 46.8% for using construction year alone. Moreover, 98.3% of uncertified buildings entered the strategy fallback, and modernisation information changed only ten harmonised categories relative to the construction-year-only comparator. The main contribution is therefore a transparent account of coverage, assumptions and certification needs, rather than a substantial improvement in the prediction of current EPC classes.

The high sensitivity is accompanied by low specificity and a PPV of 48.6% in certified buildings. Using proxy categories alone to select individual projects or allocate municipal budgets could therefore direct resources towards buildings whose official EPC performance is better than the screening label suggests. Conversely, a small number of officially D–G buildings were assigned C-or-better. Proxy results should guide evidence collection and further assessment, while individual renovation and funding decisions require verified building information. The bootstrap intervals describe stability within the certified subset and do not resolve uncertainty about performance in uncertified buildings.

The certified subset differed from uncertified buildings in age, size, registry-based physical depreciation and intervention history. These differences limit the direct application of the validation results to uncertified buildings. The higher PPV among buildings without a recorded intervention completion also coincided with a higher proportion of official D–G classes in that group. The prevalence scenarios show that PPV would increase if D–G buildings were more common and sensitivity and specificity remained unchanged. However, neither the true prevalence nor the stability of these performance measures is

known for uncertified buildings, so the scenarios do not establish the direction or magnitude of the overall validation bias.

Recorded interventions remain useful contextual information because construction-period assumptions may become less representative after later works. Nevertheless, reconstruction, capital repair and simple repair cannot automatically justify a better energy category: the registry does not verify energy improvements, intervention scope or satisfaction of the conditions associated with a particular class. Buildings with missing EPC information and recorded interventions therefore remain candidates for updated certification.

4.4. Preliminary Renovation Screening and Limits of Intervention Data (RQ3)

The official-EPC scenario demonstrates that formal classification alone does not produce a unique ordering of buildings: ties remain within EPC classes, and calculated heating demand is too incomplete to resolve every tie. The complete-stock scenario extends screening coverage, but the broad ≤D category likewise prevents an energy performance ranking within that group.

Adding the depreciation and intervention-completion indicators identified a more restricted group associated with poorer official EPC performance and higher positive calculated heating demand within the certified subset. However, the filters retained only 13.2% of official D–G buildings with recorded depreciation. The 40% threshold therefore defines an illustrative screening choice rather than an optimal cut-off; thresholds of 30% and 50% produced pools of 809 and 406 buildings, respectively. These comparisons establish an energy performance association, not a verified technical condition.

The 536-building pool is a preliminary group for further assessment. Its intervention criterion means that no completion year was recorded, and its 431 proxy-classified buildings still require energy performance verification. Qualifying interventions may have been subject to minimum energy performance requirements under STR 2.01.02:2016 [19], but administrative records do not establish work scope, regulatory applicability or verified outcomes.

The decline in recorded major interventions from 64 buildings in 2021 to 20 in 2025 cannot establish a national energy-renovation slowdown. Recent records may be incomplete, and the affected area is unknown. Similarly, the strategy's planned annual renovation of 84 educational buildings and approximately 143,000 m^2 during 2024–2030 [11] cannot be assessed directly against these registry records. Monitoring progress requires harmonised information on intervention scope, renovated area and achieved performance.

4.5. Contextual Municipal Findings

The five municipal questionnaires identify practical concerns and differences in approach, but their small, self-selected response group prevents national generalisation. Variation in response detail may reflect difficulties in identifying responsible staff or coordinating information across departments; it does not establish a lack of interest or institutional capacity.

None of the responding municipalities described consistent monitoring of indoor environmental quality before and after renovation. Design-stage hygiene requirements and energy audits do not establish conditions during actual classroom occupancy. Previous school studies support examining these conditions alongside energy performance [33,34,40,41]. The responses therefore support further evaluation and pilot monitoring, without establishing that a new national requirement is justified.

4.6. Implications for Category-Specific Renovation Planning

Lithuanian regulations identify educational-purpose buildings as a separate registered building category [11,18]. Educational buildings have specific occupancy patterns, ventilation needs, operating schedules and occupant requirements. Children are also more sensitive to poor indoor conditions [23,25,42]. Educational buildings should therefore be analysed separately from the rest of the non-residential building stock.

The EPBD allows Member States to set non-residential energy performance thresholds for separate building types [3,5,6], and educational buildings can already be identified separately in the national registry. The results of this study demonstrate this possibility for Lithuanian educational buildings, whose construction period, energy performance, registry-based physical depreciation indicator, floor area, intervention history and municipal location can be analysed at the building level.

A practical first step would be to report educational buildings as a separate category in the national renovation framework. A second step would be to extend this approach to all other non-residential building categories. Separate reporting could include the number of buildings, floor area by official EPC class, calculated or metred energy use where available, intervention history, intervention category, energy savings, indoor environmental monitoring and data completeness.

For more detailed building-level prioritisation, a dedicated educational building assessment framework could complement, rather than replace, the EPC, which should remain the principal formal measure of calculated energy performance. A broader assessment could combine official EPC information with metred energy use, on-site technical condition, technical systems, verified intervention history, indoor environmental quality, accessibility, functional suitability, intensity of use and data certainty. Because different non-residential building categories have different occupancy patterns, operating schedules, technical systems and user requirements, category-specific assessment frameworks may be more appropriate than a single framework applied uniformly to every non-residential building.

The findings identify registry information that could support a future category-specific assessment framework, together with gaps that would need to be addressed. Developing its criteria and weights and validating its performance remain tasks for a separate study.

4.7. Strengths, Limitations and Further Research

The main strength of this study is its national coverage. The Centre of Registers supplied records for 4736 building objects officially registered for educational or scientific purposes across all 60 Lithuanian municipalities. This avoids geographical selection based on individual cities or voluntary municipal participation and enables building-level analysis of construction period, registry-based physical depreciation, energy-information availability, intervention history, registered floor area and municipal location.

A second strength is the separation of official EPC observations from analytical proxy categories. The original official EPC field was retained, a source flag identified the rule used for each proxy value, and the proxy was evaluated against all 2075 buildings with known official EPC classes. This makes both the gain in coverage and the associated classification uncertainty visible.

The population is defined by registered building purpose. Separately registered premises and educational institutions operating in buildings registered for another purpose were outside the scope of the study. The findings therefore describe the registry-defined educational-purpose building stock, rather than every location used for education. The extract is also a time-specific snapshot of records supplied in 2026, and later construction, demolition, changes in purpose and registry updates are not captured.

Official EPC classes were unavailable for 2661 buildings (56.2%). Proxy agreement was evaluated among buildings with known EPCs, and those results may not apply equally to buildings without an EPC. Agreement was lower among buildings with at least one intervention completion recorded, while the registry did not verify the scope of those works, the applicable permit and financing conditions, or whether the EPC preceded or followed an intervention. The broad ≤D proxy category also combines buildings that could have different official EPC classes. Consequently, proxy categories cannot establish a building's current certified energy performance or regulatory compliance.

Registry-based physical depreciation is a property-valuation indicator, not an engineering assessment, and may partly reflect building age. Intervention records do not identify the measures taken, the area affected, or the resulting energy performance, and the absence of a recorded completion year does not establish that no work occurred. Main heating-demand analyses used the 1727 strictly positive values because the meaning of 348 recorded zeros could not be verified. The zero-inclusive sensitivity analysis showed that their treatment affected the summaries and associations. Selective-exclusion bias cannot be ruled out, and its magnitude relative to true heating demand remains unknown.

Only five of the 60 municipalities returned questionnaires, and some individual questions remained unanswered. Their responses were analysed by one researcher without independent coding. These findings provide context from the responding municipalities but cannot establish how common the reported practices are across Lithuania.

Further research could link educational institutions to the buildings they use and test a category-specific assessment framework using verified technical condition, operational performance and intervention outcomes.

5. Conclusions

This study demonstrates that Lithuania's national building register can provide a population-level profile of the registry-defined educational-purpose building stock. The 4736 records covered all 60 municipalities and approximately 8.77 million m^2 of registered floor area. Of these buildings, 91.8% were completed before 1991. In answer to RQ1, population coverage and basic construction and area information were strong, but decision-relevant variables were substantially less complete. Official EPC classes were available for 43.8% of buildings and positive calculated heating-demand values for 36.5%. Registry-based physical depreciation is a property-valuation indicator rather than an engineering assessment, while calculated heating demand is not measured operational energy use.

In answer to RQ2, analytical proxy categories increased energy performance screening coverage from 43.8% to 100%, but exact agreement with harmonised official EPC categories was 49.8% and linearly weighted Cohen's κ was 0.243. Agreement was lower among buildings with at least one intervention completion recorded. The proxy can therefore support conservative stock-level screening and identify certification needs, but it cannot replace official EPCs, represent Lithuania's official EPC distribution or establish individual EPBD rankings.

In answer to RQ3, 3534 buildings had an official D–G class or an analytical D/≤D category. Applying the additional criteria of a registry-based physical depreciation value of at least 40% and no recorded intervention completion narrowed this group to 536 buildings. This is a transparent preliminary pool for further assessment, not a list of confirmed renovation priorities. Individual ranking remains constrained by the broad ≤D category, missing EPC and depreciation information, uncertain intervention scope, and the absence of verified technical-condition and measured operational-performance data.

The five returned municipal questionnaires provide contextual rather than nationally representative evidence, but they reinforce the need for more consistent renovation information, institutional support and monitoring. The principal contribution of this study is

to make the coverage-certainty trade-off explicit. Educational buildings can be reported separately in national renovation monitoring, while a future category-specific assessment framework could complement, rather than replace, official EPCs with verified technical condition, measured energy use, intervention outcomes, indoor environmental quality and data certainty.

Author Contributions: Conceptualisation, P.V.; methodology, P.V.; software, P.V.; validation, P.V. and L.S.; formal analysis, P.V.; investigation, P.V.; resources, P.V.; data curation, P.V. and L.S.; writing—original draft preparation, P.V.; writing—review and editing, L.S.; visualisation, P.V.; supervision, L.S.; project administration, L.S.; funding acquisition, L.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: The municipality questionnaire was approved by the Kaunas University of Technology Research Ethics Commission on 26 March 2025 (protocol No. M4-2025-06).

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The building-level registry data used in this study were obtained from the Lithuanian Centre of Registers and are not publicly available. Although the extract does not include building names or addresses, combinations of municipality, floor area and other characteristics could allow individual buildings to be identified. Access to the original records is subject to the Centre of Registers' conditions, and requests for access should be directed to the data provider. Aggregated results supporting the findings are presented in this article. Municipality questionnaire responses are not publicly available to protect respondent confidentiality.

Acknowledgments: During the preparation of this manuscript, the authors used OpenAI ChatGPT (GPT-5.6 Sol and GPT-6.1 Sol) to assist with language editing and clarification, preparation and checking of Python scripts for the additional analyses, and numerical consistency checks. The authors reviewed and edited the outputs and take full responsibility for the content of this publication.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

CO_2	Carbon Dioxide
EED	Energy Efficiency Directive
EPC	Energy Performance Certificate
EPBD	Energy Performance of Buildings Directive
EU	European Union
HN	Hygiene Norm
IQR	Interquartile Range
LTRS	Lithuanian Long-Term Renovation Strategy
NBRP	National Building Renovation Plan
RQ1–RQ3	Research Questions 1–3
STR	Construction Technical Regulation
NPV	Negative Predictive Value
PPV	Positive Predictive Value

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